AZOLIGANDS AS BRIDGES IN MACROCYCLIC DINICKEL COMPLEXES

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Abstract: The coordination chemistry of dinickel macrocyclic hexaamine-dithiophenolate complexes of Robson-type with azoligands is presented in this microreview. All complexes have been characterised by IR-, UV/Vis-spectroscopy, and X-ray crystallography. The bioctahedral transition metal complexes of the type $[(L^6)Ni_2(\mu\text{-}L')]^+$ exhibit a rich coordination chemistry since the active coordination site L' is accessible for a wide range of exogenous coligands.

Keywords: coordination chemistry, structures, azoligands, nickel macrocyclic complexes, amino-thiophenolate ligands.

1. Introduction

The coordination chemistry of transition-metal complexes with well-defined binding pockets is currently attracting much interest [1-5]. By adjusting the size and form of the pocket it is often possible to coordinate coligands in unusual coordination modes, to activate and transform small molecules [6] or to stabilize reactive intermediates [7]. Such compounds also allow an interplay of molecular recognition and transition-metal catalysis [8,9] and the construction of more effective enzyme mimics [10]. Consequently, a large number of supporting ligands have been developed that create confined environments about active metal coordination sites. The majority of these ligands form mononuclear compounds, as for instance the calixarenes [11], the cyclodextrins [12,13] and some tripod ligands [14,15]. In contrast, there are only a few ligand systems that impose cagelike structures about polynuclear cores [16-18].

2. Binucleating thiophenolate macrocycles

One of the most efficient syntheses of macrobinucleating ligands such as the tetraimine-diphenol H_2L^1 (Fig. 1) involves a Schiff base condensation of 2,6-diformyl-4-methyl-phenol with an aliphatic α,ω-diamine in the presence of a labile first-row transition metal ion. This elegant one-step method provides the ligands in good to excellent yield as their dinuclear metal (II) complexes $[M_2LX_2]$ (X = anion). Since its discovery by Robson and co-worker in 1970 [19], this reaction has been successfully applied to a large number of other phenolate-based Schiff bases.

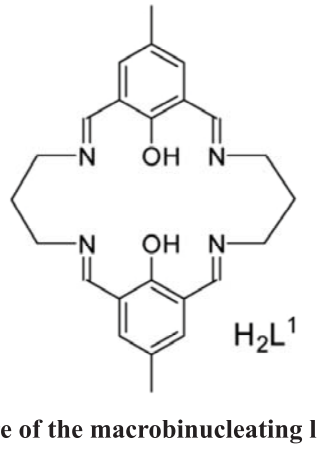


Fig. 1. Structure of the macrobinucleating ligand H_2L^1 [19].

The reader is directed to earlier reviews on macrobicyclic polyaza-phenolate ligands for excellent introductions to this area [20–23]. The synthesis of the free Schiff bases has been described by Schroder et al. [24].

The synthesis of macrocyclic ligands incorporating thiolate donors has also been actively pursued within the past several years, motivated primarily by their ability to model the active site of dinuclear metallo-enzymes [25–27]. An early example incorporating alkyl thiols is the hexadentate N_4S_2 ligand H_2L^2 (Fig. 2) derived from the condensation of bis(1,5-diamine-pentane-3-thiolato)dinickel(II) with formaldehyde and nitroethane in aqueous basic solution [28].

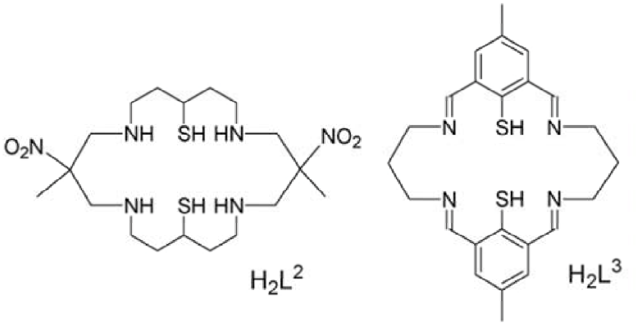


Fig. 2. Structure of macrobinucleating ligands H_2L^2 [28] and H_2L^3 [29].

Concurrently, Brooker et al. had independently developed a robust synthesis of H_2L^3 and this was subsequently detailed in the literature [30]. This approach makes use of the protected thiophenolate precursor S-(2,6-diformyl-4 methylphenyl) dimethylthiocarbamate, whose masking $CO(NMe_2)$ group is readily removed in situ by base hydrolysis. The work incorporating the synthesis of the (2 + 2) thiophenolate Schiff-base macrocyclic complexes can be found in recent reviews by Schroder [24], Brooker [31] and Tamburini and co-workers [32].

3. Polyamine-dithiophenolate macrocycles

The reduction of the imine donors is expected to affect the ligating properties of the Schiff-base thiophenolate ligands significantly due to significantly decreased ligand field strength and the sterically more demanding (sp^3-hybridized) amine functions of the resulting polyamine-dithio-phenolates [33]. In addition, such macrocycles should be hydrolytically more robust than their parent Schiff bases [34–37]. Brooker and co-workers described the first such complex, $[Ni_2(L^4)](ClO_4)_2$, in 1998 (Fig. 3).

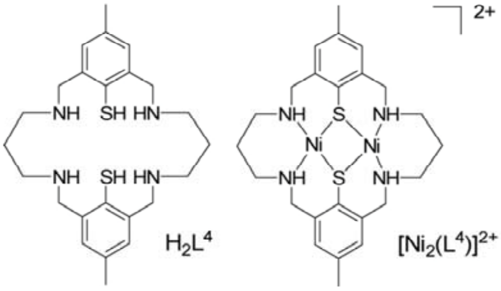
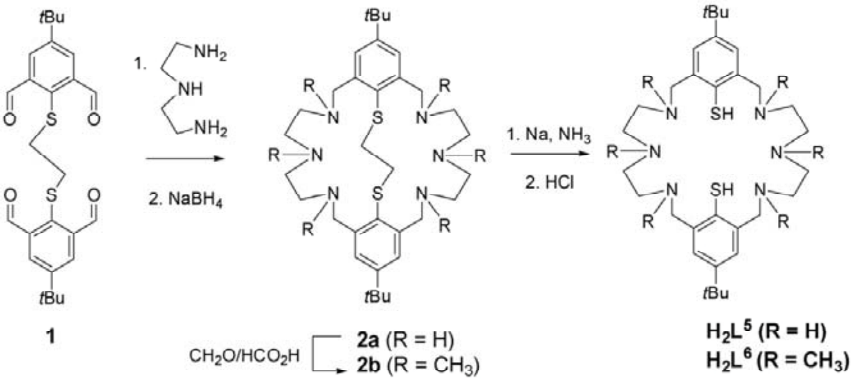


Fig. 3. Structure of H_2L^4 and its dinickel(II) complex [38].

The complex $[Ni_2(L^4)](ClO_4)_2$ was prepared in good yields by the reduction of $[Ni_2(L^3)](ClO_4)_2$ with $NaBH_4$ in MeOH followed by acidic workup [38].

The 24-membered Robson-type hexaaza-dithiophenolate ligand H_2L^5 and its various derivatives have been utilized by Kersting and co-workers as supporting ligands for dinuclear complexes with a bioctahedral $N_3M(\mu\text{-}S_2)_2(L')MN_3$ core structure (Scheme 1).



***Scheme 1.* Synthesis of H_2L^5 and H_2L^6 [49,50].**

The macrocycle H_2L^5 was prepared by a [1 + 2] condensation reaction of the tetraaldehyde 1 with 2 equiv. of diethylenetriamine in EtOH/CH_2Cl_2 using medium-dilution conditions followed by two successive reductions with $NaBH_4$ and Na/NH_3 [39,40]. The yield of the macrobicycle 2a is excellent (>90%), attributable to the template effect of the bridging ethylene unit which predisposes the four aldehyde groups during the Schiff-base formation step [41–43]. Similar reactions of 1 with ethylenediamine or propylenediamine yielded tricyclic [2 + 4] macrocycles because these diamines cannot easily span the aldehyde functions of 1 [44,45]. An attractive feature of the macrobicyclic intermediate 2a compared to unprotected thiolate ligands is that its secondary amines are readily alkylated without affecting the masked thiolate functions [46]. Thus, reductive methylation of 2a with formaldehyde and formic acid under Eschweiler–Clarke conditions, followed by deprotection of 2b with Na/NH_3 provides the permethylated derivative H_2L^6 in nearly quantitative yield. The H_2L^7 macrocycle ligand without t-Bu-groups was obtain in the same way as H_2L^6, begin from 1,3-dimethyl-benzene.

The ligand H_2L^6 is effective dinucleating ligand towards various divalent metal ions. Complexes of composition $[M^{II}_2(L^6)(\mu\text{-}L')]^+$ (M = Mn, Fe, Co, Ni, Zn, Cd) bearing Cl^- and OAc^- coligands (L') (Fig. 4) can be readily obtained by treatment of the free ligands H_2L^6 with two equivalents of the corresponding metal(II) dihalogenides (MCl_2) or acetates ($M(OAc)_2$) in methanolic solution in the presence of a base.

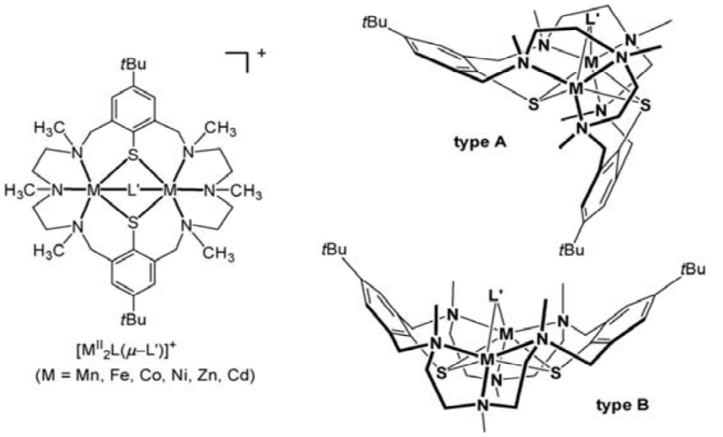


Fig. 4. Cationic $[M^{II}_2(L^6)(\mu\text{-}L')]^+$ complexes supported by the ligands $(L^6)^{2-}$ and schematic representation of their structures (L' = coligand) [46,47].

Interestingly, the macrocycles can adopt two different conformations A and B (Fig. 4), which are reminiscent of the "partial cone" and "cone" conformations of the calixarenes. A detailed comparison of the individual structures has shown that the conformation of the amino thiophenolates $(L^6)^{2-}$ is coupled to the size of the coligand L'^- and the metal ion radii [48,49]. For the complexes of the 3d elements the type A conformation is only seen for small monoatomic bridging ligands such as $L^- = OH^-$ and Cl^-. For large monoatomic coligands (such as SH^-) or a multiatom bridging ligand (such as OAc^-) the bowl-shaped conformation B is assumed, the driving force being the more regular octahedral coordination environments about the M^{II} ions [50].

The complexes are thus invariably bioctahedral with either a face-sharing or edge-sharing $N_3M(\mu\text{-}SR)_2(\mu\text{-}L')MN_3$ core structure depending on the coordination mode of the coligands. Note that the metal–metal separations (d (M···M)) correlate with the bridging mode of the coligands, i.e., (d (μ-L')<d($\mu_{1,2}$-L')<d($\mu_{1,3}$-L')). Some of the complexes feature unusual ligand coordination modes.

4. Macrocyclic dinickel complexes colligated by molecules containing nitrogen

So far, our studies have been confined to complexes bearing different coligands, we have now examined the capability of the $[(L^6)Ni_2]^{2+}$ fragment to bind as coligands some azocompounds, such as: nitrate, nitrite, azide, hydrazine, pyrazolate (pz), pyridazine (pydz), phthalazine (phtz), and benzoate (OBz). These molecules are known to act as bridging ligands between metal ions, [51] and some of them are biologically important molecules.

Table 1

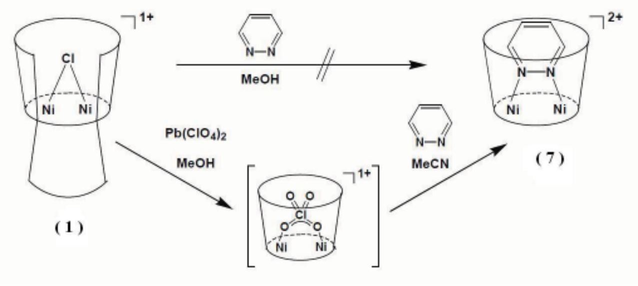
Synthesized complexes and their labels [a]

	$[(L^6)Ni_2(\mu\text{-}L')]^+$	L'
1[b]	$[(L^6)Ni_2(\mu\text{-}Cl)]^+$	Chloride, Cl^-
2	$[(L^6)Ni_2(\mu\text{-}NO_3)]^+$	Nitrate, NO_3^-

3	$[(L^6)Ni_2(\mu\text{-}NO_2)]^+$	Nitrite, NO_2^-
4	$[(L^6)Ni_2(\mu\text{-}N_3)]^+$	Azide, N_3^-
5	$[(L^6)Ni_2(\mu\text{-}N_2H_4)]^{2+}$	Hydrazine, N_2H_4
6	$[(L^6)Ni_2(\mu\text{-pz})]^+$	Pyrazolate, $N_2C_3H_3^-$
7	$[(L^6)Ni_2(\mu\text{-pydz})]^{2+}$	Pyridazine, $N_2C_4H_4$
8	$[(L^6)Ni_2(\mu\text{-phtz})]^{2+}$	Phthalazine, $N_2C_8H_6$
9	$[(L^6)Ni_2(\mu\text{-OBz})]^+$	Benzoate, $C_6H_5CO_2^-$
10[c]	$[(L^6)Ni_2(\mu\text{-OAc})]^+$	Acetate, $CH_3CO_2^-$
11	$[(L^6)Ni_2(\mu\text{-ttz})]^+$	Tetrazole, HCN_4
12	$[(L^6)Ni_2(\mu\text{-mettz})]^+$	Methyltetrazole, CH_3CN_4
13	$[(L^6)Ni_2(\mu\text{-phttz})]^+$	Phenyltetrazole, $C_6H_5CN_4$
14	$[(L^6)Ni_2(\mu\text{-bpz})]^+$	4,4'-bipyrazolyl, $C_6H_4N_4^{2-}$
15	$[(L^6)Ni_2(\mu\text{-bpdz})]^{2+}$	4,4'-bipyridazine, $C_8H_6N_4$
16	$[(L^6)Ni_2(\mu\text{-bpzb})]^{2+}$	1,4-bis(4-pyrazolyl)-benzene, $C_{12}H_8N_4^{2-}$
17	$[(L^7)Ni_2(\mu\text{-bpz})]^{2+}$	4,4'-bipyrazolyl, $C_6H_4N_4^{2-}$

[a] The complexes were isolated as ClO_4^- or BPh_4^- salts. [b] Ref. 46. [c] Ref. [47].

Table 1 lists the synthesized complexes and their lebels. Of these, the chloro- and acetate-bridged complexes 1 and 10 have been reported earlier. Complexes 2-6 and 9 were synthesized by treatment of 1-ClO_4 with a two- to fivefold excess of the sodium salt of the corresponding anion (or neat hydrazine hydrate in the case of 5) in aqueous methanolic solution. In general, these reactions were complete within a few hours at ambient temperature and produced clear solutions from which, upon addition of an excess of $LiClO_4$, the yellow (4-ClO_4) or green perchlorate salts (2-ClO_4, 3-ClO_4, 5-$(ClO_4)_2$, 6-ClO_4, and 9-ClO_4) of the desired complexes precipitated as microcrystalline solids in good to excellent yields (73-89%) (Table 1). The dicationic pyridazine and phthalazine derivatives 7 and 8 were prepared in acetonitrile solution, by treatment of 1-ClO_4 with lead perchlorate in acetonitrile, followed by removal of $PbCl_2$(s) by filtration and subsequent addition of the neutral diazine heterocycles. In this way, the diperchlorate salts 7-$(ClO_4)_2$ and 8-$(ClO_4)_2$ were obtained as brown crystals in similarly good yields (Scheme 2).



***Scheme 2.* Synthesis of dinickel complexes with pyridazine.**

In the IR spectra of 2-9 most of the stretching frequencies of the coligands are completely obscured by the absorptions of the $[(L^6)Ni_2]^{2+}$ fragment and the counterions (ClO_4^- or BPh_4^-). Nevertheless some absorptions of the coligands could be detected. In the spectrum of 2, for example, the bands at 1384 and 1277 cm^{-1} can be assigned to the asymmetric and symmetric stretching modes of a $\mu_{1,3}$-bridging nitrate ion. [52] Similarly, the band at 1183 cm^{-1} in the spectrum of 3 reveals the presence of a bridging NO_2^- group. [53] Likewise, in the spectrum of the azido complex 4 the strong band at 2059 cm^{-1} implicates a coordinated azide ion. The IR spectrum of hydrazine complex 5 shows sharp absorptions for the asymmetric and symmetric NH_2 stretching modes between 3300 and 3250 cm^{-1}, similar to other hydrazine complexes. [54,55] Unfortunately, for 6-8 no characteristic IR absorptions due to the coligands could be detected. Finally, in the spectrum of 9 the most prominent features are the intense bands at 1600 and 1427 cm^{-1}, which can be readily assigned to the asymmetric and symmetric carboxylate stretching modes [56]. The observed values are very similar to those of the acetato-bridged complex 10, suggesting that the benzoate moiety in 9 is also in the $\mu_{1,3}$-bridging mode. The UV/Vis spectra of the pale-green nickel complexes are similar but not identical. Each compound displays two weak absorption bands. One appears in the 620 to 670 nm range, the other one is observed between 1050 and 1180 nm. These absorptions can be attributed to the d-d transitions $\nu_2(^3A_{2g}(F)\rightarrow{}^3T_{1g}(F))$ and $\nu_1(^3A_{2g}(F)\rightarrow{}^3T_{2g}(F))$, respectively, of an octahedral nickel(II) (d^8) ion. The higher energy features below 400 nm result from π-π* transitions within the $(L^6)^{2-}$ ligand. In summary, the slight differences in the position of the d-d transitions indicate that each complex retains its coligand in the solution state. This is also supported by the electrochemical properties described below. All complexes were further characterized by cyclic voltammetry. Figure 5 shows the cyclic voltammogram of the benzoate-bridged complex 9.

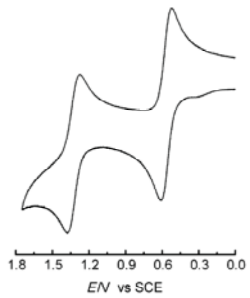


Fig. 5. Cyclic voltammogram of $[(L^6)Ni_2(\mu\text{-}O_2CPh)]ClO_4$ (9-ClO_4) in CH_3CN (ca $1x10^{-3}$ M). scan rate 100 mV s^{-1}.

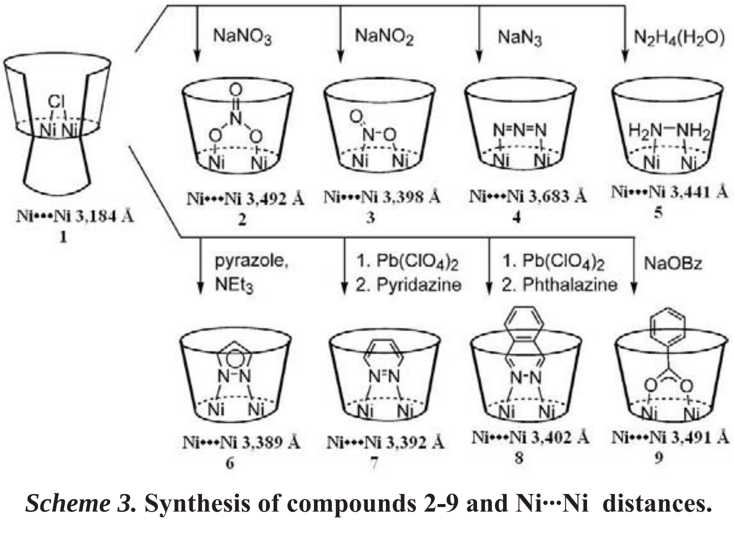
This complex undergoes two reversible one-electron oxidations at very positive potentials, the $E_{1/2}$ values being +0.51 (ΔEp = 0.11 V) and +1.28 V (0.11) versus SCE. The two processes are tentatively assigned to the formation of the mixed-valent $Ni^{II}Ni^{III}$ and $Ni^{III}Ni^{III}$ species, [57] as indicated in Equation (1).

$$[(L^6)Ni_2^{III}(\mu\text{-}L')] \underset{-e^-}{\overset{+e^-}{\rightleftharpoons}} [(L^6)Ni^{III}Ni^{II}(\mu\text{-}L')]^{2+} \underset{-e^-}{\overset{+e^-}{\rightleftharpoons}} [(L^6)Ni_2^{II}(\mu\text{–}L')]^{+} \quad (1)$$

The cyclic voltammograms of the other dinickel(II) complexes also reveal two redox waves with very positive oxidation potentials. However, the redox waves above about 0.90 V are all irreversible. Nevertheless, it can be clearly, that the redox potentials of the $[(L^6)Ni^{II}_2\ (\mu\text{-}L')]^{n+}$ complexes depend on the coligand L'. The complexes 2-4, 6, and 9 with anionic coligands are all easier to oxidize (by ca. 0.40 V) than the complexes 5, 7, and 8 bearing neutral coligands. The lowering of the redox potentials in the former is presumably due to a stabilizing Coulomb attraction between the anionic coligands and the positively charged $[(L^6)Ni^{III}Ni^{II}]^{2+}$ species formed upon oxidation. The electrochemical data thus confirm the conclusions drawn from the UV/Vis spectroscopic studies that the $[(L^6)Ni_2(\mu\text{-}L')]^{n+}$ complexes retain their bioctahedral structures in the solution state.

Herein we demonstrate that all species can be readily accommodated in the binding pocket of $[(L^6)Ni_2]^{2+}$. In each case we have obtained single crystals suitable for X-ray structure determinations. Therefore, it has been possible to study in detail the effect of the size and form of the binding pocket of the $[(L^6)Ni_2]^{2+}$ fragment on the coordination mode of the coligands and vice versa.

It is appropriate to discuss the structure of the $[(L^6)Ni_2]^{2+}$ subunit in 2-9 first. In all new dinickel(II) complexes the macrocycle adopts the conical calixarene-like conformation previously reported for the acetate-bridged complex 10 (Figure 4, type B) [47,58]. In this nearly C_{2v}-symmetric structure, the two nickel atoms are coordinated in a square-pyramidal fashion by two *fac*-$N_3(\mu\text{-}S)_2$ donor sets of the doubly deprotonated macro-cyclic $(L^6)^{2-}$. Upon coordination of the exogenous coligands distorted octahedral environments result for the two metal atoms. The structures of the dinuclear subunits are similar but not identical within the series (Scheme 3).



***Scheme 3.* Synthesis of compounds 2-9 and Ni···Ni distances.**

For example, the Ni··Ni distance varies from 3,392(1) to 3,683(1) Å. The metal-metal separations correlate with the nature of the bridging ligands. Complexes having multiple atom bridges such as $\mu_{1,3}$-carboxylate display longer Ni···Ni distances than complexes with $\mu_{1,2}$-bridges, such as NO_2^-. In addition the respective metal-ligand bond lengths and angles of the $[(L^6)Ni_2]^{2+}$ unit also differ significantly from one structure to other (see Figure 6).

As in previously reported structures of this ligand system (e.g. $[(L^6)Ni_2(\mu\text{-}OAc)]^+$, M = Co^{II}, Ni^{II} and Zn^{II}, [47,58] the Ni-N bond lengths involving the four benzylic nitrogen donors are invariably longer (by~0,1 Å) than the ones comprising the central nitrogen atoms of the linking diethylenetriamine units. The short Ni-N2 and Ni-N5 bonds are therefore not a reflection of a *trans* influence of the coligand. Rather, the disparities in the metal-nitrogen bond lengths are almost certainly a consequence of the steric constraints of the macrocycle. The average bond lengths and angles, however, are in good agreement with those of other octahedral nickel(II) complexes with mixed thiophenolate/amine legation [59]. The dimensions of the bowl-shaped cavity of the $[(L^6)Ni_2]^{2+}$ fragment can be described by the intramolecular distance between the two opposing aryl ring carbon atoms C4 and C20 (see Figure 7). Interestingly, this distance varies considerably across the present structures. The values range from 8,693 to 9,760 Å. This implies secondary interactions between the guest molecules and the N-alkyl and S-4-*tert*-butyl-phenyl residues of the distance $[(L^6)Ni_2]^{2+}$ subunit. Remarkably, the shortest distance occurs in the benzoato-bridged complex, in spite of the benzoate group being amongst the largest of the investigated guest molecules. For the smaller ionic ligands (NO_3^-, NO_2^-, N_3^-, OAc^-) the C4…C20 distance is in all cases longer by up to 1 Å. The distortions imposed by the benzoate moiety are indicative of attractive van der Waals interactions between the CH functions of the bowl-shaped host and its guest. As will be shown in more detail below, these secondary host-guest interactions play an important role as they confer unusual binding modes on the coligands.

As can be seen all coligands act as bidentate $\mu_{1,n}$-bridges (n = 2 or 3). Apparently, in $[(L^6)Ni_2(\mu\text{-}L')]$ complexes of structure type B L' cannot be a single-atom ($\mu_{1,1}$)-bridging ligand. This seems to be possible only for complexes of the alternative structure type A. In other words, multi-atom bridging ligands induce the $[(L^6)Ni_2]^{2+}$ fragment to adopt a structure of the kind B, whereas single-atom bridges such as Cl^- or OH^- support the conformation of type A. It is also worth mentioning, that the hexaazadithiophenolate ligand supports triply bridged $N_3M(\mu\text{-}SR)_2(\mu\text{-}L')MN_3$ core structures at all. Martell and coworkers, for example, have recently investigated the ligating properties of the analogous hexaazadiphenolate ligand systems. Despite the identical ligand backbones only doubly bridged $N_3M(\mu\text{-}OR)_2MN_3$ core structures are supported [60]. In addition, these compounds have flat structures in striking contrast to the bowl- or cleft-like structures of the amine-thiophenolate complexes. Another highly significant difference is that the nickel atoms in the phenolate complexes do not bind exogenous coligands, and remain five-coordinate. Similar differences have been noted by Brooker, who compared the coordination chemistries of analogous phenolate and thiophenolate Schiff-bases [31]. The structure differences can be traced to the different hybridizations of the phenolate-oxygen (sp^2, trigonal-planar) and the thiophenolate-sulfur atoms (sp^3, tetrahedral). The former macrocycles tend to enforce a planar $M(\mu\text{-}OR)_2M$ core structure, while the latter feature a bent $M_2(\mu\text{-}SR)_2$ structure, which can be spanned more easily by the coligands.

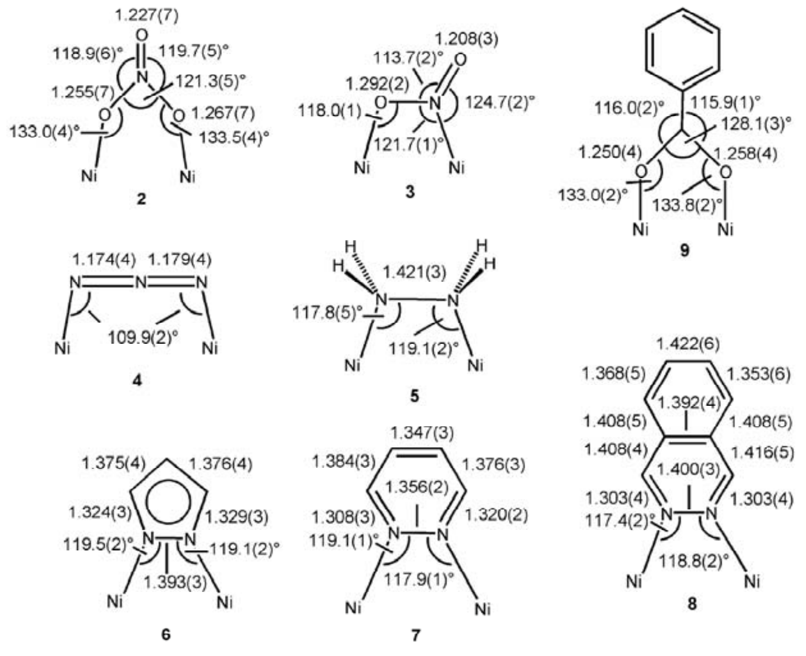
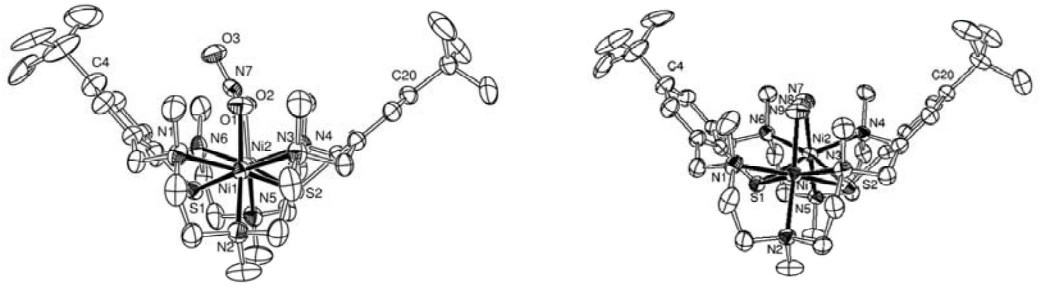


Fig. 6. Binding modes, bond lengths [Å], and angles [°] of the coligands in 2-9.

In the following the binding modes of the coligands are described in detail. As can be seen in Figure 7, the nitrate ion in 2 is coordinated in a symmetrical $\mu_{1,3}$-fashion. This is a typical coordination mode of this anion [61] and it has been observed previously in other nitrato-bridged complexes [62,63]. The average Ni-O bond length (2,071(4) Å) is significantly longer than in the $\mu_{1,3}$-carboxylato-bridged species 9 and 10, employing that the Ni-nitrate bonds are weaker than the Ni-carboxylate bonds. This nicely corroborates with the results of the binding studies presented below, which reveal that the nitrate group is readily replaced by carboxylate anions, but not vice-versa. The planar NO_3^- group aligns almost parallel with an adjacent phenyl ring. It is 3,30 to 3,44 Å from the mean plane of this phenyl ring. This is indicative of an intramolecular π-π stacking interaction [64]. (Figure 7, cation 2).

The nitrite ion can bridge two metal ions in several ways [51, 65-67]. In the present case, the $\mu_{1,2}$- (N,O-bound NO_2^-) and the $\mu_{1,3}$-modes (O,O-bound NO_2^-) are of relevance. The symmetrical $\mu_{1,3}$-binding motif seems to be geometrically feasible in view of the observed $\mu_{1,3}$-nitrate function in 2, but the crystal structure reveals the bridging $\mu_{1,2}$-nitro-form. This is presumably due to a more “relaxed” structure of the $[(L^6)Ni_2]^{2+}$ fragment in the latter mode of coordination. This is also supported by the fact that the octahedral Ni centers in 3 are much less distorted than in 2.



2 4

Fig. 7. Molecular structure of the cation 2 and 4 in the crystal.

The large numbers of dinuclear nickel complexes with azide linkages exists in the literature [68-70]. This linear triatomic anion can join two Ni centers in an end-on ($\mu_{1,1}$-N_3) or an end-to end motif ($\mu_{1,3}$-N_3). The latter is seen in the present structure. Of note are the Ni-N-N angles of 109,9 (2)^o (which are remarkably obtuse for a $\mu_{1,3}$-bridging azide ion) in combination with the planarity of the Ni-N_3-Ni assembly (torsional angle $\tau = 0^o$). This clearly shows that the binding pocket of the $[(L^6)Ni_2]^{2+}$ complex allows for the accommodation of anionic guest molecules in unusual coordination modes. A similar effect has been observed by McKee and Nelson. They were able to stabilize a nearly linear Ni-($\mu_{1,3}$-N_3)-Ni linkage in the cavity of a dinuclear nickel cryptate complex [71].

The hydrazine complex 5 provides an example for an unusual conformation of a small inorganic molecule. It is known that free hydrazine exist predominantly, in the gauche conformation at room temperature (dihedral angle $\tau \sim 100^o$) [72]. This conformation is also most commonly seen in dinuclear hydrazine complexes [73]. In the present complex the N_2H_4 ligand can only adopt the *cis* (ecliptic) conformation ($\tau \sim 3,7^o$). To the best of our knowledge, such a coordination mode is without precedence in dinuclear transition-metal hydrazine complexes [74,75], albeit it is documented for mononuclear species [76]. The hydrazine has a N7-N8 bond length of 1,421(3) Å consistent with a N-N single bond. A perchlorate ion is located above the N_2H_4 molecule, between the two *tert*-butyl groups (see Figure 8).

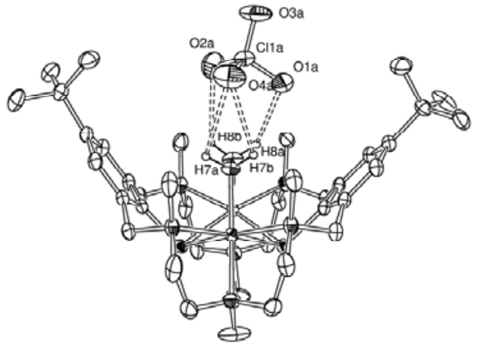


Fig. 8. Intermolecular Hydrogen bonding interactions between hydrazine complex 5 and a ClO_4^- counteranion.

Three of its oxygen atoms form weak hydrogen bonds with the N_2H_4 hydrogen atoms (average NH···O and N···O distances 2,370 and 2,914 Å), but on the basis of similar long NH···C distances to some of the adjacent aryl carbon atoms (i.e. C2, C6, C16, C18; average value 2,968 Å), the presence of repulsive NH···C_{aryl} van der Waals interactions cannot be excluded. The observed ecliptic N_2H_4 conformation would not argue against such an intramolecular steric interaction. It should also be remembered that NH_4^+ ions can form hydrogen bounds with the π-electrons of phenyl rings [2].

As expected, pyrazolate, pyridazine and phthalazine [77] bind to the $[(L^6)Ni_2]^{2+}$ fragment as bidentate bridges through their two ring nitrogens. Consequently, the Ni···Ni distances are nearly identical in these three compounds (average value is 3,394(1) Å). The average Ni-N(heterocycle) bond lengths to the pyrazolate moiety at 2,041 Å are shorter than to the pyridazine (2,128 Å) and phthalazine heterocycles (2,122 Å), indicating that the pyrazolate anion interacts more strongly with the $[(L^6)Ni_2]^{2+}$ subunit than the two neutral diazine molecules. This is further supported by the ligand exchange reactions (see below), which reveal that $[(L^6)Ni_2]^{2+}$ binds the pyrazolate anion preferentially over the neutral diazines. The C-N and N-N distances of the η^2-bound heterocycles do not deviate significantly from the distances found in the free heterocycles alone [78] or in other dinuclear nickel(II) complexes of these N-heterocyclic ligand systems [79]. Unlike the pyrazolate and the pyridazine, the phthalazine moiety is tilted out of the Ni1-N7-N8-Ni2 plane towards one of the *tert*-butyl groups, presumably again as a result of hydrophobic interactions between the adjacent CH groups of the phthalazine moiety and the *tert*-butyl methyl groups. The pyrazolate and pyridazine structures strongly support these assumptions. These heterocycles are smaller than the phthalazine ring and cannot experience these interactions, because they are too far away from the *tert*-butyl groups. In 8, there is also an intermolecular π-π interaction that occurs between the exposed phthalazine faces of two opposing complexes (Figure 9).

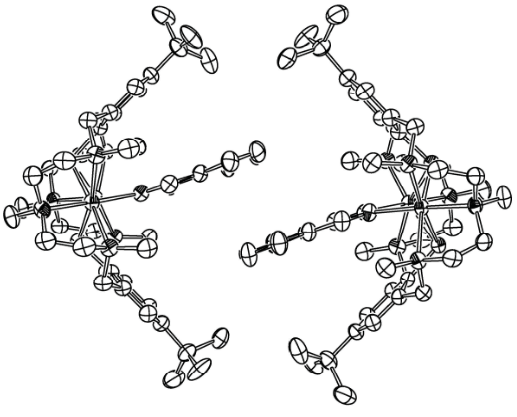


Fig. 9. Intermolecular π-π-stacking interaction between the phthalazine rings of two adjacent complexes 8.

Last but not least, the benzoate ion in 9 chelates the two Ni^{II} ions in a symmetrical $\mu_{1,3}$-fashion, as was previously observed for the acetate group in 10 and already indicated by the IR data. The benzoate phenyl ring is twisted slightly out of the Ni1-O1-C39-O2-Ni2 mean plane such that relatively short contacts between the aryl-hydrogen atoms H44a,b, H42a,b and the hydrogen atoms of the *tert*-butyl methyl groups (2,397-3,236 Å) result. The structure is otherwise identical with that of 10.

We have carried out a series of simple exchange experiments to estimate the relative binding affinities of the coligands. Each reaction was conducted at ambient temperature in a mixed acetonitrile/ethanol (1:1) solvent system using a tenfold excess of the coligand L", according to Equation (2):

$$[(L^{Me})Ni_2(\mu\text{-}L')]^{n+} + L'' \leftrightarrow [(L^{Me})Ni_2(\mu\text{-}L'')]^{n+} + L' \quad (2)$$

The reactions were terminated after 5 h (the time after which no more changes occurred) and the solid products examined by IR spectroscopy, [The reactions could not be monitored by UV/Vis spectroscopy. The spectral changes were too insensitive for some of the reactions.], if the IR spectrum of the isolated solid matched more closely with that of the starting material, $[(L^6)Ni_2(\mu\text{-}L')]^{n+}$, the binding affinity of the coligand L" was estimated to be less than that of L'. This was ascertained by successive control experiments, in which the same reactions were run in the reverse direction, but now with L' in tenfold excess over $[(L^6)Ni_2(\mu\text{-}L'')]^{n+}$. This finding could result from the different solubility's of the two species in question. To eliminate this possibility, the reactions were also monitored by infrared spectroscopy in CH_2Cl_2 solution. This gave the same ordering of the coligands. In this way the relative binding affinities were determined as follows: pyridazine(7)~ phthalazine(8) <nitrate(2) <hydrazine(5) <nitrite(3) <pyrazolate(6) <azide(4) <acetate(10) <benzoate(9).

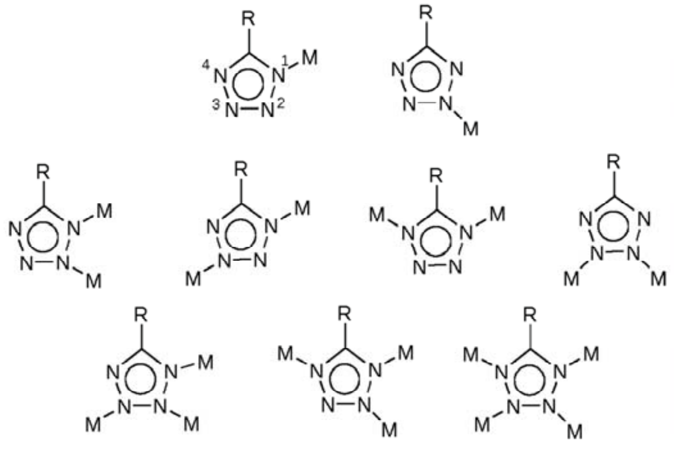
Two trends are apparent. First, the $[(L^6)Ni_2]^{2+}$ complex binds anionic ligands preferentially over neutral species.

This can be readily explained by the Coulomb attraction between the positively charged $[(L^6)Ni_2]^{2+}$ subunit and the negatively charged coligands. Second, the binding affinity of the anions parallels their position in the spectrochemical series [80]. This suggests that strong-field ligands are preferentially bound over weak-field ligands. It is, however, surprising that the benzoate group binds more strongly than the acetate group, in spite of the fact that the acetate is a stronger ligand [81]. We assume that these differences are due to hydrophobic effects, as was already indicated by the crystal structure of 9. This shows that the secondary host-guest interactions also contribute to the stability of the complexes.

5. Macrocyclic dinickel complexes colligated by tetrazolate ligands

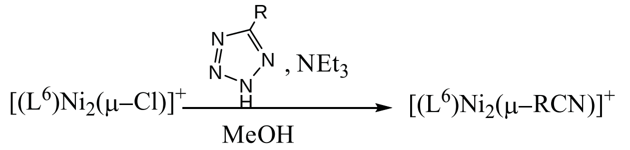
In view of the biological and medicinal importance of azoles [82], we considered it worth-while to prepare further complexes of this type to gain more insight into the binding of these compounds towards the $[(L^6)Ni_2]^{2+}$ fragment. Here we describe the synthesis and characterization of three novel dinickel complexes bearing tetrazolate ligands and explore their structural features. A survey of the literature reveals that little is known of such coordination compounds [83].

The tetrazolate ligands have been shown to exhibit a rich variety of coordination modes [83]. As shown in Scheme 4 the tetrazolate can either coordinate by means of one, two, three or four endocyclic nitrogen atoms. The actual type of coordination depends on the electronic and steric characteristics of the substituient R and its capability to participate in binding with the metal ion. Additionally, in mixed ligand complexes the coligand also influences the coordination modes of tetrazolates [83]. Based on previous structures of hexaazadithiophenolate complexes $[(L^6)Ni_2(L')]^{n+}$ with N-heterocycles [49] one can assume a coordination of tetrazolate anions through two neighbor-ring nitrogen atoms. In general, the 2,3-bridging mode [84] is favored over the 1,2-bridging mode [85] such that the former is expected for the present compounds.



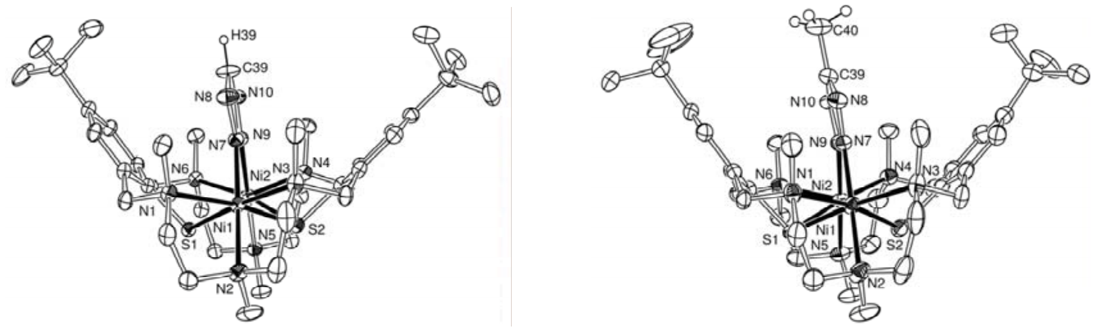
Scheme 4. **Coordination modes of tetrazolate ligands in metal complexes.**

The tetrazolates (5-R-tetrazoles, R = H, Me, Ph; prepared in situ from the free tetrazoles and triethylamine) were found to react smoothly with complex 1-ClO_4 in methanol over reaction times of several hours to give the green tetrazolate complexes 11–13, which could be isolated as highly crystalline perchlorate salts in yields > 80% (Scheme 5) [86]. The behaviour of the tetrazolate ligands is thus much like that of carboxylate ligands, which also readily displace the bridging halide ion in 1-ClO_4. Complexes 11[ClO_4] – 13[ClO_4] are quite stable in solution and could therefore be subjected to salt metathesis with $NaBPh_4$ to generate the corresponding tetraphenylborate salts. The crystal structure determinations described below have shown that this is indeed the case for all three complexes 11-13.



11 (R = H)
12 (R = CH_3)
13 (R = C_6H_5)

Scheme 5. **Synthesis of tetrazolate complexes 11-13.**



11 12

Fig. 10. Structure of cations 11, and 12 in crystals of 11·[BPh$_4$]·MeCN, and of 12·[BPh$_4$]·2MeCN with thermal ellipsoids drawn at 30% probability. Hydrogen atoms, except H(39) and those bonded to C(40), are omitted for reasons of clarity.

All tetrazolates bind to the [(L^6)Ni$_2$]$^{2+}$ fragment as bidentate bridges through their two ring nitrogen atoms N(7) and N(9). Consequently, the Ni···Ni distances are nearly identical in the three compounds (average 3,394(1) Å). The macrocycle assumes a bowl-shaped conformation, which is typical for [(L^6)Ni$_2$(L')]$^+$ complexes when colligated by multi-atom bridging ligands L' [48,49]. All tetrazolate units are essentially planar. The N-N and N-C distances of the tetrazolate rings in 11-13 differ significantly from the corresponding distances of the free 5-R-tetrazoles. Particularly affected are the N(7)-N(9) bonds. Thus, for 1-H-tetrazole and 5-methyl-tetrazole these bonds lengths are 1,295(3) Å [87] and 1,285(3) Å [88], much shorter than in 11-13, averaging at 1,354(3) Å. Similar changes were observed for a related tetrazolate complex with 2,3-μ-coordination [84] albeit to a lesser extent. The larger differences in 11-13 presumably relate to the stronger Lewis acidity of the nickel (II) ions. All three N-N bond lengths in 12 are identical within experimental error, while they vary from 1,317(2) to 1,367(2) Å in 11 and from 1,317(4) to 1,360(4) Å in 13.

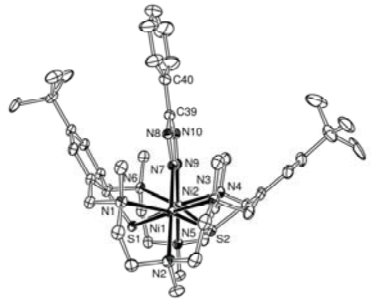


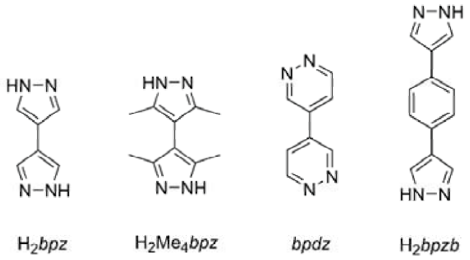
Fig. 11. Structure of cation 13 in crystals of 13·[BPh$_4$]·MeCN with thermal ellipsoids drawn at 30% probability. Hydrogen atoms are omitted for reasons of clarity.

The average Ni-N(heterocycle) bond lengths are 2,079(2) Å (2), 2,067(2) Å (3), and 2,061(3) Å (4), intermediate between those in the pyrazolato and pyridazine complexes 5 (mean 2,043(2) Å) and 6 (mean 2,175(2) Å). This suggests that the binding affinity of the tetrazolate anions towards the [(L^6)Ni$_2$]$^{2+}$ subunit is intermediate between that of pyrazolate and the neutral diazine heterocycles. There are no unusual features as far as bond lengths and angles around the Ni atoms are concerned. The average Ni-N^{amine} and Ni-S distances are 2,239(2) and 2,4870(8) Å, respectively. Similar values have been observed in other Ni$_2$ complexes of (L^6)$^{2-}$ with N donor ligands [49]. Overall, the three structures clearly show that the [(L^6)Ni$_2$]$^{2+}$ units can expand their binding pockets sufficiently to accommodate 2,3-bridging tetrazolate ligands.

6. 4,4'-Bipyrazolyl ligands as linker in macrocyclic dinickel complexes

The coordination chemistry of the potentially quadridentate ligands, 4,4'-bipyrazolyl [89,90] and its derivative [91-94] has been studied in some detail, primarily due to their capability to form porous coordination polymers with potential uses as solid sorbents, ion exchangers or heterogeneous catalysts [95-99]. In this context, a large body of work has been carried out concerning the formation of polypyrazolate based coordination networks with open framework structures [100,101]. It is surprising that such ligands have not yet been used in the construction of discrete polynuclear complexes. The olinuclear Pd$_3$ and Pd$_4$ complexes reported by Yu et al., may serve as rather rare examples of this class of compounds [102].

In view of the strong interest in the targeted design of molecular-based magnetic materials using highspin molecules of higher nuclearity, [103–109] we have initiated a study on the synthesis of complexes in which pairs of exchange coupled [(L^6)Ni$_2$] units are linked by 4,4'-bipyrazole (H$_2$bpz) and 1,4-bis(4-pyrazolyl)-benzene (H$_2$bpzb). The neutral ligand 4,4'-bipyridazine (bpdz) was also included in this study.



Attempts to link two [(L^6)Ni$_2$]$^{2+}$ units by a (bpz)$^{2–}$ dianion did not meet with any success. Treatment of [(L^6)Ni$_2$Cl][ClO$_4$] with triethylammonium 4,4-bipyrazolate in methanol in varying molar ratios resulted always in the formation of the green 1:1 complex [(L^6)Ni$_2$(Hbpz)][ClO$_4$] (14·[ClO$_4$]), presumably as a result of the sterically demanding *tert*-butyl groups. Nickel complexes of the neutral bpdz ligand were found to be inaccessible from [(L^6)Ni$_2$Cl][ClO$_4$]. The substitution reaction succeeded only with the more labile perchlorato complex [(L^6)Ni$_2$(ClO$_4$)] [ClO$_4$], but again only 1:1 complexes formed. Thus, treatment of a dark green acetonitrile solution of [(L^6)Ni$_2$(ClO$_4$)][ClO$_4$] with bpdz produced a brown-yellow solution, from which brown crystals of [(L^6)Ni$_2$(bpdz)][ClO$_4$]$_2$ (15·[ClO$_4$]$_2$) could be isolated in 80% yield [110]. It was clear at this stage that tetranuclear Ni$_4$ complexes would only be accessible with longer bipyrazolyls or with less bulky [(L^7)Ni$_2$] precursor subunits. Indeed, reaction of [(L^6)Ni$_2$Cl][ClO$_4$] with a 0.5 molar equivalent of (bpzb)$^{2–}$ (prepared in situ from H$_2$bpzb and NEt$_3$) in methanol followed by addition of an excess of LiClO$_4$ and recrystallization from acetonitrile affords the green complex [(L^6)Ni$_2$)$_2$(bpzb)][ClO$_4$]$_2$ (16·[ClO$_4$]$_2$) in 76% yield. Similarly, reaction of [(L^7)Ni$_2$Cl][ClO$_4$] with half a molar equivalent of (bpz)$^{2–}$ in methanol followed by addition of an excess of LiClO$_4$ furnished the tetranuclear species [(L^7) Ni$_2$)$_2$(bpz)] [ClO$_4$]$_2$ (17·[ClO$_4$]$_2$) as a dark-green, air-stable solid. Complexes 8 and 9 were also isolated as tetraphenylborate salts.

The IR spectra of compounds display the bands expected for the macrocyclic ligands and counterions, but were not informative with respect to the conformations of the supporting or coligands. Only the band at 3385 cm^{-1} in the IR spectrum of 14·[BPh$_4$] can be attributed to the N···H stretching vibration of the protonated pyrazole moiety. The electronic absorption spectra of the nickel complexes display two weak absorption bands around 640 and 1190 nm typical of octahedral Ni^{II} (S = 1) ions.

Single-crystals of 14·1,5MeCN were obtained by slow evaporation of 1:1 acetonitrile/ethanol solution of 14·[BPh$_4$]. The crystal structure is composed of dinuclear [(L^6)Ni$_2$(Hbpz)]$^+$ cations, tetraphenylborate anions and acetonitrile molecules of solvent of crystallization. An Ortep plot of the structure of complex 6 is depicted in Figure 12.

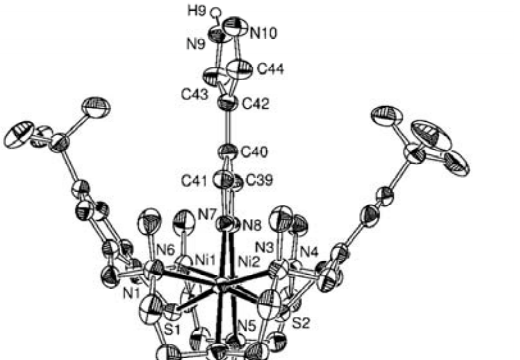


Fig. 12. ORTEP representation of the structure of the [(L^6) Ni^{II}$_2$(Hbpz)]$^+$ cation in crystals of 14·[BPh$_4$]· 1.5MeCN. Ellipsoids are represented at the 50% probability level. Hydrogen atoms except H(9) have been omitted for clarity.

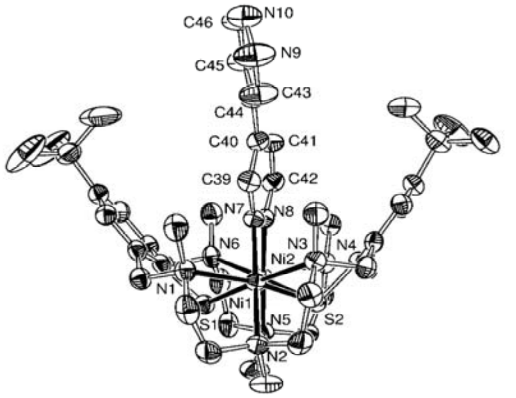


Fig. 13. Structure of the [(L^6)Ni^{II}$_2$(bpdz)]$^{2+}$ dication in crystals of 15·[ClO$_4$]$_2$·3MeCN with thermal ellipsoids at the 50% probability level. Hydrogen atoms are omitted for reasons clarity.

The bipyrazolato ligand acts only as a bidentate ligand towards one dinuclear $[(L^6)Ni_2^{II}]^{2+}$ unit through the ring atoms N(7) and N(8). The atoms N(9) and N(10) remain uncoordinated, but the hydrogen atom bonded to N(9) is involved in a hydrogen bonding interaction with an adjacent acetonitrile solvate molecule [N(9)···N(11) 2,975 Å]. The distance between the N atom of the acetonitrile and N(10) is 3,652 Å. The corresponding C-C, C-N, and N-N distances of the two five membered rings of the $(bpz)^{2-}$ dianion do not deviate significantly from each other, the largest difference being in the N-N bonds [N(7)-N(8) 1,384(2) Å, N(9)-N(10) 1,329(2) Å]. Note that the two heterocycles are not strictly coplanar. The dihedral angle between the two five-membered rings is 25,6°. The C(40)-C(42) bond is of length 1,472(2) Å indicative of a C-C single bond. The $[(L^6)\,Ni_2]^{2+}$ subunits in 14 and the compounds described below are structurally very similar, and the Ni-N and Ni-S distances lie within very narrow ranges. The Ni···Ni distance is at 3,373(1) Å, which is nearly identical with that in $[(L^6)Ni_2(pz)]\,[BPh_4]$ [3,389(1) Å] [49]. Overall, this structure clearly shows that the bipyrazolate moiety cannot link two $[(L^6)Ni_2]^{2+}$ units. This can be attributed to the steric demand of the *t*-Bu groups which hinder the formation of a tetranuclear complex. This assumption is nicely corroborated by the crystal structure determinations of $17{\cdot}[BPh_4]_2$.

Figure 13 shows the structure of the dinuclear Ni^{II}_2 complex 15 in crystals of $15{\cdot}[ClO_4]{\cdot}3MeCN$. Again, the 4,4'-bipyridazine ligand acts only as a bidentate group coordinating to only one bioctahedral $[(L^6)Ni_2]^{2+}$ entity through the ring nitrogen atoms N(7) and N(8). Metal complexes of 4,4''-bipyridazine have not been reported previously. The average $Ni\text{-}N_{pyridazine}$ bond length of 2,159(2) Å is significantly longer than the $Ni\text{-}N_{pyrazolate}$ distance in 6 [2,043(2) Å], implying that the neutral bipyridazine binds more weakly to the dinuclear $[(L^6)Ni_2]^{2+}$ fragment in 15 than does the charged pyrazolato ligand in 14. A similar behavior has been noted previously for $[(L^6)Ni_2(pydz)]^{2+}$ and $[(L^6)Ni_2(pz)]^{2+}$ [49]. As in 14, the coordination of the pyridazine ring to the Ni^{II} ions results in a slight elongation of the N-N bond length [N(7)-N(8) =1,336(2) Å vs. N(9)-N(10) = 1,366(2) Å]. Likewise, the two six-membered rings are also tilted by 25,2° with respect to each other. The Ni···Ni distance is at 3,401(1) Å.

Complex $16{\cdot}[BPh_4]_2{\cdot}6MeCN{\cdot}2H_2O$ crystallizes in the triclinic space group P1 with six cocrystallized acetonitrile and two water molecules. The $[(L^6)Ni_2)_2(bpzb)]^{2+}$ complex is centro-symmetric (figure 14). The structure of 16 unambiguously confirms the ability of the deprotonated 1,4-bis(4'-pyrazolyl)-benzene to link two $[(L^6)Ni^{II}_2]^{2+}$ units. The four six-coordinate Ni atoms are arranged in a rectangular fashion, the Ni···Ni distance being 3,349(1) Å [Ni(1)···Ni(2)] and 14,040(1) Å [Ni(1)···Ni(2')], respectively. Note that the Ni_2 pyrazolato planes are coplanar with each other, but that the central aromatic ring is slightly twisted out of this plane (τ = 23,8°). The metal-ligand bond lengths within the $[(L^6)\,Ni_2(pyrazolato)]^{2+}$ units reveal no anomalities and are very similar to those in 14. There are no significant intermolecular interactions between the Ni_4 complexes. The shortest intermolecular Ni···Ni distance is at 7,806(1) Å.

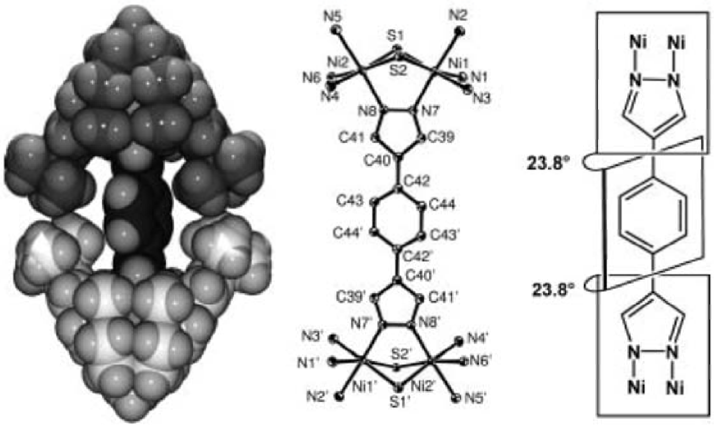


Fig. 14. Left: Van der Waals plot of the $[(L^6)Ni_2)_2(bpzb)]^{2+}$ dication in crystals of $16{\cdot}[BPh_4]_2{\cdot}6MeCN{\cdot}2H_2O$.
Middle: ORTEP representation of the core structure of 16 with the atom labeling.
Scheme. Ellipsoids are represented at the 50% probability level.
Right: Mutual orientation of the Ni_2pyrazolato planes in 16.

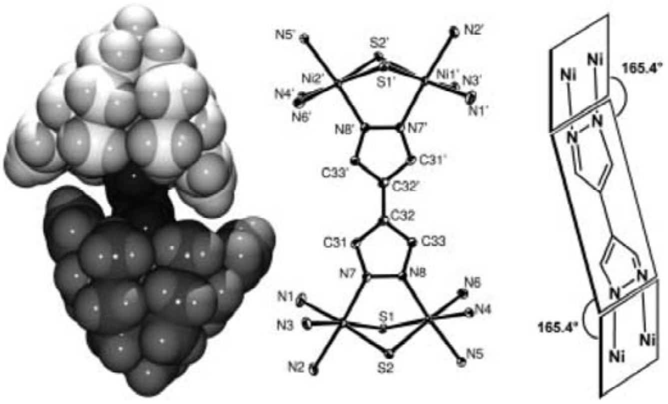


Fig. 15. Left: Van der Waals plot of the $[\{(L^7)Ni^{II}_2\}_2(\mu\text{-bipyrazolato})]^{2+}$ dication in crystals of $17\cdot[BPh_4]_2\cdot 2CH_2Cl_2$.
Middle: ORTEP representation of the core structure of 17 with the atom labeling.
Scheme. Ellipsoids are represented at the 50% probability level.
Right: Tilting of the Ni_2pyrazolato planes in 17.

Crystals of $17\cdot[BPh_4]_2\cdot 2CH_2Cl_2$ are triclinic, space group P1. Ortep views of the structure of the dication 17 and the central core are provided in Figure 15. Again, 17 exhibits crystallographically imposed inversion symmetry. In striking contrast to 6, the bipyrazolate moiety in 9 behaves as a tetradentate bridging ligand joining two binuclear $[(L^7)Ni_2]$ subunits, most likely as a consequence of the absence of the *tert*-butyl groups in $(L^7)^{2-}$. The bipyrazolate ligand assumes a planar conformation and the Ni_2N_2 planes are only slightly folded with respect to the bipyrazolato plane (folding angle 165,4°). The Ni···Ni distance of 3,448(1) Å is the same as that in 6. The distance d between the centre of the Ni···Ni axes of the binuclear subunits amounts to 9,184(1) Å, which is significantly smaller than the corresponding distance in 16. The bond lengths and angles around the Ni atoms within the $[(L^7)Ni_2]^{2+}$ unit reveal no unusual features. The average Ni-S, $Ni\text{-}N_{amine}$ and $Ni\text{-}N_{pyrazolato}$ distances are at 2,018(3), 2,291(3) and 2,517(1) Å, respectively. Virtually, the same distances are seen in 14. A large number of polymeric metal complexes containing bipyrazolato ligands have been structurally characterized [90-95] to the best of out knowledge, 17 is the first discrete species of $(bpz)^{2-}$. Overall, this structure clearly shows that two bioctahedral $[(L^7)Ni_2]^{2+}$ units can be linked by bipyrazolate dianions.

7. Conclusions

In summary, we presented the synthesis and investigation of the capability of the $[(L^6)Ni_2]^{2+}$ complex to bind a range of coligands other than chloride, hydroxide, and acetate has been demonstrated. The structural characterization of new complexes bearing anionic (NO_3^-, NO_2^-, N_3^-, pyrazolate, benzoate) and neutral coligands (hydrazine, pyridazine, phthalazine) shows that in each case only one of several possible coordination modes is realized. In some cases, the binding pocket confers very unusual coordination modes ($\mu_{1,3}$-N_3) or conformations (ecliptic N_2H_4) on the coligands. In other instances, intramolecular host-guest interactions are present. Overall, the crystal structures of tetrazolates, clearly show that the $[(L^6)Ni_2]^{2+}$ units can expand their binding pockets sufficiently to accommodate 2,3-bridging tetrazolate ligands.

The synthesis of the first members of a new class of tetranuclear nickel(II) complexes in which pairs of dinuclear $[(L^6)Ni_2]^{2+}$ fragments are united by $(bpz)^{2-}$ and $(bpzb)^{2-}$ groups, clearly show that the ease of formation of such cluster depends critically on two factors: (i) the length of the bridging coligand and (ii) the steric demand of the supporting ligand. The dinuclear amine-thiophenolate complexes have a rich coordination chemistry since their active coordination site is accessible for a large variety of neutral and charged coligands (L').

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STABILIZATION OF UNUSUAL SUBSTRATE COORDINATION MODES IN DINUCLEAR MACROCYCLIC COMPLEXES

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Abstract: The steric protection offered by the macrobinucleating hexaaza-di tiophenolate ligand (L) allows for the preparation of the first stable dinuclear nickel(II) borohydride bridged complex, which reacts rapidly with elemental sulphur producing a tetranuclear nickel(II) complex $[\{(L)Ni_2\}_2(\mu\text{-}S_6)]^{2+}$ bearing a helical μ_4-hexasulfide ligand. The $[(L)Co^{II}_2]^{2+}$ fragment have been able to trap a monomethyl orthomolybdate in the binding pocket. Unusual coordination modes of substrate in dinuclear macrocyclic compounds was demonstrated.

Keywords: coordination chemistry, borohydride, hexasulphide, molybdate, amino-thiophenolate ligands.

1. Introduction

The study of the coordination chemistry of classical coordination compounds with deep binding cavities is an active research area [1,2]. Motivations in this area are diverse and include molecular recognition of neutral or charged guest molecules, [3,4] stabilization of unusual substrate coordination modes, isolation of reactive species, [5] promotion of reactions within their interiors, [6-11] and construction of more effective enzyme active site mimetics, [12] to name but a few. Various types of supporting ligands for such complexes have been developed. Most of them represent mononucleating systems derived from cyclodextrines, [6] calixarenes [13], Schiff-base calixarene hybrids, and some highly functionalized tripod ligands [14-18]. Much less is known of ligand systems that encapsulate polynuclear core structures, and the chemistry of such systems is not well explored [19-21]. The coordination chemistry of binucleating hexaazadithiophenolate macrocycles has been reviewed [22-24].

The ligand H_2L is effective dinucleating ligand towards various divalent metal ions. Complexes of composition $[(L)M^{II}_2(\mu\text{-}L')]^+$ (M = Mn, Fe, Co, Ni, Zn, Cd) bearing Cl^- and OAc^- coligands (L') (Fig. 1) can be readily obtained by the treatment of the free ligand H_2L with two equivalents of the corresponding metal(II) dihalogenides (MCl_2) or acetates ($M(OAc)_2$) in methanolic solution in the presence of a base [24]. Interestingly, the macrocycles can adopt two different conformations A and B (Fig. 1), which are reminiscent of the "partial cone" and "cone" conformations of the calixarenes. The complexes of the 3d elements of the type A conformation is only seen for small monoatomic bridging ligands such as L' = OH^- and Cl^-. For large coligands (such as N_3^-) or a multiatom bridging ligand (such as OAc^-) the bowl-shaped conformation B is assumed, the driving force being the more regular octahedral coordination environments about the M^{II} ions.

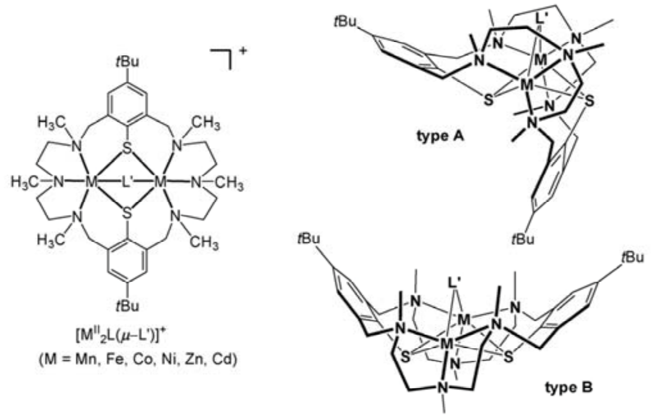


Fig. 1. Cationic $[M^{II}_2(L)(\mu\text{-}L')]^+$ complexes supported by the ligands $(L)^{2-}$ and schematic representation of their structures (L' = coligand)

These complexes have a rich coordination chemistry since the $[(L)M_2]^{2+}$ fragments are able to coordinate a large variety of coligands such as Cl^- [26], OH^- [27], NO_2^- , NO_3^-, N_3^- [28], and various carboxylates [29-33]. Some of the complexes feature unusual ligand coordination modes. The azide complex $[(L)Ni_2(\mu\text{-}N_3)]^+$ is a representative example. The planarity of the Ni–N_3–Ni assembly (torsional angle $\tau = 0^o$) together with the remarkably obtuse Ni–N–N angles at $109.9(2)^o$ has never been observed before for M–$\mu_{1,3}$-N_3–M linkages [34-36]. The presence of this distinct binding mode can be traced to the complementary size and form of the binding pocket of the $[(L)Ni_2]^{2+}$ complex. The hydrazine complex $[(L)Ni_2(\mu\text{-}N_2H_4)]^{2+}$ is an example for a complex that features an unusual conformation of a small neutral inorganic molecule. Free hydrazine exists predominantly in the gauche conformation at room temperature (dihedral angle τ ~100°) [37], also most commonly seen in dinuclear hydrazine complexes [38,39]. In $[(L)Ni_2(\mu\text{-}N_2H_4)]^{2+}$ the N_2H_4 ligand can only adopt the *cis* (ecliptic) conformation (τ = 3.7°). To the best of our knowledge, such a coordination mode is without precedence in dinuclear transition metal hydrazine complexes [40–44], albeit it is documented for mononuclear species [45,46]. The ecliptic N_2H_4 conformation is presumably a consequence of repulsive $NH\cdots C_{aryl}$ van der Waals interactions between the N_2H_4 molecule and $(L)^{2-}$.

Table 1 lists the synthesized complexes and their labels. Of these, the complexes 1, 2, 3 and 9 have been reported earlier [26,27,30,47].

Table 1

Synthesized complexes and their labels [a]

$[(L)Ni_2(\mu\text{-}L')]^+$		**L'**
1[b]	$[(L)Ni_2(\mu\text{-}Cl)]^+$	Chloride, Cl^-
2[c]	$[(L)Ni_2(\mu\text{-}OH)]^+$	Hydroxide, OH^-
3[d]	$[(L)Ni_2(\mu\text{-}ClO_4)]^+$	Perclorate, ClO_4^-
4	$[(L)Ni_2(\mu\text{-}BH_4)]^+$	Borohydride, BH_4^-
5	$[(L)Ni_2(\mu\text{-}HCOO)]^+$	Formiate, $HCOO^-$
6	$[(L)Ni_2(\mu\text{-}SH)]^+$	Hydrosulfide, HS^-
7	$[\{(L)Ni_2\}_2(\mu\text{-}S_6)]^{2+}$	Hexasulfide, S_6^-
8	$[(L)Ni_2(\mu\text{-}SPh)]^{2+}$	Thiophenol, $C_6H_5S^-$
9[e]	$[(L)Co_2(\mu\text{-}Cl)]^+$	Chloride, Cl^-
10	$[(L)Co_2(\mu\text{-}MoO_4)]^+$	Molybdate, MoO_4^{2-}
11	$[(L)Co_2(\mu\text{-}MoO_3(OMe))]^+$	Methylmolybdate, $MoO_3(OMe)^-$

[a] The complexes were isolated as ClO_4^- or BPh_4^- salts. [b] Ref. [26]. [c] Ref. [27]. [d] Ref. [47]. [e] Ref. [30].

In the following, selected examples of unusual substrate coordination modes originating from this work will be presented and discussed.

2. Stabilisation of a bridging borohydride co-ligand in dinickel(II) macrocyclic complex

The search for dinuclear dithiolato-bridged complexes which model key features of the active site of hydrogenase enzymes is an active research area [48,49]. Two main strategies exist to access such compounds. One involves the addition of an electrophilic metal-carbonyl fragment to a nucleophilic metal complex with *cis*-oriented thiolate functions [50]. The resulting $[NiFeS_2]$, or $[Fe_2S_2]$, assemblies are co-ligated with CO and CN^- and represent good structural analogues of the proposed active site structures, as demonstrated recently by a number of research groups [51–54]. In the other strategy, macrocyclic dinucleating polyaza-dithiolate ligands are used for the cluster assembly [55]. Until now this strategy has only allowed for the production of homodinuclear nickel complexes, and it is unclear at present whether these more classical Werner type coordination compounds will ever be able to bind the biologically relevant co-ligands CO, CN^- and H^-. Herein we provide the first evidence for nickel–hydrogen interactions in such compounds. Our study was initiated by the recent discovery of Desrochers et al. [56], who demonstrated that the sterically encumbered hydrotris-(3,5-dimethyl-pyrazolyl)borate ligand (Tp^{*-}) can stabilize a hydrogen-rich nickel environment in $[Tp^*Ni^{II}(\mu_{1,3}\text{-}BH_4)]$. In order to test whether similar dinickel(II) complexes with a bridging borohydride coligand are supported by the dinucleating hexaaza-dithiophenolate ligand $(L)^{2-}$ [26] an acetonitrile solution of the chloro-bridged complex $[(L)Ni^{II}_2(\mu\text{-}Cl)]\,ClO_4$ (**1**-ClO_4) was treated with n-Bu_4NBH_4 under an argon atmosphere at ambient temperature. Unlike $[Tp^*Ni^{II}Cl]$, [56] however, no reaction occurred. In a second approach, the reaction was carried out using the dark green perchlorato-bridged complex $[(L)Ni^{II}_2(\mu\text{-}ClO_4)]ClO_4$ (**3**·ClO_4) which was prepared by Cl^- abstraction from **1**-ClO_4 with $Pb(ClO_4)_2$. This gave a pale-green solution of the desired borohydrido-bridged complex **4**, which was isolated as its BPh_4^- salt in ca. 75% yield. In the absence of air and protic reagents this compound is stable for weeks, both in the solid state and in solution. This stability is quite remarkable given that nickel(II) complexes of sterically less demanding ligands are readily reduced to nickel boride [57].

IR measurements of solid **4**·BPh_4 showed intense absorption bands at 2390, 2360, 2153 and 2071 cm^{-1} indicative of terminal B–H and bridging $B\text{–}H\cdots Ni$ functions [58]. The UV-Vis spectrum recorded in acetonitrile suggested the presence of octahedral Ni(II) ions [λ = 650 (ν_2) and 1074 nm (ν_1)] [29]. Final confirmation came from an X-ray crystal structure determination of **4**$\cdot$BPh$_4$$\cdot$2MeCN (Fig. 2). As can be seen, the BH_4^- ion bridges the two Ni(II) centres in a symmetrical fashion to generate a bioctahedral $N_3Ni^{II}(\mu\text{-}S)_2(\mu\text{-}BH_4)Ni^{II}N_3$ core structure that has never been observed before in nickel–thiolate chemistry. There are no interactions between the MeCN of solvent of crystallization and the $[(L)Ni^{II}_2(\mu\text{-}BH_4)]^+$ cations. The average Ni–H distance at 1.89(4) Å compares well with that in the mononuclear NiS_4H_2 complex $[Ni^{II}(bmp)_2]$ (bmp = bis(2-mercapto-1-methyl-imidazolyl)-borate), [59] the only other sulfur-rich Ni(II) complex with B–H···Ni interactions that has been structurally characterised.

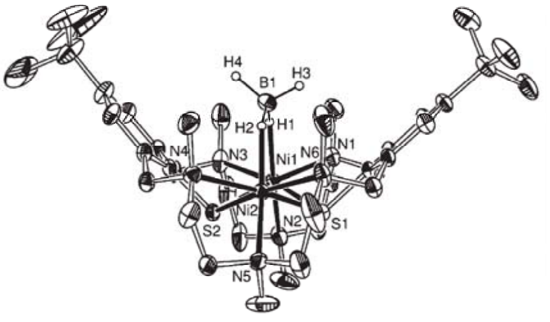


Fig. 2. ORTEP representation of the structure of complex 4 at 50% probability ellipsoids. Hydrogen atoms, except those of the BH_4^- coligand, have been omitted for clarity.

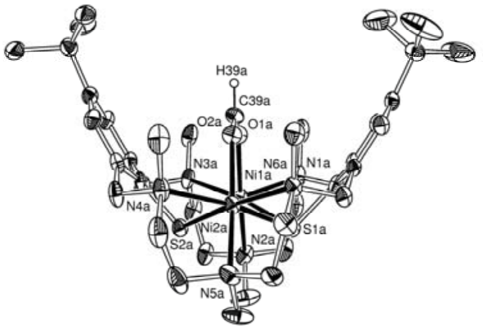


Fig. 3. ORTEP representation of the structure of the formato complex 5 with thermal ellipsoids drawn at the 50% probability level. Hydrogen atoms, except that of the formato coligand, have been omitted for clarity.

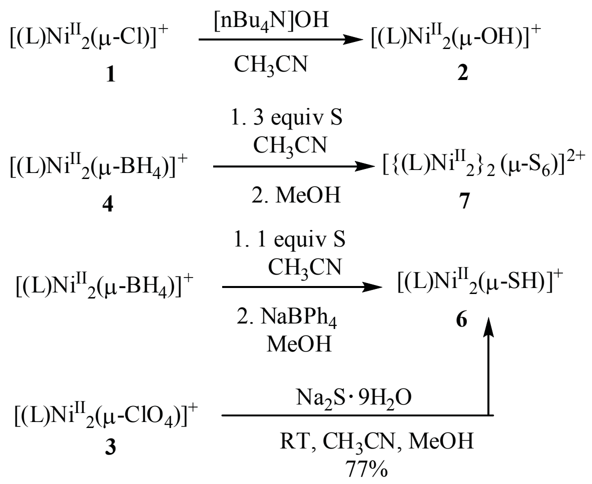
Preliminary results show that **4** reacts with protic reagents HA, such as HCl, H_2O, or HCO_2H with liberation of H_2 and formation of the respective $[(L)Ni^{II}_2(A)]^+$ species (A = Cl^- **1**, OH^- **2** and HCO_2^- **5**). The new complex **5** is also readily produced by the reaction of **3** with CO_2. IR measurements of **5**$\cdot$BPh$_4$ showed two absorption bands at 1602 and 1424 cm^{-1}, attributable to the symmetric and antisymmetric stretching frequencies of a $\mu_{1,3}$-bridging formate ion. This was also confirmed by an X-ray crystal structure determination of **5**$\cdot$BPh$_4$ (Figure 3). The electronic absorption spectra of **5** exhibits two weak absorption bands at 651 and 1114 nm which can be assigned to the spin-allowed ${}^3A_{2g} \rightarrow {}^3T_{1g}$ (ν_2) and ${}^3A_{2g} \rightarrow {}^3T_{2g}$ (ν_1) transitions of a nickel(II) (S = 1) ion in O_h symmetry [37]. There is also a weak shoulder around 910 nm attributable to a spin-forbidden ${}^3A_{2g} \rightarrow {}^1E_g(D)$ transition which gains intensity due to the lowering of the symmetry. The ${}^3A_{1g} \rightarrow {}^3T_{1g}(P)$ transition (expected below 400 nm) is obscured in each case by the strong thiolate-to-Ni(II) LMCT transitions which occur in the same spectral region.

In summary, we have prepared the first stable dinuclear nickel(II) borohydrido-bridged complex of a macrodinucleating hexaaza-dithiophenolate ligand. Work in progress is directed towards the synthesis of related compounds with bridging hydride ligands by taking advantage of the steric protection offered by the supporting ligand. Such compounds may also aid in understanding the electronic structures and the reactivities of the dinuclear active sites of the hydrogenase enzymes.

3. Macrocyclic dinickel(II) complexes colligated by hydrosulfide and hexasulfide ions

So far, our studies have been confined to complexes bearing different coligands, we have now examined the capability of the $[(L)Ni_2]^{2+}$ fragment to bind as coligand hydrosulfide (HS^-). Our motivation in this area are diverse and include: a) hydrosulfide complexes of labile transition-metal ions are rather scarce [60–64]; b) the hydrosulfide ion is a biologically relevant molecule [65]; c) nickel sulfur bonding is of importance in bioinorganic [66–68] and biomimetic chemistry [69–70]; d) the chemistry of SH^- - containing complexes is of relevance to metal sulfide hydrosulfurization catalysts [71-73]; and e) coligands with “soft” donor atoms have not been incorporated in the binding pocket of the $[M^{II}_2L]^{n+}$ complexes.

A general problem associated with the preparation of hydrosulfide complexes is further aggregation which leads to the formation of polynuclear sulfido complexes and eventually to insoluble metal sulfides. Herein we demonstrate that the sterically demanding supporting ligand L^{2-} enables the isolation and characterization of the stable hydrosulfide. The synthetic procedures are depicted in Scheme 1.



***Scheme 1.* Preparation of complexes 6 and 7.**

Initial attempts aimed at the synthesis of the hydrosulfide complex $[Ni_2L(SH)]^+$ (**6**) followed the method of preparing the hydroxide complex $[Ni_2L(OH)]^+$ (**2**) from $[Ni_2L(Cl)]^+$ (**1**) and $(n\text{-}Bu_4N)OH$, [27] but surprisingly, **1** proved to be substitutionally inert in reactions with $Na_2S{\cdot}9H_2O$ or $(Et_4N)SH$ [74]. The reduction of elemental sulfur by the borohydride complex $[Ni^{II}_2L(BH_4)]^+$ (**4**) [75] was sought as an alternative procedure. Indeed, when green **4**$\cdot ClO_4$ was treated with 1 equiv of S powder in CH_3CN, a yellow-brown solution forms immediately, and the desired hydrosulfide complex **6** can be isolated from methanol as a brown-yellow ClO_4^- salt in >70% yields. This reaction presumably involves thioborate/polysulfide intermediates (as in the $LiBH_4/S_8$ system) [76,77] which hydrolyze during workup to produce hydrosulfide anions which are trapped by the $[Ni^{II}_2L]^{2+}$ fragment. It should be noted that complex **6** is also obtained, in similarly high yields, from reactions in acetonitrile of the extreme labile perchlorato complex $[Ni_2L(ClO_4)]ClO_4$ (**3**$\cdot ClO_4$) with 1 equiv of $Na_2S{\cdot}9H_2O$, followed by workup from methanol. That polysulfide ions are indeed involved in these transformations was confirmed by the isolation of the hexasulfide complex $[\{Ni_2L\}_2(\mu\text{-}S_6)](BPh_4)_2$ (**7**$\cdot(BPh_4)_2$). This material could be reproducibly obtainned in yields as high as 70% when elemental sulfur is reacted with **4**$\cdot ClO_4$ in MeCN in a 3:1 molar ratio followed by workup from wet methanol as indicated in Scheme 1. At larger (4:1) or smaller (2:1) S/3 ratios a yellow-brown solid of unknown composition precipitates. The complexes **6** and **7** are stable for weeks in the absence of air and protic reagents both in the solid state and in solution. This stability is quite remarkable given that hydrosulfide complexes of sterically less demanding ligands are readily transformed into polysulfides or metal sulfides [63]. In the presence of air the yellow-brown color of solutions of **6** and **7** fades away within about 24 h and green products of unknown compositions precipitate.

The ESI-MS of a freshly prepared acetonitrile solution of **6** shows two nickel-containing fragments at m/z = 472.68 and 412.68 neither of which is the parent peak. The infrared spectrum of **6**$\cdot BPh_4$ shows a weak sharp ν(SH) band at 2552 cm^{-1} typical for complexes with SH^- groups [78]. For **7**$\cdot(BPh_4)_2$ two weak IR bands appeared at 468 and 440 cm^{-1}, attributable to the S-S stretching modes of the S_6^{2-} unit. These values agree well with those reported for K_2S_6 and other compounds with a S_6^{2-} unit [79]. Electronic absorption spectra for **6**$\cdot ClO_4$ and **7**$\cdot(ClO_4)_2$ complexes feature three intense absorption maxima in the UV at ~270 nm, ~300 nm, and 330 nm. These are characteristic for nickel complexes of L^{2-}. The former two can be attributed to π-π^* transitions within the aromatic rings of the supporting ligand whereas the latter corresponds to a thiophenolate → Ni^{II} charge transfer absorption. Unfortunately, the ligand-to-metal charge transfer (LMCT) bands involving the SH^- and S_6^{2-} groups are not resolved. Above 500 nm complex **4** exhibits two weak absorption bands at 663 and 1175 nm which can be assigned to the spin-allowed ${}^3A_{2g} \rightarrow {}^3T_{1g}$ (ν_2) and ${}^3A_{2g} \rightarrow {}^3T_{2g}$ (ν_1) transitions of a nickel(II) (S = 1) ion in O_h symmetry [80]. The corresponding values for **6** are significantly blue-shifted to 647 and 1102 nm, respectively. The ${}^3A_{1g} \rightarrow {}^3T_{1g}$ (P) transition (expected below 400 nm) is obscured in each case by the strong LMCT transitions. From the ν_1 transition one can obtain rough estimates of the octahedral splitting parameters Δ_{oct} for **4** (≈8511 cm^{-1}) and for **6** (≈9074 cm^{-1}), respectively. Such low values for Δ_{oct} (i.e., Δ_{oct} (**4**, **6**) < Δ_{oct} $[Ni(H_2O)_6]^{2+}$) 8500 cm^{-1}) are quite typical for $N_3Ni^{II}(\mu\text{- }SR)_3$ chromophores [81]. In general, thiolates induce only weak ligand field strengths because of their poor σ-donor bonding abilities. The same is true for the SH^- and S_6^{2-} ligands as indicated by the data in Table 2. Complexes **4** and **6** have the lowest Δ_{oct} values. The Δ_{oct} value for the $[(L)Ni_2(\mu\text{-}SPh)]^+$ complex **8** (8764 cm^{-1}) lies between the values of **4** and **6**. On the basis of these data, the σ-donor bonding ability of the SR-groups can be ranked as follows: $S_6^{2-} > SPh^- > SH^-$.

Table 2

Selected UV/Vis Data for complexes 1-4 and 6-8

complex	**coligand**	**ν_2/nm**	**ν_1/nm**	**Δ_0/cm^{-1}**
1^a	Cl^-	658(41)	998(67)	10020
2^a	OH^-	655(52)	1056(40)	9470
3^b	ClO_4^-	578(129)	1066(86)	9381
4^a	BH_4^-	650(43)	1074(77)	9311
6^b	SH^-	663(32)	1175(49)	8511
7^b	S_6^{2-}	647(56)	1102(72)	9074
8^a	SPh^-	667(52)	1141(68)	8764

^{a} Data refer to the BPh_4^- salts. ^{b} Data refer to the ClO_4^- salts

The structures of complexes **6** and **7** were further substantiated by X-ray crystallography. The atomic numbering scheme used for the central $N_3Ni(\mu\text{-}S)_3NiN_3$ core in **6** was also applied for **7** to facilitate structural comparisons. The structure determination of $[Ni_2L(SH)]BPh_4{\cdot}MeOH{\cdot}2H_2O$ unambiguously confirmed the presence of the cationic hydrosulfide complex $[Ni_2L(\mu\text{-}SH)]^+$ (Figure 4).

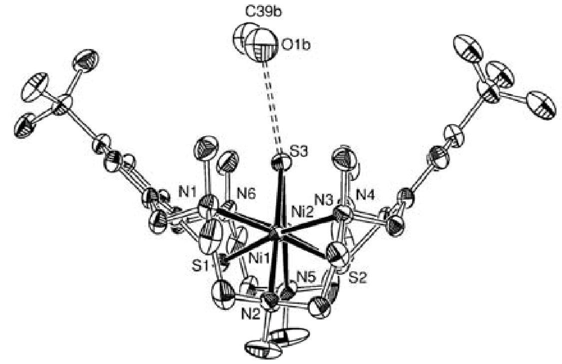


Fig. 4. Structure of the hydrosulfide complex 6 in crystals of $6{\cdot}BPh_4{\cdot}MeOH{\cdot}2H_2O$. Hydrogen atoms are omitted for reasons of clarity. The dashed line indicates a hydrogen bond between the SH moiety and the MeOH solvate molecule (S(3)···O(1b) 3.285 Å).

Although the SH hydrogen atom could not be located from difference Fourier electron density maps, its presence is implied by IR spectroscopy and charge considerations (assuming the presence of one dianionic L^{2-}, one BPh_4^-, one SH^-, and two Ni^{2+} ions). There is also a MeOH solvate molecule that lies in the vicinity of the SH unit (S···OMeOH 3.285 Å) indicative of a weak SH···OMeOH hydrogen bond [82,83]. Unlike in isoelectronic $[(L)Ni_2(\mu\text{-}Cl)]^+$ (**1**) or in $[(L)Ni_2(\mu\text{-}OH)]^+$ (**2**), the macrocycle adopts the bowl-shaped conformation B as observed in $[(L)Ni_2(\mu\text{-}ClO_4)]^+$ (see Figure 1 for a schematic representation of the two conformations) [47]. The presence of the type B conformation of L^{2-} in **4** presumably relates to the larger ionic radii of the SH-group (OH^-: 1.19 Å, Cl^-: 1.67 Å, SH^-: 1.93 Å) [84]. Previous work has shown that the conformation of L^{2-} is coupled to the size of the coligand L′ in the $[Ni_2L(L')]^+$ complexes [28,85] L^{2-} adopts the bowl-shaped conformation when L′ is large, the driving force being the more regular octahedral coordination environment about the Ni^{2+} ions. Similar arguments can be used to explain the different structures of **1**, **2**, and **6** (which bear all single-atom bridging ligands). Thus, upon going from the μ-OH complex **2** to the μ-Cl complex **1** the macrocycle maintains conformation A and the deviations of the L-M-L angles from the ideal values increase; particularly affected are the N-M-X *trans* angles. On the other hand, upon going from **2** to the SH complex **6**, L^{2-} changes its conformation and the NiN_3S_3 polyhedra become more regular. A number of dinuclear nickel complexes with μ-SR groups have been reported in the literature [86,87]. Pohl has reported a dinickel complex with two bridging SH groups [88]. As far as we are aware, **6** is the first dinickel complex with a single μ-SH group. The average Ni-SR (thiolate) bond length of 2.479(1) Å in **6** is quite typical for six-coordinate Ni^{II} thiolate complexes. For example, the Ni-μ-SPh bonds in the octahedral complexes $[Ni(terpy)(\mu\text{-}SPh)_2]_2{\cdot}6MeOH$ [89] and $[(L)Ni_2(\mu\text{-}OAc)]BPh_4$ [90] are 2.465(2) Å and 2.471(1) Å long, respectively. However, the Ni-μ-SH distances in **6** (mean 2.527(1) Å) are significantly longer than the Ni-μ-SR(thiolate) bonds. This is in good agreement with the notion that the SH^- ligands are weaker σ-donors than thiophenolates. It should be noted that the Ni···Ni distance in **6** at 3.295(1) Å is quite long for complexes containing face-sharing $N_3Ni(\mu\text{-}SR)_3$ NiN_3 structures. In the trinuclear complexes $[\{Ni_2L''\}_2Ni]^+$ and $[\{Ni_2L''\}_2Ni]^{2+}$

(L''- octadentate N_3S_3 ligand), the nickel atoms are separated by only 3.008(2) and 3.029(1) Å [91]. Likewise, for $[Ni_2L'''_3]^{2+}$ (L''' - tridentate N_2S ligand) the Ni···Ni distance is 3.064(1) Å [92]. The Ni-S-Ni angles in these complexes range from 78.9 to 80.16° and are thus more obtuse than in **6** (83.3-81.4°).

The crystal structure of $[\{Ni_2L\}_2(S_6)]\cdot(BPh_4)_2\cdot5MeCN$ (**7**$\cdot(BPh_4)_2\cdot5MeCN$) consists of discrete tetranuclear $[\{Ni_2L\}_2(\mu\text{-}S_6)]^{2+}$ dications, tetraphenylborate anions, and acetonitrile solvate molecules. Figure 5 provides an ORTEP view of the structure of **7**. Two dinuclear $[Ni_2L]$ subunits are linked via a helical S_6^{2-} chain. Again, both $[Ni_2L]^{2+}$ subunits feature a bowl-shaped conformation for reasons likely to be similar to those detailed above for **6**. The average S-S bond length is 2.065(2) Å, and the dihedral S-S-S-S angles range from 76.4 to 94.3°. Similar values are observed in plastic sulphur [93] and other S_6^{2-} systems [94,95]. It should be noted that the Ni-μ-S_6 bond lengths in **7** (mean 2.479(2) Å) are significantly shorter than the Ni-μ-SH bonds in **6** averaging 2.527(1) Å, an observation that correlates nicely with the stronger σ-bonding ability of the S_6^{2-} ion (vide infra). There are no unusual features as far as bond lengths and angles of the $[Ni_2L]^{2+}$ units are concerned. The average Ni-N (2.262(7) Å) and Ni-S (2.498(2) Å) bond lengths in **6** are similar to the values of the compound above. There are no significant intermolecular interactions between the Ni^{II}_4 complexes within the lattice. The shortest intermolecular Ni···Ni distance is at 7.711(1) Å. The present coordination mode of the S_6^{2-} dianion linking two binuclear $N_3Ni(\mu\text{-}SR)_3NiN_3$ cores is also without precedence in the literature.

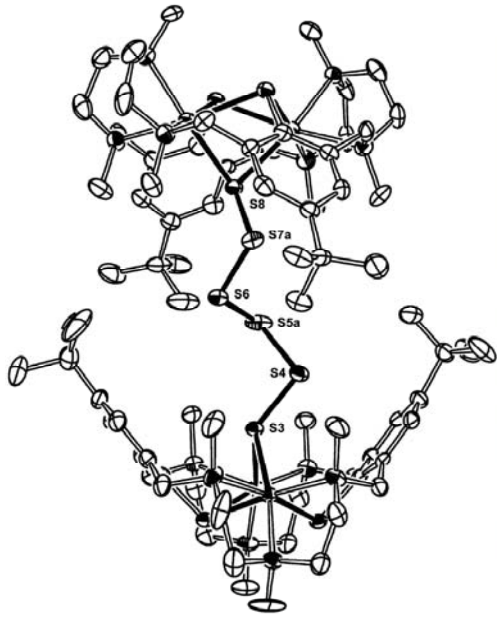


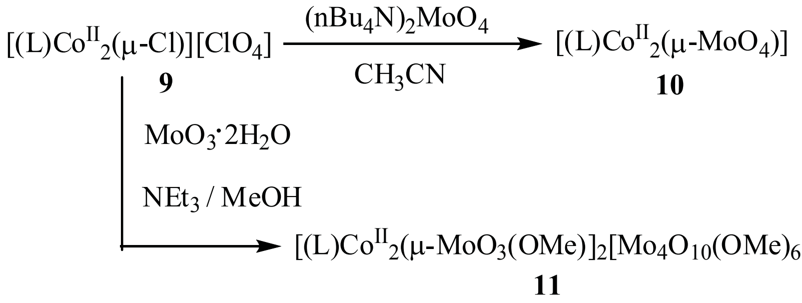
Fig. 5. Structure of the $[\{(L)Ni_2\}_2(\mu\text{-}S_6)]^{2+}$ dication in crystals of 7·$(BPh_4)_2$·5MeCN. Thermal ellipsoids are drawn at the 30% probability level. Only one orientation of the disordered S_6^{2-} unit is displayed. Hydrogen atoms are omitted

The main findings of these investigations can be summarized as follows: (a) the steric protection-offered by the supporting ligand L^{2-} allows for the preparation and isolation of stable hydrosulfide complexes of labile transition metal ions; (b) the $[(L)Ni_2(\mu\text{-}BH_4)]^+$ complex reacts rapidly with elemental sulfur and represents a versatile starting material for $[(L)Ni_2(\mu\text{-}SH)]^+$; (c) polysulfide complexes such as $[\{(L)Ni_2\}_2(\mu\text{-}S_6)]^{2+}$ are also accessible from $[(L)Ni_2(\mu\text{-}BH_4)]^+$ and S_8; (d) unlike in $[(L)Ni_2(\mu\text{-}Cl)]^+$ or in $[(L)Ni_2\ (\mu\text{-}OH)]^+$, the larger SH^- and S_6^{2-} ions induce the bowl-shaped macrocycle conformation of type B; (e) the SH^- and S_6^{2-} ions groups are characterized by their poor σ-donor bonding abilities.

4. Trapping of monomethyl orthomolybdate in the binding pocket of the $[(L)Co^{II}_2]^{2+}$ fragment

The synthesis and structural characterization of a large number of polynuclear oxo-alkoxo species of hexavalent Mo have been reported. Typical examples are polymeric $[Mo_2O_5(OMe)_2]$ [96], tetranuclear $[Mo_4O_{10}(OMe)_6]^{2-}$ [97], and octanuclear $[Mo_8O_{24}(OMe)_4]^{4-}$ [98], which can be readily prepared by solvolysis reactions of soluble isopolymolybdate anion precursors, such as $(n\text{-}Bu_4N)_2[Mo_2O_7]$ and $(n\text{-}Bu_4N)_4[Mo_8O_{28}]$, in methanol [99]. While the coordination chemistry of the polynuclear oxo-alkoxo molybdates is now fairly well-understood [100], surprisingly little is known about their monomeric $Mo^{VI}O_x(OR)_y$ congeners. In particular, four coordinate molybdenum oxoalkoxides are difficult to stabilize. The neutral alkyl esters, $MoO_2(OR)_2$, bearing primary alkoxy groups (R = Me, Et, Pr) are Lewis acidic [101] and tend to oligomerize in the solution as well as in the solid state [102]. Monomeric, four-coordinate species, such as $MoO_2(O\text{-}t\text{-}Bu)_2$ [103], $MoO_2(OSiPh_3)_2$ [104], and $MoO_2(O\text{-}2,6\text{-}t\text{-}Bu_2C_6H_3)_2$ [105], are only accessible with bulky alkoxides. The same is true for the anionic $MoO_3(OR)$- compounds. Stable species, such as $[MoO_3(OSi\text{-}t\text{-}Bu_3)]^-$ [106], do exist but only with bulky ligands [107,108]. Our study was initiated by the finding that tetrahedral oxoanions, such as ClO_4^- [47] and $H_2PO_4^-$ [29] can be readily accommodated in the binding pocket of the dinuclear $[(L)M_2]^{2+}$ complexes. This led us to study the ability of the $[(L)M_2]^{2+}$ fragment to bind tetrahedral oxoanions of the transition metals [109]. In the course of our studies, we have been able to trap the elusive $MoO_3(OMe)^-$ ion.

The neutral Co^{II}_2 complex **10** was chosen as the target compound. Following the method of preparation of $[(L)Ni_2(O_2P\text{-}(OH)_2)]^+$ from $[(L)Ni_2(Cl)]^+$ and $(n\text{-}Bu_4N)H_2PO_4$ [29], **1** was treated with $(n\text{-}Bu_4N)_2MoO_4$, [110, 111] in CH_3CN at ambient temperature for 12 h, as indicated in Scheme 2, to yield **10** as a pale-red powder. Recrystallization from dichloromethane/ethanol produced analytically pure material in 84% yield.



***Scheme 2.* Synthesis of complexes 10 and 11.**

In another attempt, we tried to synthesize **10** by the direct reaction of **9** with an excess of $(HNEt_3)_2MoO_4$ (prepared in situ from $MoO_3{\cdot}2H_2O$ and NEt_3) [112,113] in methanol, but this resulted in the formation of **11**, which was reproducibly obtained as a dark-red-brown microcrystalline solid in ca. 45% yield. Attempts to generate a similar product by methanolysis of **9** have failed. Thus, the formation of **11** is simply a matter of trapping this species from solution.

The IR spectrum of **10** in KBr shows three strong absorptions at 861, 848, and 807 cm^{-1}, which are tentatively assigned to the $\nu_1(A_1)$ and $\nu_3(F_2)$ stretching modes of the MoO_4^{2-} unit [114]. The splitting of ν_3 can be traced back to the lower local symmetry of the η^2-bonded MoO_4^{2-} ion (see the crystal structure described below). The IR spectrum of **11** exhibits several absorbances in the 950-678 cm^{-1} region. The bands at 941, 913, 880, 751, and 678 cm^{-1} can be assigned to the various Mo-O stretching frequencies of the $[Mo_4O_{10}(OMe)_6]^{2-}$ anion. Similar values have been reported for $[Ph_3MeP]_2[Mo_4O_{10}(OCH_3)_6]$ [100]. The two remaining absorptions at 803 and 818 cm^{-1} can then be attributed to the Mo-O stretching modes of the $[MoO_3(OCH_3)]^-$ unit, but these values should be taken as indicative rather than definitive. There may be further bands associated with the coligand that are obscured by the $[Mo_4O_{10}(OMe)_6]^{2-}$ absorptions. The UV/vis spectrum of **10** is very similar to that of **9**, displaying typical weak d-d transitions of octahedral high spin Co^{II} in the 300-1600 nm range [90]. The weak broad band at 1307 nm can be assigned to the $^4T_{1g}(F)\rightarrow {}^4T_{2g}$ transition. The features in the 500-630 nm region are attributable to components of the parent octahedral $^4T_{1g}(F)\rightarrow {}^4T_{1g}(P)$ and $^4T_{1g}(F)\rightarrow {}^4A_{2g}$ ligand field transitions split by lower symmetry.

In view of the air stability of **10**, it was of interest to determine its redox properties. Figure 6 shows its cyclic voltammogram in a dichloromethane solution. Two waves, one at $E^1_{1/2} = +\ 0.10$ V (vs SCE) with a peak-to-peak separation of 140 mV and one at $E^2_{1/2} = +\ 0.55$ V with a peak-to-peak separation of 146 mV, are observed. These oxidations correspond to metal-centered oxidations of the $Co^{II}Co^{II}$ species **10** to its mixed-valent $Co^{II}Co^{III}$ and fully oxidized $Co^{III}Co^{III}$ forms (eqs 1 and 2, respectively). Thus, as was observed previously for **9**, the divalent Co^{II} oxidation level is enormously stabilized over the trivalent state. Likewise, within our potential window, no reductions of theMoO_4^{2-} ion are detected.

$$[(L)Co^{III}Co^{II}(MoO_4)]^+ + e^- \leftrightarrow [(L)Co^{II}_2(MoO_4)] \qquad E^1_{1/2} \qquad (1)$$
$$[(L)Co^{III}Co^{III}(MoO_4)]^{2+} + e^- \leftrightarrow [(L)Co^{III}Co^{II}(MoO_4)]^+ \qquad E^2_{1/2} \qquad (2)$$

The normal potentials for **10** are slightly shifted to more negative potentials when compared with those of the acetate-bridged complex $[(L)Co^{II}_2(\mu\text{-}OAc)]^+$ ($E^1_{1/2} = 0.21$ V; $E^2_{1/2} = 0.60$ V) [30]. These differences are likely a consequence of the charge differences. Recall that **10** is a neutral species whereas $[(L)Co^{II}_2(\mu\text{-}OAc)]^+$ is a mono-cation. It should be noted that the oxidized species are only stable on the time scale of a cyclic voltammetry experiment. All attempts to prepare these compounds by electrochemical or chemical oxidation led to unidentified decomposition products. Thus, while some of the above oxidations appear electrochemically reversible, they are all chemically irreversible.

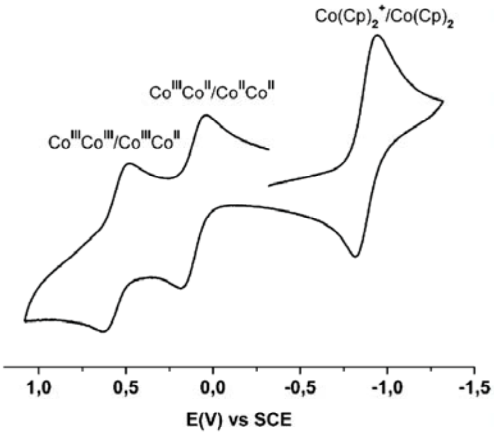


Fig. 6. Cyclic voltammogram of 10 in dichloromethane at 295 K.

The X-ray crystal structures of complexes **10** and **11**·6MeOH were determined to establish the geometries about the metal ions as well as the bonding modes of the coligands.

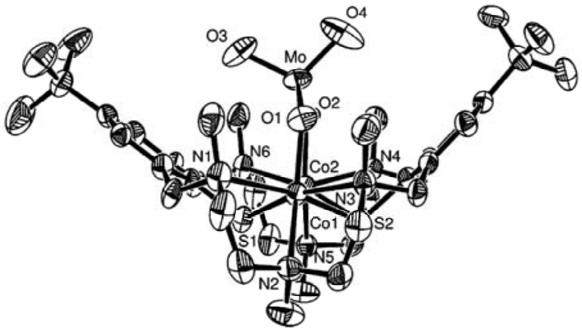


Fig. 7. Structure of the neutral complex 10 in crystals of 10·CH_2Cl_2. Thermal ellipsoids are drawn at the 50% probability level. H atoms are omitted for reasons of clarity.

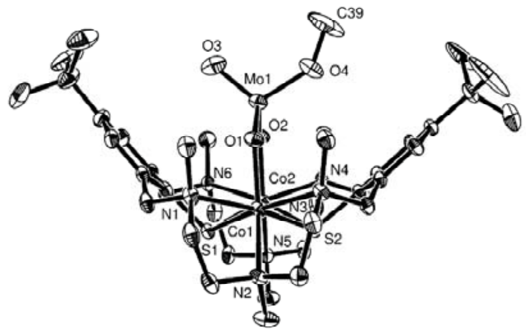
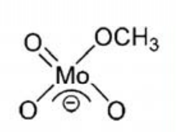


Fig. 8. Structure of the $[(L)Co^{II}_2(MoO_3(OCH_3))]^+$ cation in crystals of 11·6CH_3OH. Thermal ellipsoids are drawn at the 50% probability level. H atoms are omitted for reasons of clarity.

The structure of **10**·CH_2Cl_2 consists of neutral complexes **10** and CH_2Cl_2 solvate molecules. There are no intermolecular interactions between the components. Figure 7 provides an ORTEP view of the structure of **10**. The macrocycle adopts a bowl-shaped conformation, as observed in $[(L)Co^{II}_2(OAc)]^+$ [30]. Each Co atom is coordinated by two S and three N atoms from the supporting ligand and an O atom of a $\mu_{1,3}$-bridging MoO_4^{2-} ion in a severely distorted octahedral fashion. The distortions from the ideal octahedral geometry are manifested in the *cis* and *trans* L-Co-L bond angles, which deviate by as much as 24.9° from their ideal values. The Co-metal ligand bond lengths in **10** are very similar to those in **9**, indicative of a high-spin configuration for the Co^{2+} ions [90]. The MoO_4^{2-} unit is slightly tilted out of the Co_2O_2 plane, with the oxo atom O(3) pointing in the direction of one benzene ring [distance O(3)···centroid of phenyl ring = 3.612 Å]. The coordination about Mo is not perfectly tetrahedral. The mean Mo=O [1.712(7) Å] and Mo-O [1.761(6) Å] bond lengths differ by ca. 0.05 Å, and the O-Mo-O bond angles range from 106.3(3) to 111.5(3)°. Similar values have been observed for other molybdato-bridged complexes[115] and for the oxo-alkoxo compounds $MoO_2(OSiPh_3)_2$ [104] and MoO_2(O-2,6-*t*- $Bu_2C_6H_2)_2$ [105]. It is also worth mentioning that the Co-O distances in **10** [mean 1.988(6) Å] are shorter than those in **11** [2.027(4) Å], an effect that may be traced to stronger electrostatic coligand-metal interactions in **10**.

The crystal structure determination of **11**·6MeOH unambiguously confirmed the presence of a η^2- coordinated monomethyl orthomolybdate situated in the pocket of the $[(L)Co^{II}_2]^{2+}$ fragment (Figure 9). Further components are a centrosymmetric $[Mo_4O_{10}(OCH_3)_6]^{2-}$ counterion and MeOH solvate molecules. Note that the asymmetric unit contains only half of the atoms of the formula unit. The three independent MeOH molecules are H-bonded to each other (O···O) 2.81-2.87 Å). One of them is also H-bonded to the polymolybdate ion, but there are no H bonds with the $MoO_3(OMe)^-$ unit. The tilting of the latter toward the *t*-Bu group of the supporting ligand is indicative of an intramolecular Van der Waals interaction [H(39a)···H(36b)) 2.313 Å].

The Mo-O distance to the methoxide ligand [1.852(5) Å] is significantly longer than the Mo=O distance [1.685- (5) Å] to the terminal oxo function. The Mo-O distances to the bridging oxides (mean value 1.734 Å) lie between these two extreme values. This is in contrast to the free $MoO_3(OSiCPh_3)_3^-$ ion for which one long, one intermediate, and two short Mo-O distances have been reported [106]. The bonding situation in the $MoO_3(OMe)^-$ ion may be described by the resonance structure depicted below, where bond orders of 2, 1.5, and 1 have been assigned to the individual M-O bonds.



It can be seen from Figure 9 that the centrosymmetric $[Mo_4O_{10}(OMe)_6]^{2-}$ counterion in **11** (Figure 8) is isostructural with that in $(MePPh_3)_2[Mo_4O_{10}(OCH_3)_6]$ [97]. There are no unusual features as far as bond lengths and angles are concerned. The average Mo-(μ-O) [1.923(4) Å], Mo-OCH_3 [1.919(4) Å], Mo-(μ-OCH_3) [2.135(4) Å], Mo-(μ_3-OCH_3) [2.287(4) Å], and Mo-O_t [1.692(4) Å] bond lengths are similar to the values of the compound above [100].

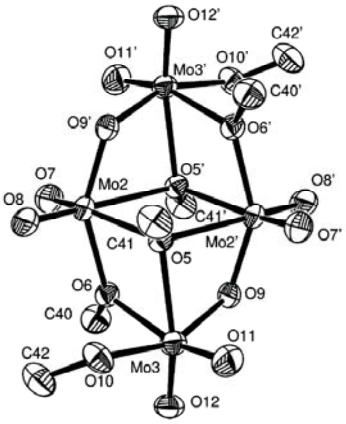


Fig. 9. Structure of the $[Mo_4O_{10}(OCH_3)_6]^{2-}$ anion in crystals of 11·6CH_3OH. Thermal ellipsoids are drawn at the 50% probability level. H atoms are omitted for reasons of clarity.

In summary, we have been able to trap a monomethyl orthomolybdate in the binding pocket of the $[(L)Co_2]^{2+}$ fragment. Work in progress is directed toward the synthesis of other ortho esters of the transition metals by taking advantage of the steric protection offered by the supporting ligand. These compounds may also exhibit novel reactivity features that are not seen for the free oxoanions.

5. Conclusions

The main findings of these investigations can be summarized as follows: a) It was prepared the first stable dinuclear nickel(II) borohydrido-bridged complex of a macrodinucleating hexaaza-dithiophenolate ligand (L^{2-}); b) the steric protection-offered by the supporting ligand L^{2-} allows for the preparation and isolation of stable hydrosulfide complexes of labile transition metal ions; c) the $[(L)Ni_2(\mu\text{-}BH_4)]^+$ complex reacts rapidly with elemental sulphur and represents a versatile starting material for $[(L)Ni_2(\mu\text{-}SH)]^+$ and polysulfide complexes such as $[\{(L)Ni_2\}_2(\mu\text{-}S_6)]^{2+}$; d) it was demonstrate that the parent $MoO_3(OCH_3)^-$ complex can be stabilized by the steric protection of the supporting ligand L^{2-} in the dinuclear cobalt complex $[(L)Co^{II}_2]^{2+}$. Work in progress in this area directed toward the synthesis of new macrocyclic complexes with more deeper binding cavities.

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IONIC LIQUIDS DERIVATIVE OF 1H-IMIDAZOLE AS NOVEL REAGENTS, CATALYSTS AND SOLVENTS

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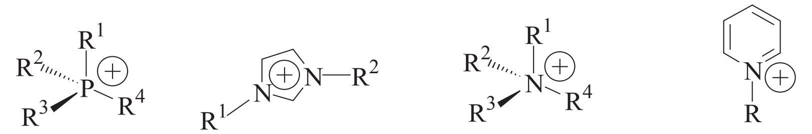
Dedicated to the member-correspondent of the ASM professor Turtă C.I. on his 70th birthday

Abstract: Ionic liquids are becoming widely used in chemical processes. Taking this into account we focus on recent advances in the synthesis and the investigation of 1*H*-imidazole derived ionic liquids. The first part of this paper focuses on describing the developments in the synthesis and physical properties of 1,3-disubstituted imidazolium salts. The second part describes the application of these unique reagents, as catalysts and solvents in organic chemistry.

Keywords: 1*H*-imidazole, ionic liquids, reagents, catalysts, solvents, organic synthesis.

1 Introduction

1*H*-Imidazole **1** is a structural fragment of numerous natural compounds as well as synthetic medicinal preparations [1]. Despite a wide variety of imidazole derivatives, organic and bioorganic syntheses as well as different fields of medicine continuously require novel biologically active compounds, reaction mediums, solvents and more efficient and environmentally friendly catalysts. One of promising research areas today is the chemistry of melted salts, which are usually called “ionic liquids”. Ionic liquids in most cases are nitrogen-containing organic substances (Figure 1*)*, except the derivatives of phosphorus, which account for not more than 10% of the total number of specific liquids described in the literature. Ionic liquids derived from 1*H*-imidazole **1** are one of the most representative and interesting groups due to their properties.



phosphonium imidazolium ammonium pyridinium

common cations

$F_3CO_2S\text{-}N\text{-}SO_2CF_3^-$ PF_6^- $CF_3SO_3^-$ BF_4^-

common anions

Figure 1

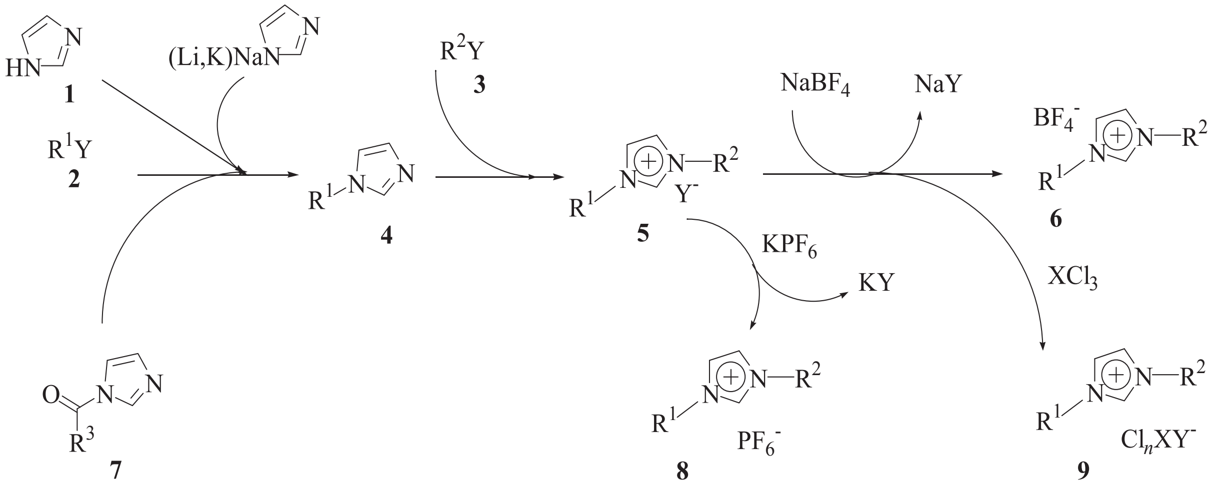
Literature data on the synthesis and investigation of ionic liquids based on diazole **1** were previously summarized in the monograph [2], as well as in a series of reviews [3-20]. In this review, an emphasis will be laid on the most meaningful and promising, in the authors’ point of view, works on the synthesis and properties of ionic liquids, as well as those not discussed in the publications [1-20].

We shall begin the study of the chemical transformations of compound **1** with the analysis of the data of the synthesis of 1,3-dialkyl imidazolium salts. The second part of the review will focus on functionalized imidazolium salts. The third part will present the data on physical properties of imidazolium derivatives. Finally, data will be given on the use of imidazolium salts in organic synthesis, without any special sub-section dedicated to chiralic representatives. Questions regarding the synthesis and properties of 1*H*-4,5-dihydroimidazole and its derivatives, as well as of 2,4,5-substituted 1*H*-imidazoles will not be discussed in this work.

1.1. Syntheses of 1,3-dialkylimidazolium salts

Imidazole **1** has a five-member heterocyclic ring with two nitrogen atoms in positions 1 and 3. One of these nitrogen atoms is similar to the one in pyrrole and is responsible for the acidic properties of imidazole. The other one is similar to the nitrogen atom in pyridine and is responsible for the basic properties of imidazole. In general, it may be said that imidazole **1** has different properties, may react at different rates and gives various derivatives. Theoretically, the number of ionic liquids is indefinite and is limited only by the availability of necessary components: cations (organic) and anions (inorganic, organic and metal complexes). According to various estimates, the number of possible combinations of cations and anions in such liquids may reach 10^{18} [8].

The known methods of N-alkylation of imidazole **1** include: the reaction with halo alkanes **2**; the reaction of imidazole alkaline metals salts with halo alkanes **2**; the reaction with trialkylphosphates; thermal decarboxylation of N-alkoxycarbonylimidazoles **7**; the reaction with alcohols, in the presence of acidic catalysts; quaternization of N-acylimidazoles **7** with subsequent deacylation and others (scheme 1) [21-27].



$R^1 = R^2 =$ alkil, Bn, $SiMe_3$, etc.; R^3 =OH, alkil, Ar, Im, etc; X=Na,K,Li,Al,Fe; Y=Cl,Br,I

Scheme 1

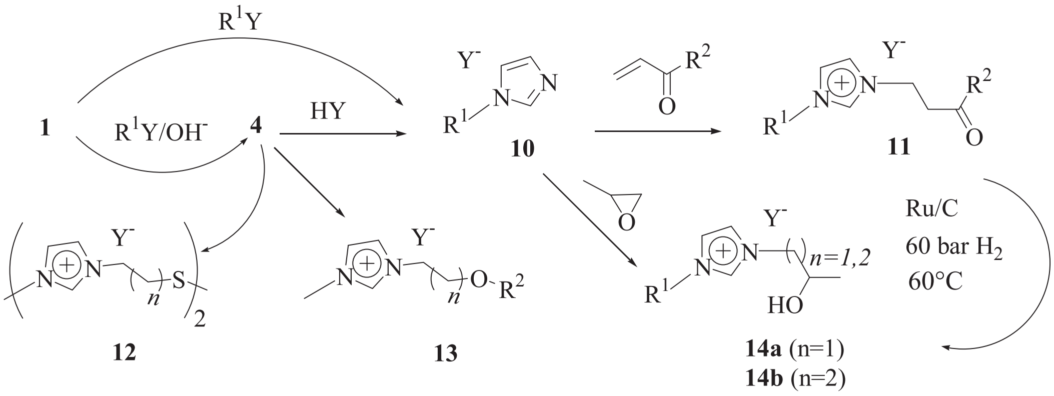
It should also be mentioned that the synthesis of 3-bis-((S), 2-methyl-butyl)-1 *H* -imidazole-1-ium bromide (yield 21%) can be carried out by alkylation of trimethylsilylimidazole **4** (R^1=$SiMe_3$) with (S)-1-bromo-2-methylbutane [28].

Syntheses of mono N-substituted imidazoles **4** are performed in most cases in absolute conditions, or with the use of at least double equivalents of the initial 1*H*-imidazole **1**.

Imidazoles **4** may react with the halo alkanes to give the salts **5** (Y = halogen). This group of substances is involved in the reaction with $AlCl_3$ or $FeCl_3$, leading to ionic liquids of structure **9** [22, 29-32]. Borates **6**, phosphates **8** and aluminates **9** can be synthesized by exchange reactions involving salts of the corresponding acids on N,N'**-** dialkyl imidazoles **5** [21-29, 33]. Also described are the syntheses of ionic liquids *"in situ*" directly in the reactor. In this case, the N-alkyl imidazoles **4** and the halo metals are mixed together in the reactor, and the ionic liquid is formed just before the beginning of the chemical process or the catalytic reaction [7]. For the purification of ionic liquids from chloride-ions electrochemical methods or ion exchange on ionites are used [27, 34, 35]. As to other approaches, the synthesis of ionic liquids with methyl and ethyl sulphate anions should be mentioned [36]. When synthesizing ionic liquids in the absence of a solvent (quaternization stage) a significant amount of heat is eliminated. The solution to this problem lies in performing the reaction under microwave or ultrasound radiation [37-40]. Eventually, the reaction product yield increases, the reaction time diminishes, the content of impurities in the product is minimized, and in some cases, the stage of the purification of the final product could be avoided.

1.2. Syntheses of functionalized 1,3-disubstituted imidazolium salts

In addition to the above-mentioned salts**,** derivatives of **11-14** with functional groups in side chain are also known (scheme 2).



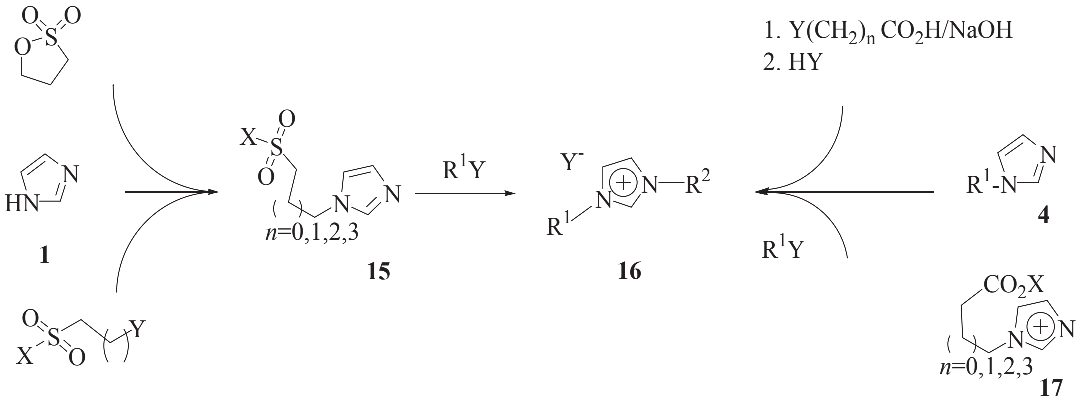
R^1=alkil, Bn, etc.; R^2=H, OH, alkil, O-alkyl, etc; Y=Cl,Br,I,BF_4,PF_6, $MeSO_3$,$(CF_3SO_2)_2N$

Scheme 2

Imidazolium salts **10** are added to α, β-unsaturated carbonyl compounds to give salt **11**. This is called the Michael reaction and it involves conjugate addition. [41]. Variants of functional group such as ether or thio- may be present in the final substrates **12** or **13** [6, 23, 27, 42, 43].

Hydroxy functionalized ionic liquids **14a** can be prepared by the reduction of ketone **11** (R^2=Me) or the treatment of 2-methyloxirane with salts **10** [44, 45]. In addition to the above-mentioned ionic liquids primary alcohols **13** may be synthesized directly by quaternization **4** [44].

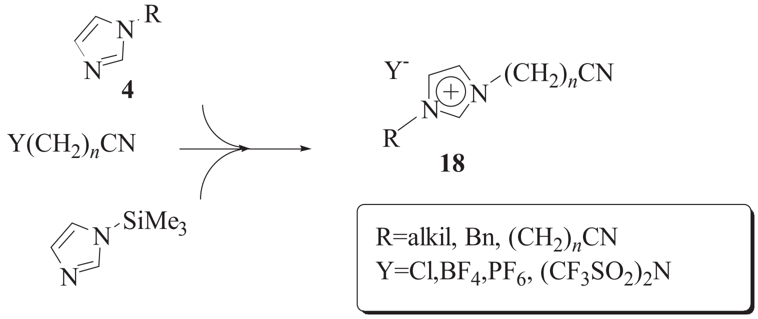
The synthesis of imidazolium salts with amino- [46-49], carboxy-, sulfo- and nitrile groups in the side chain should also be mentioned. Imidazole **1** easily transforms into salts **16**. There are many reagents that are added to imidazoles **4,15** according to (scheme 3). The same result can be achieved in one step with carboxy-functionalized imidazoles **17** [56-60].



R^1= alkil, Bn, $(CH_2)_nCO_2H$, etc.; X=Cl, H, OH; Y=Cl,Br,I, BF_4, PF_6, HSO_4

Scheme 3

Specialized literature also describes the precursors of carboxy-functionalized imidazolium salts (scheme 4) [61-69].



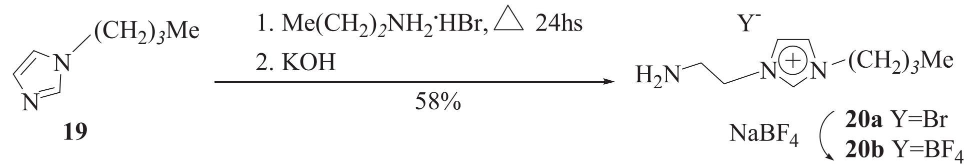
R=alkil, Bn, $(CH_2)_nCN$
Y=Cl,BF_4,PF_6, $(CF_3SO_2)_2N$

Scheme 4

There are two possible ways. The initial product is always mono-substituted imidazoles.

Reaction has been performed on a number of imidazoles, including 1*H*-imidazolyl(trimethyl)silane. In this case symmetrically dinitrile imidazole chlorides are obtained. The anionic exchange of chlorides with HPF_6, $NaBF_4$ and $LiTf_2N$ gives the corresponding imidazolium salts **18**.

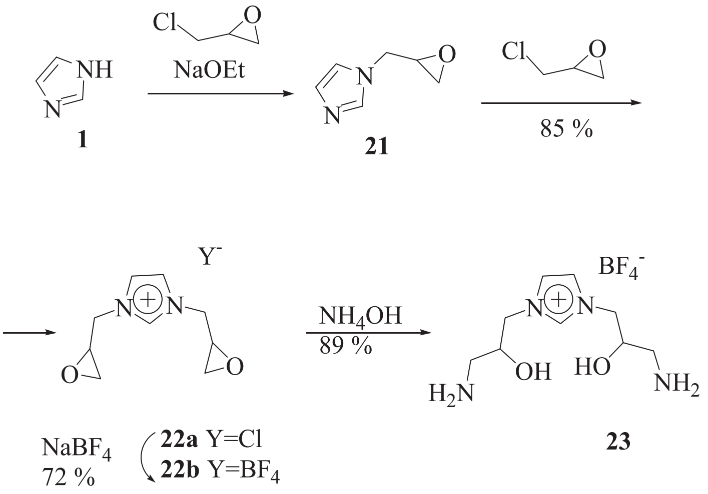
The synthesis of the functionalized ionic liquids with the primary amino group in the side chain is presented in (scheme 5) [70].



Scheme 5

The reaction of imidazole **19** with 3-brompropylamine is easily carried out at room temperature. $NaBF_4$ are added to aqueous ethanol solution of bromide **20a** to give ionic liquid **20b**.

Methyloxirane group can be introduced into the 1 and 4 positions of imidazole **1** by the treatment with 2-chloromethyloxirane following the quaternization of the product **21** until the chloride **22a** (scheme 6) [71].

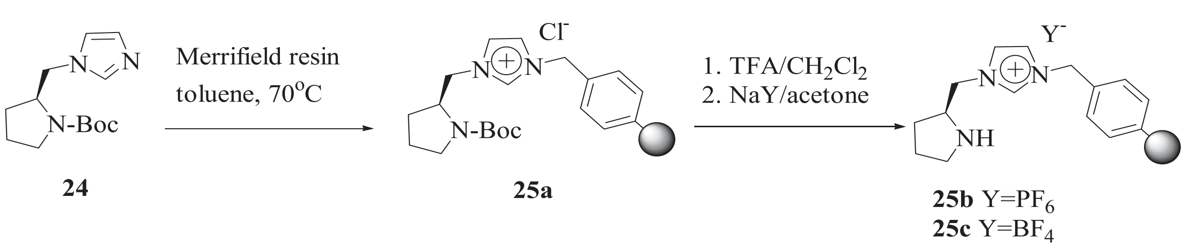


Scheme 6

The opening of the epoxides **22b** to amino-alcohols **23** has been accomplished at 2 atm.

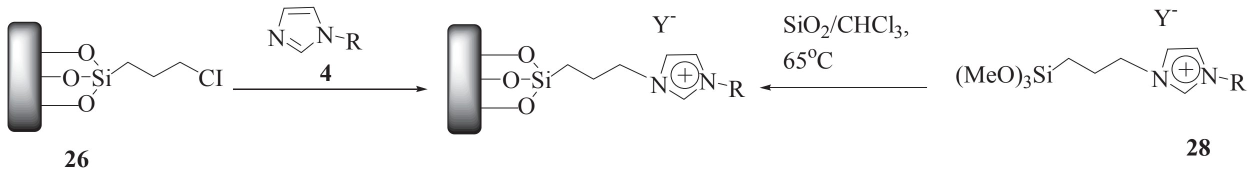
Lately, the number of the investigations dedicated to linking or immobilizing the ionic liquids on Al_2O_3, SiO_2, microporous polymers, clays and media based on coals and mesoporous materials has increased.

Polymers immobilizing ionic liquids can be prepared in a number of ways. In one method, chiral imidazolium salts **25a-c** have been obtained starting with imidazole **24** according to (scheme 7) [72].



Scheme 7

If the activated silica gel contains a functional group such as OH, corresponding ionic liquids **27** may be the products from chloride **26** or salts **28** (scheme 8).



26

28

27 Y=Cl,Br,I,PF_6, BF_4 or Proline

Scheme 8

This group of substances demonstrates the advantages over homogeneous ion liquids in simplifying the separation after the reaction, facilitating the regeneration which follows reusing, etc [73-80 62-69].

1.3. Physical properties of 1,3-disubstituted imidazolium salts

The theoretical dependence of the melting temperature of the discussed salts on the nature of the anion and the substituents has not been determined. Only the correlation between the melting temperature and the length of the radical in typical ionic liquids, which has a clear minimum: for C_3-C_5 the interval lies between -10°C and +10°C has been mentioned. Reducing the length of the radical leads to the increase of the "ionicity", which eventually leads to a higher melting temperature, while increasing the size of the anion leads to the decrease of the melting temperature. This can also be facilitated by the introduction of fluorine in the structure of ionic liquids. High viscosity and density are characteristic of ionic liquids, which increase when the replacing of chlorine or fluorine by bromine takes place.

Numbers of imidazolium salts have different stability. For example, ionic liquids containing $AlCl_3$ decompose in the presence of water or at the elevated temperature. An example of thermally stable ionic liquid is 1-ethyl-3-methyl imidazole triphtalate [emim]($(CF_3SO_2)_2N$] **29**, which is resistant to heating up to 450 °C [23]. It should be noted that many imidazolium ionic liquids can be used at the temperature up to 200 °C (see table 1).

Table 1

Physical properties and solubility of imidazolium salts 30a-e

Salt	M.p./ color	Temperature range of liquid phase	Solubility in solvents					
			H_2O	MeOH	Acetone	$CHCl_3$	hexane	toluene
[bmim][BF_4] **30a**	226.06/ Yellow	-48.96/ +399.20	+	+	+	+	-	-
[bmim][PF_6] **30b**	284.48/ Yellow	13.50/ +388.34	-	+	+	+	-	-
[bmim][$AlCl_4$] **30c**	154.01/ Brown	-88.69/ +263.10	0	0	+	+	-	+
[bmim][Br/$AlCl_3$] **30d**	154.01/ Black	13.61/ +272.51	0	0	+	-	-	-
[emim][PF_6] **30e**	256,13/ Yellow	2.71/ +304.65	-	-	+	+	-	-

(+) - mixes; (-) – doesn't mix; (0) – interacts with the salt.

The solubility of different substances in imidazolium salts **30a-e** depends on the dielectric permeability, polarity of both types of products, etc. It should be noted that hydrocarbons possess limited solubility in imidazolium salts. This property is used to simplify their application in two-phase systems, including separation procedures. It has been established that increasing the chain length of the substituent at nitrogen atoms can increase the solubility of olefins and aromatic hydrocarbons.

One of interesting properties of ionic liquids is presented below. Complexes of imidazolium salt with Cl^-, Br^-, I^-, BF_4^-, $CF_3CO_2^-$, $CF_3SO_3^-$ form homogeneous mixtures with H_2O, while salts with $(CF_3SO_2)_2N^-$ and PF_6^- practically don't mix with water and can be used in two-phase systems with water.

One of the tasks solved with the help of ionic liquids includes the increase in the solubility of salts and transition-metal complexes, frequently used in homogeneous catalysis, as they are characterized by low solubility in organic solvent. This makes imidazolium salts good alternatives to traditional solvents.

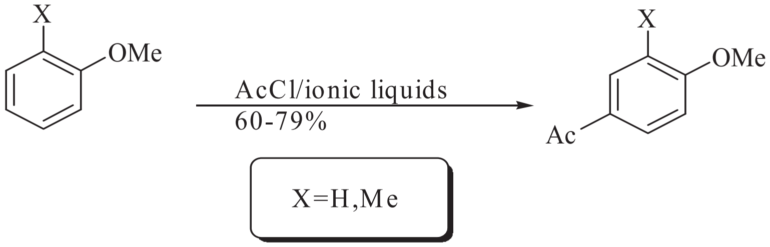
1.4. 1,3-Disubstituted imidazolium salts in organic synthesis

It is known that up to 90% of chemical processes on earth occur under catalytic conditions [81]. High specificity and/or efficiency are the main requirements of catalysts.

In the last decade we witnessed a significant increase of the interest in the use of 1,3-disubstitutedimidazole salts in organic synthesis. This is due to the fact that they are positively different from traditional solvents in their resistance towards oxidative actions, their non-volatility, and, in some cases, their catalytic activity.

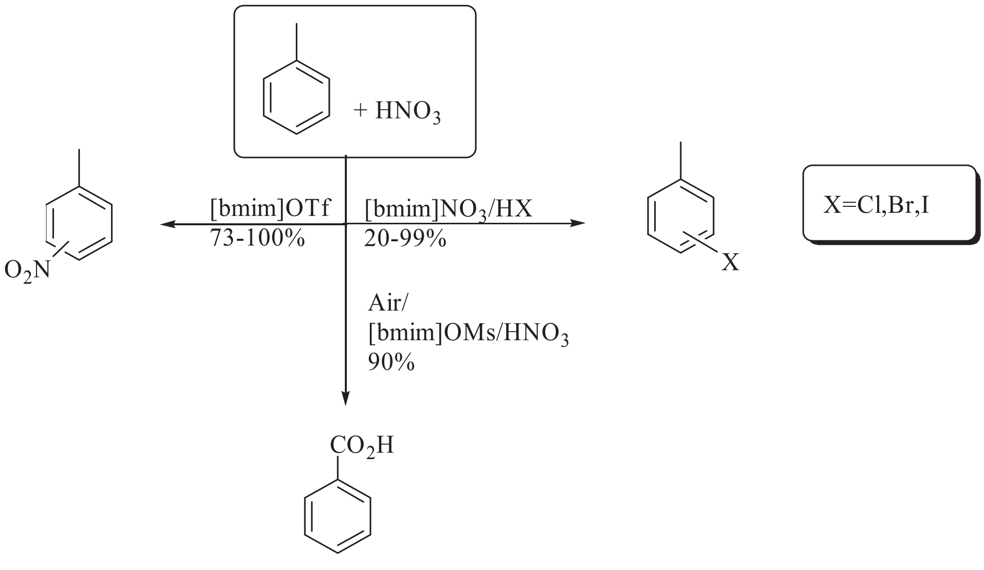
Imidazolium salts based on metals chlorides are considered an alternative to the traditional homogeneous and heterogeneous catalysts like $AlCl_3$, etc. These kinds of ionic liquids are strong Lewis acids, immobilized in the phase of ionic liquid by analogy with catalytic systems on solid media.

The processes associated with the chemistry of carbocations are one of the important areas that would allow us to explore the possibilities of the use of ionic liquids. Primary formation of reactive carbocations may occur in ionic liquids under the action of Lewis acids on the haloacyl- or alkyl derivatives, during the protonation of esters or molecules containing multiple links, etc. The reactions of alkylation and acylation of aromatic hydrocarbons according to Fridel-Kraft reaction (scheme 9) should be mentioned as an example [48, 82-89].



Scheme 9

An example of the relationship of the nature of the anion on the chemo- and regioselectivity is illustrated on the reaction of nitration, chlorination and oxidation of toluene (scheme 10) [90].

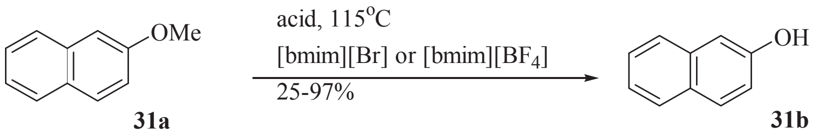


Scheme 10

The authors have shown that this approach is acceptable for benzene, biphenyl, anisole and naphthalene.

It should be emphasized that these articles and patents described alkylation and acylation of aromatic hydrocarbons in ionic liquids. This area is not limited to the reactions of electrophilic substitution and there are a number of publications on the use of ionic liquids in the alkylation of isobutene by butenes with the formation of isooctane or benzene fractions.

Another example of the alkylation is the C-alkylation of phenol, 2-naphthol or indole with yield up to 99% [91, 92, 80, 81]. One should also mention the communication about the use of the mixture of ionic liquid/mineral acid for the decomposition of methyl ether **31a** to alcohol **31b** (scheme 11) [93 82].

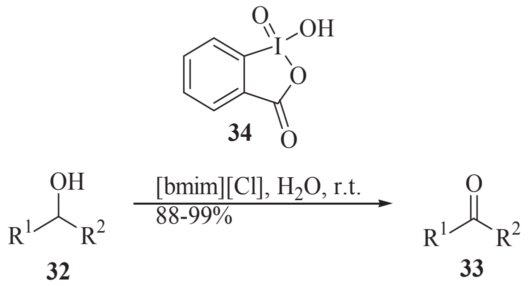


acid=HCl (35%),HBr (47%), H_2SO_4 (50%), AcOH, p-TsOH, MsOH

Scheme 11

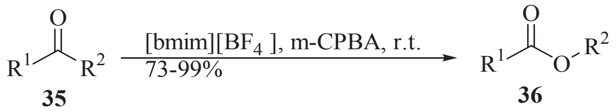
the reactions with similar mechanisms to the reactions of alkylation, such as etherification, were also investigated in ionic liquids [94-96, 83-85].

The oxidation of primary and secondary alcohols **32** to carbonyl derivatives **33** under the action of **34** in aqueous solutions of ionic liquids is shown in (scheme 12) [97].



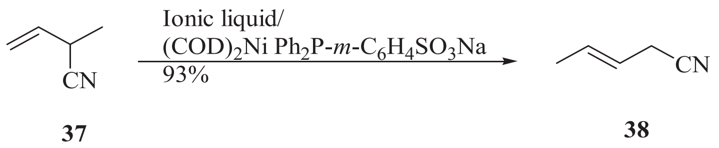
Scheme 12

The oxidation of ketones and aldehydes **35** according to the Baeyer-Villiger reaction in the solution of ionic liquids was proposed by a group of Indian chemists (scheme 13) [98].



Scheme 13

Catalytic processes involving ionic liquids give a new impulse to developing processes of dimerization, oligomerization, polymerization and copolymerization [99]. Isomerization of 2-methyl-3-buthenenitrile **37** in 3-pentenonitrile **38** was performed in a two-phase system (ionic liquid/n-heptane/ Ni(cod)$_2$, [Ph$_2$P*m*-PhSO$_3$Na]) with 96% conversion and 93% selectivity (scheme 14) [100-106].

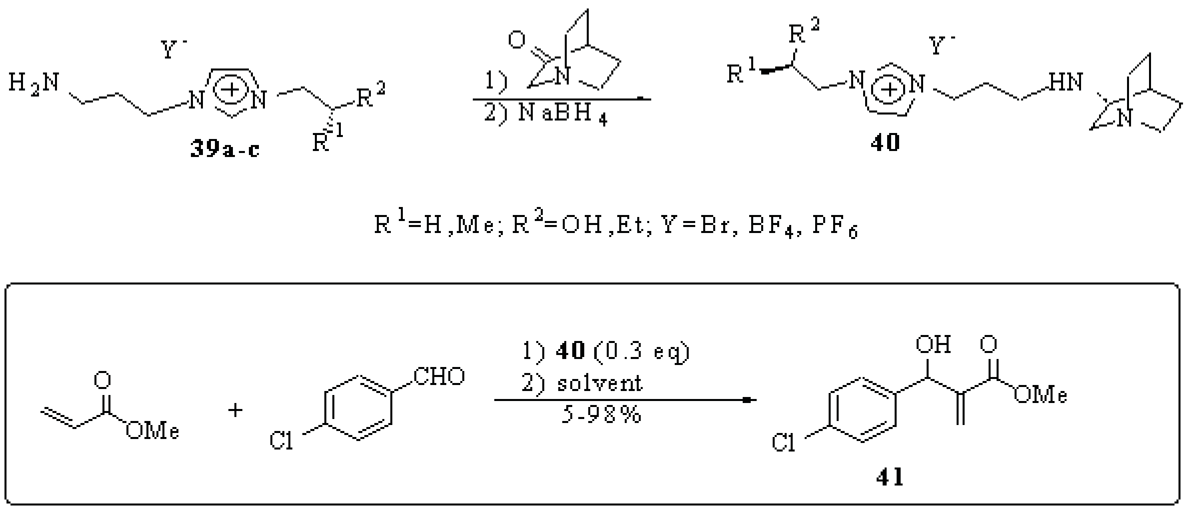


Scheme 14

It has been found that this system does not lead to the isomerization or the degradation of the n-heptane itself. The latter phenomenon has been observed with $Al_2Cl_7^-$ anion containing ionic liquids [107-113].

A group of researchers [114,115] reported the possibility of using ionic liquids **40** to perform the Morita-Baylis-Hillman reactions (scheme 15).

The authors suggested using amino- and amino hydroxy- functionalized salts **39a-c** for the synthesis of ionic liquids **40,** which catalyze the 1,3-adition of methyl acrylate to *p*-chlorbenzaldehyde. It was shown that the yield of alcohol **41** varies greatly from the nature of the solvent. The best yield was obtained using MeOH, while replacing it by ionic liquids **30a** or **30b** reduced the yield to 13% (scheme 15).



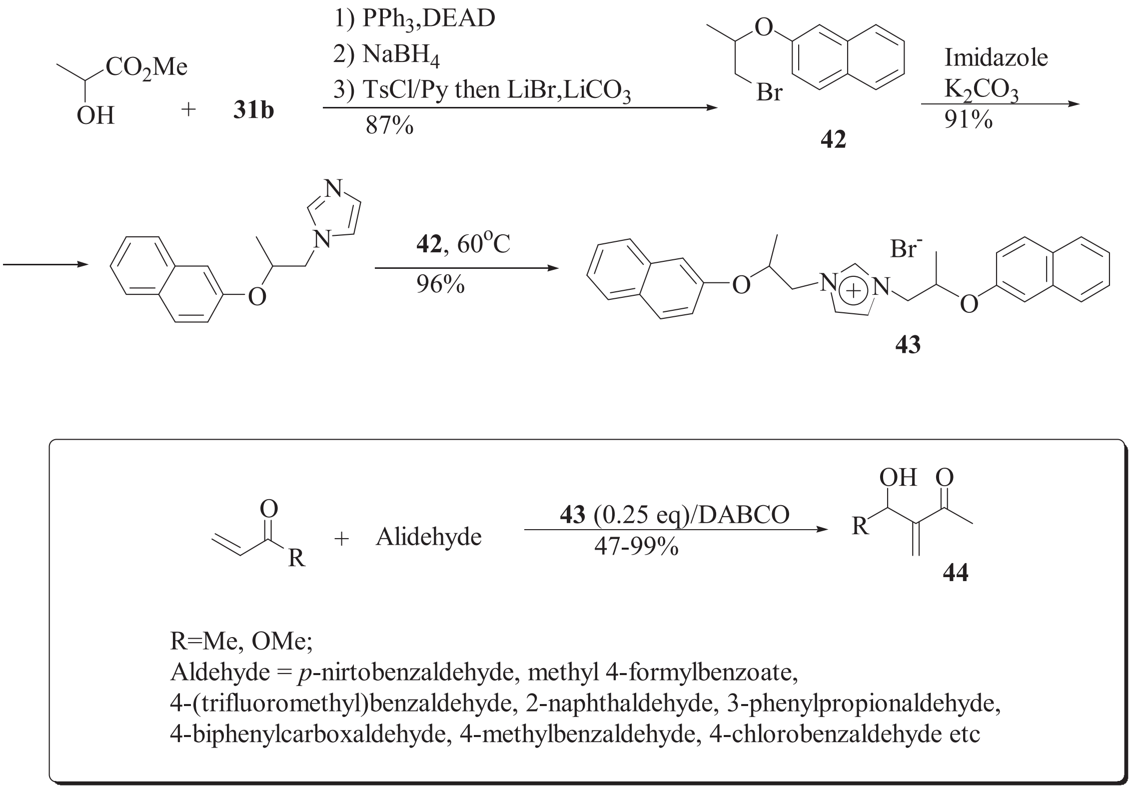
39a-c **40**

R^1=H,Me; R^2=OH,Et; Y=Br, BF_4, PF_6

41

Scheme 15

The synthesis and catalytic properties of another type of imidazolium salt **43** is described in [116]. The key intermediate **42** was obtained from the methyl ether of lactic acid and naphthol **31b** according to (scheme 16).



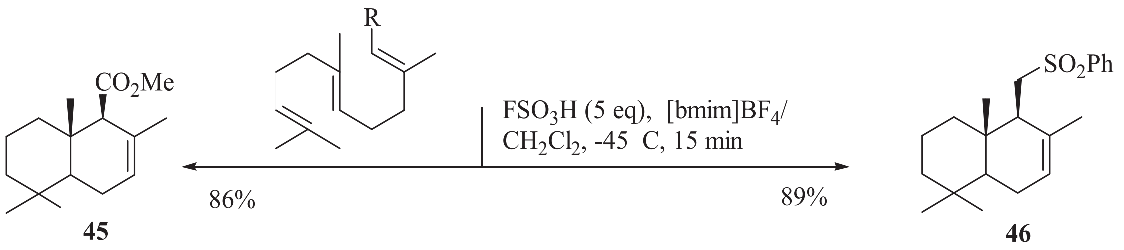
42 **43** **44**

R=Me, OMe;
Aldehyde = *p*-nirtobenzaldehyde, methyl 4-formylbenzoate, 4-(trifluoromethyl)benzaldehyde, 2-naphthaldehyde, 3-phenylpropionaldehyde, 4-biphenylcarboxaldehyde, 4-methylbenzaldehyde, 4-chlorobenzaldehyde etc

Scheme 16

The reaction yield of allylic alcohols **44** ranges from 47% to 99% and depends on the nature of the aldehyde.

Ionic liquids have been applied to superacidic cyclization of the terpenic phenyl sulphones to bicyclic compounds **45, 46** (scheme 17) [117].

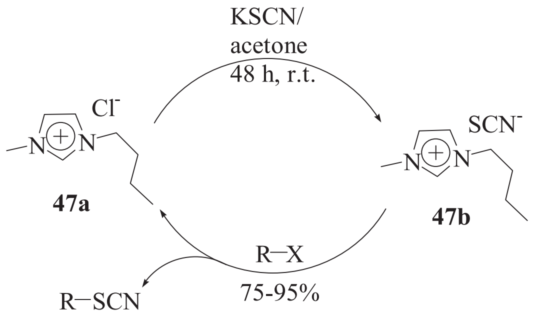


R=CO_2Me or CH_2SO_2Ph

Scheme 17

Similar reactions can be carried out on substances stable in acid media.

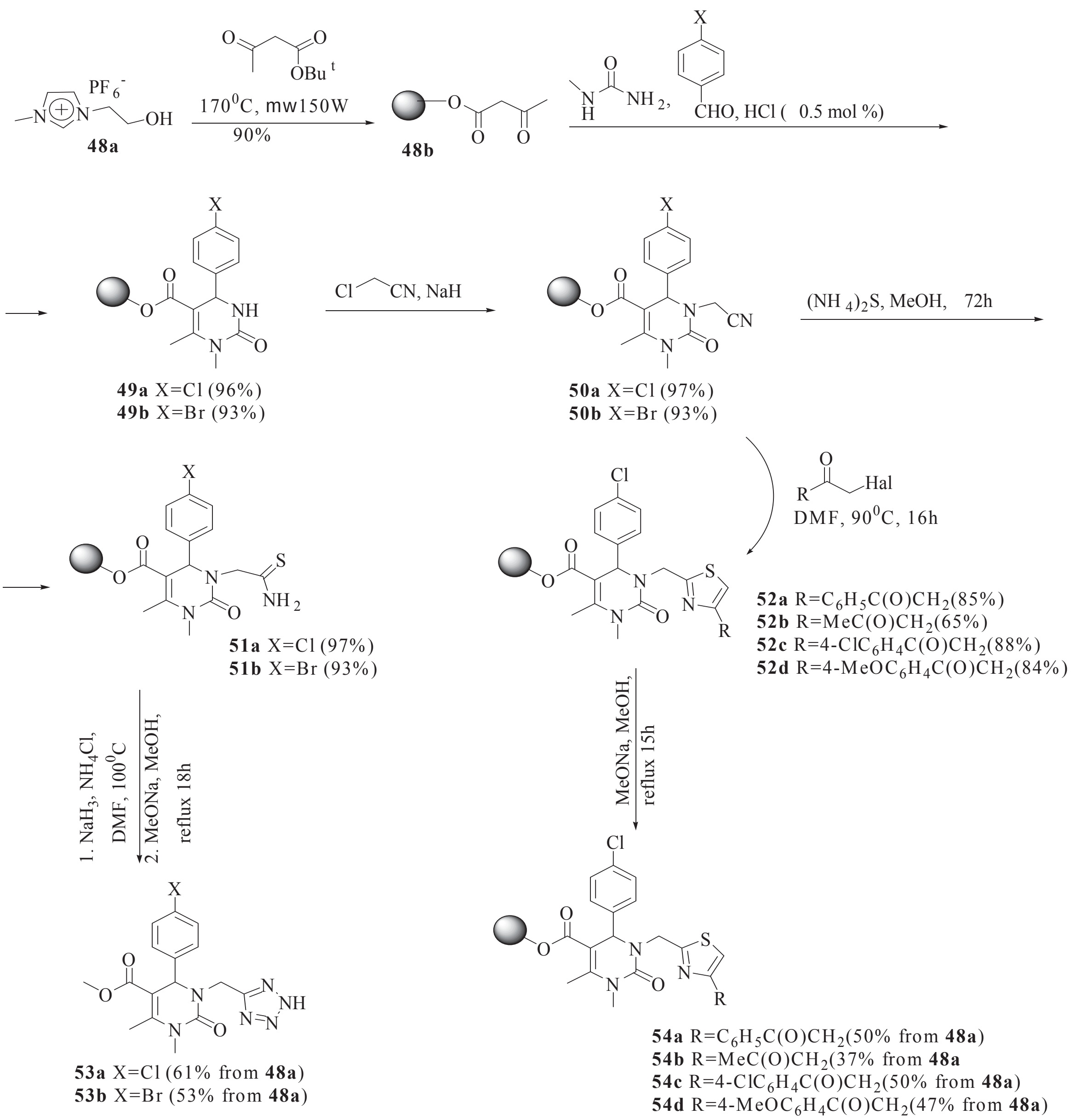
An Indian group of researchers reported the use of chloride of methylbutylimidazole **47a** for the thiocyanation of alkyl halogenides through the ionic liquid **47b** (scheme 18) [118].



R=$C_6H_5CH_2$, $HOCH_2H_4$, HOOC-C_3H_6; X=Cl, Br

Scheme 18

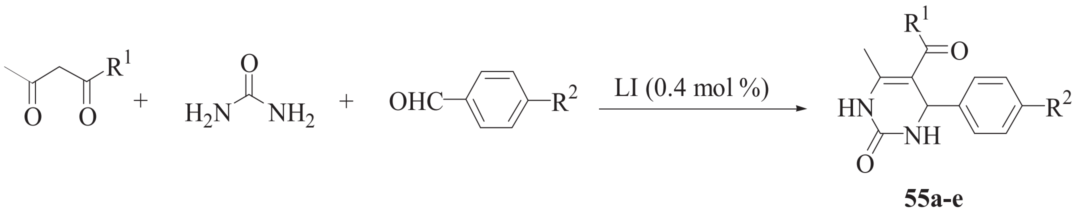
There are publications regarding the use of ionic liquids in the synthesis of the biologically active thioureas and ureas [119,120]. The strategy of the synthesis of 2-thioxo tetrahydropyrimidin-4-(1*H*)-ones is shown in (scheme 19).



Scheme 19

The trans-esterification of acetoacetic ester of hydroxy-functionalized ionic liquid **48a** under microwave radiation gives ester **48b**. The cyclocondensation of β-ketoester, N-methylurea with aromatic aldehydes according to Biginelli reaction occurs with the formation of cyclic products **49a,b**. Tetra-substituted ureas **50a,b** were used to obtain the ionic liquids **51a,b, 52a-d**. The final stage of obtaining tetrazoles **53a,b** and thiazoles **54a-d** was realized by a long heating of salts **51a,b** and **52a-d** with sodium methylate in MeOH.

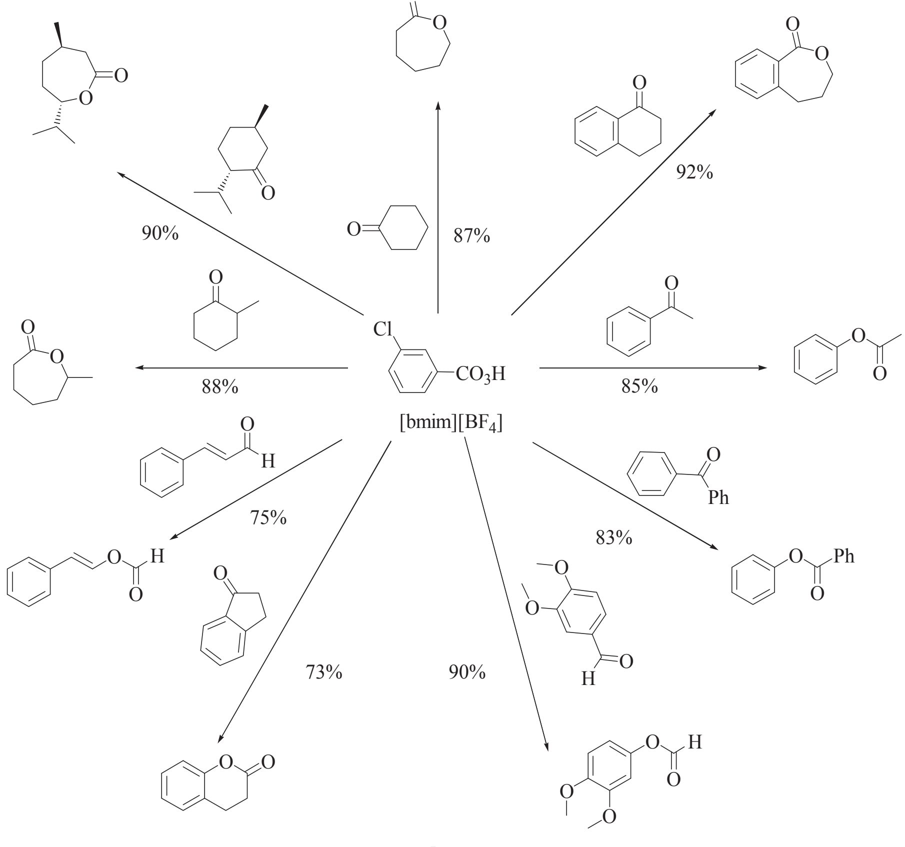
Analogously built 3,4-dihydropyrimidine-2(1 *H*)-ones **55a-e** have been synthesized (scheme 20) [121].



a: R^1=OC_2H_5, R^2=C_6H_5(85%, cat (**30a**) ; 94%, cat (**30b**)
b: R^1=OC_2H_5, R^2=4-$MeOC_6H_4$(95%, cat (**30a**) ; 98%, cat (**30b**)
c: R^1=OC_2H_5, R^2=4-ClC_6H_4(96%, cat (**30a**) ; 98%, cat (**30b**)
d: R^1=OC_2H_5, R^2=4-$NO_2C_6H_4$(90%, cat (**30a**) ; 92%, cat (**30b**)
e: R^1=Me, R^2=4-$NO_2C_6H_4$(92%), cat (**30a**)

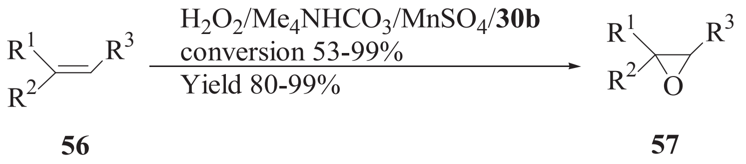
Scheme 20

Under the action of *m*-chlorperbenzoic acid, cyclic and non-cyclic ketones are to esters or lactones oxidized according to Baeyer-Villiger in the solution of the tetrafluorborate **30a** (scheme 21) [112,122].



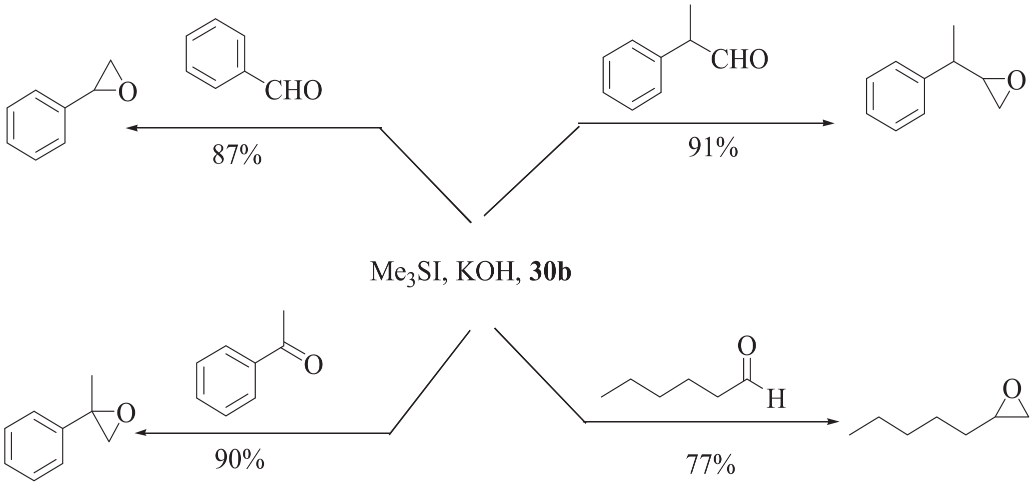
Scheme 21

The ionic liquid plays the role of solvent and activator of *meta*-chlorperbenzoic acid. On the other hand, the tetrafluorborate **30a** is suggested for the epoxidation of olefins **56** to oxides **57** in the system with $H_2O_2/Me_4NHCO_3/MnSO_4$ (scheme 22) [123].



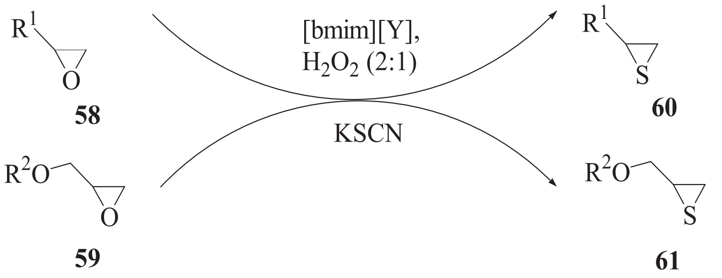
Scheme 22

Another type of epoxidation according to the Corey-Chaykovsky reaction was performed by Me_3SI and KOH in the solution of hexafluorphosphate **30b** (scheme 23) [124].



Scheme 23

Epoxides **58, 59** may be transformed into thioranes **60, 61** under the action of the mixture KSCN/ionic liquid/H_2O_2 (scheme 24) [125].

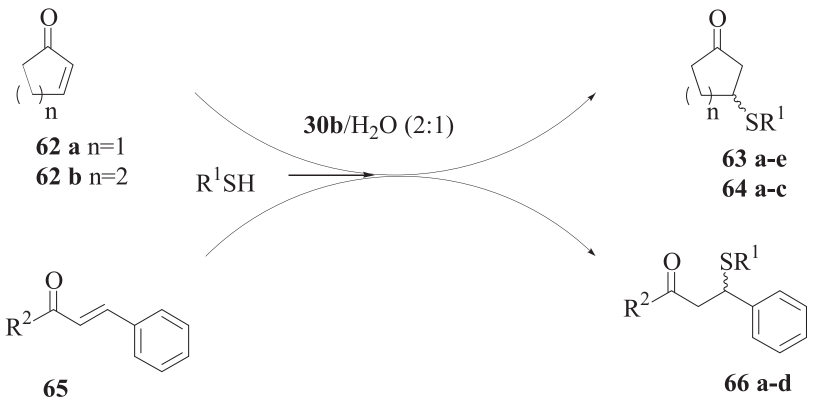


R^1=C_6H_5(Y=BF_4, 89% ; Y=PF_6, 93%) R^2=C_6H_5(Y=BF_4, 91% ; Y=PF_6, 95%)
R^1=CH_2Cl (Y=BF_4, 80% ; Y=PF_6, 91%) R^2=allyl (Y=BF_4, 85% ; Y=PF_6, 92%)
R^1=n-hexyl (Y=BF_4, 87%) ; Y=PF_6, 92%) R^2=n-butyl (Y=BF_4, 87% ; Y=PF_6, 90%)
R^2=C_6H_5(Y=BF_4, 91% ; Y=PF_6, 95%) R^2=4-Cl-C_6H_4(Y=BF_4, 85% ; Y=PF_6, 96%)
R^2=4-MeO-C_6H_4(Y=BF_4, 89% ; Y=PF_6, 92%) R^2=4-Me-C_6H_4(Y=BF_4, 90% ; Y=PF_6, 95%)

Scheme 24

The authors have shown that the sulfides **60, 61** are formed with the yield up to 95%.

In addition, the group has reported the synthesis of β-ketosulfides **63a-e**, **64a-c**, **66a-d** by conjugated addition of thiols to enones **62a, 62b, 65** in the mixture of hexafluorphosphate **30b** / H_2O (scheme 25) [126].



63a R^1= C_6H_5, n=2, 10 min, 95% ; **63b** R^1= 4-Cl-C_6H_4, n=2, 15min, 93% ;
63c R^1= 4-MeO-C_6H_4, n=2, 10 min, 97% ; **63d** R^1= Benzil, n=2, 25min, 91% ;
63e R^1= 2-Naphthyl, n=2, 20min, 90% ; **64a** R^1= C_6H_5, n=1, 15 min, 95% ;
64b R^1= 2-Naphthyl, n=1, 20min, 90% ; **64c** R^1= 4-MeC_6H_4, n=1, 10 min, 94% ;
66a R^1= R^2= C_6H_5, 15 min, 95% ; **66b** R^1= 4-MeC_6H_4, R^2= C_6H_5, 10 min, 92% ;
66c R^1= 4-MeC_6H_4, R^2= Methyl, 20 min, 92% ; **66d** R^1= 4-MeC_6H_4, R^2= Sthiryl, 25 min, 89%.

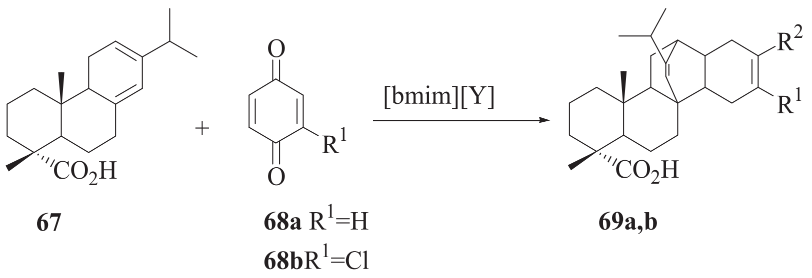
Scheme 25

The reaction has the character of universality: the reaction time and the yield of products practically do not depend on the nature of enones and aromatic thiols.

Ionic liquids can also be used in various condensation reactions, as both catalysts and solvents [2-20, 81].

It is known, that the Diels-Alder reaction is useful for the preparing of cyclic compounds from the corresponding unsaturated substances under mild conditions, even in the absence of a catalyst.

Diene **67** reacts rapidly with quinones **68a** in the presence of ionic liquids to give cyclic compound **69a** (scheme 26) [127].



Scheme 26

Table 2

Reaction time and product yield of the reaction 67 with *n*-benzoquinone 68a

Catalyst	Solvent	Reaction time, h	Yield, %
[bmim][PF$_6$] **30b**	$C_6H_6+C_6H_{14}$	1	100
[bmim][BF$_4$] **30a**	$C_6H_6+C_6H_{14}$	3.5	54
[bmim][CF$_3$CO$_2$]	$C_6H_6+C_6H_{14}$	4	87

As can be seen from table 2, the most effective catalyst in the synthesis is a mixture of [bmim] [PF$_6$]-benzene-hexane.

The authors performed the reaction of the diene **67** with 2-chloro-*p*-benzoquinone **68b** using catalytic quantities of [bmim][PF_6], [bmim][BF_4] or [bmim][CF_3CO_2] (see table 3).

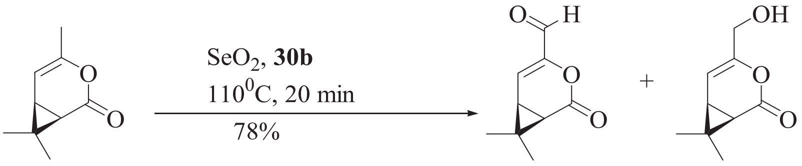
Table 3

Reaction time and product yield of the reaction 67 with 2-chloro-*p*-benzoquinone 68a

Catalyst	Solvent	Reaction time, h	Yield, %
[bmim][PF_6] **30b**	CH_2Cl_2+C_6H_{14}	3	100
[bmim][BF_4] **30a**	CH_2Cl_2+C_6H_{14}	6	90
[bmim][CF_3CO_2]	CH_2Cl_2+C_6H_{14}	20	75

The Diels-Alder reaction has been performed regioselectively. The major product is the compound **69b** (R^1=Cl, R^2=H).

The allylic oxidation of the lactone **70** (scheme 27) has also been investigated [128].



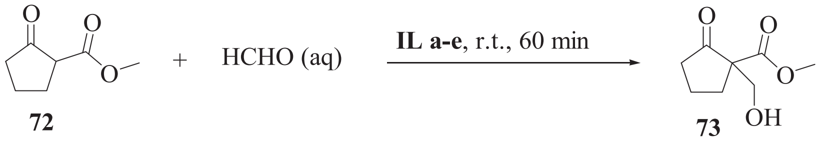
70 **71a** **71b**

Scheme 27

It was shown that increasing the amount of SeO_2 up to a 3 eq. and carrying out the reaction in the ionic liquid **30b** leads to a single product **71a.**

When compound **70** is heated with SeO_2 in ionic liquids at 50°C, the product is the mixture **71a,b** (total yield 60%).

Aldehydes are obtained by the hydroformylation of olefins on Rh, Pt, Co, or Ru-catalysts, which are quite expensive. However, acetylacetonic and carbonylic metal complexes dissolved in imidazole with the hexafluorophosphate as the anion showed high activity and selectivity in obtaining products of hydroformylation [31,32]. Metal containing ionic liquids were proposed for the hydroformylation of the β-keto ether **72** [32].



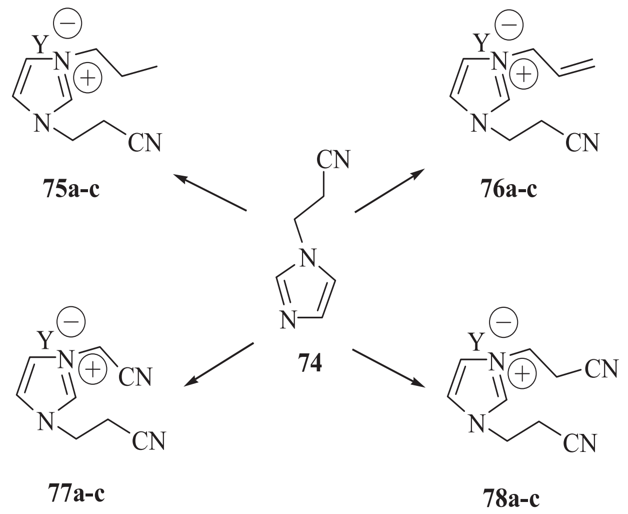
72 **73**

IL : **a** [bmim][$FeCl_4$], 90%; **b** [bmim][$NiCl_4$], 77%; **c** [bmim][$CoCl_4$], 76%;
d [bmim][$CuCl_4$], 44%; **e** [bmim][$TiCl_5$], 32%.

Scheme 28

A convenient method of preparing hydroxy derivative **73** consists in the treatment of compound **72** with system -aqueous formaldehyde / 0.1mol-% of [bmim][$FeCl_4$]. The utilization of titanium tetrachloride decreased the yield of the product **73** (scheme 28).

We also began by designing solvents/catalysts which would be prepared from imidazole **74** (scheme 29).



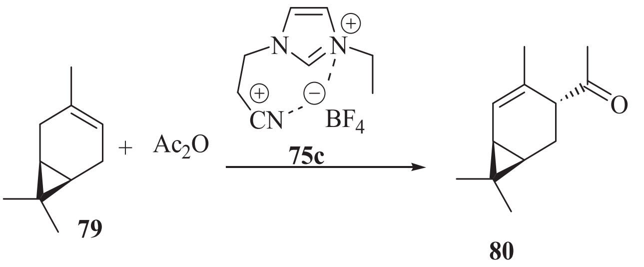
a=Br or Cl; **b**=PF_6; **c**=BF_4

Scheme 29

The imidazolium salts **75a,76a,77a, 78a** (Y=Br or Cl), which can be prepared by the treatment of imidazole **74** with alkyl halides, can be converted to ionic liquids **75b,76b,77b, 78b** as well as **75c,76c,77c, 78c** by the treatment with inorganic salt ($NaBF_4$ or KPF_6) [61-67].

Olefins can be acylated or hydroxyformylated with an acyl halide or paraformaldehyde and Lewis-acid catalyst [130-141].

We have previously seen that (+)-3-carene **79** can be acylated in the position 4 in the presence of compound **75c** (scheme 30) [137,138].



Scheme 30

The catalytic action of the synthesized imidazolium salts is probably linked to the initial formation of the acylcation from Ac_2O with the participation of the bipolar particle $\text{-}CH_2C^{+}\text{=}N\cdots BF_4^{-}$.

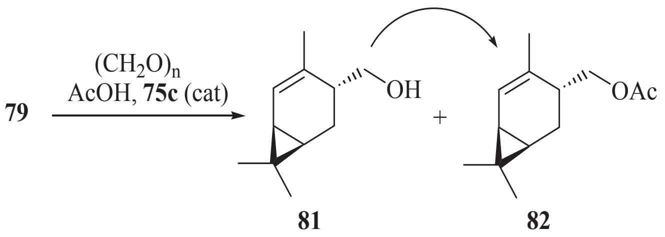
Compound **79** can be also acylated by the treatment with mixture Ac_2O/**75a** or Ac_2O/**75b** to give target **80a,b** (table 4).

Table 4

The reaction conditions and product 80 yield

Ionic liquid	Quantity of IL	Yield, %	Reaction time, h
75a	6 mol %	33	49
75a	200%	37	25
75b	6 mol %	29	48
75c	6 mol %	38	46

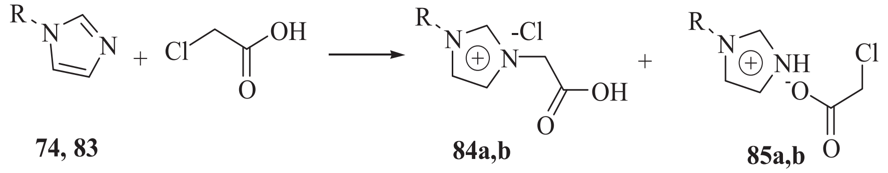
Since (+)-3-carene **79** is converted to ketone **80,** this is also a method for the preparing of 4-substituted 2-carenes **81, 82** (scheme 31).



Scheme 31

The presence of a free carboxymethyl group in the imidazole molecule may enhance the hydrophility of substances and therefore broaden the area of their utilization [139-141]. Due to this, investigations connected to the search of novel carboxy-functionalized ionic liquids and to the elaboration of effective catalysts on their basis, are promising and present practical interest.

Carboxymethyl group can be introduced by the treatment of N-methyl imidazole **83** (R=Me) with monochloroacetic acid in acetonitrile (scheme 32) [56-59].



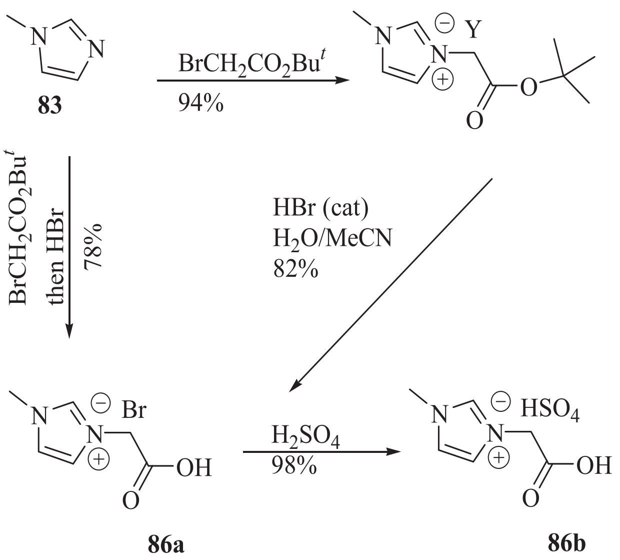
a:R=Me ; **b**:R=CH_2CH_2CN.

Scheme 32

The mixture **84a,85a** is presented as oil-like liquid.

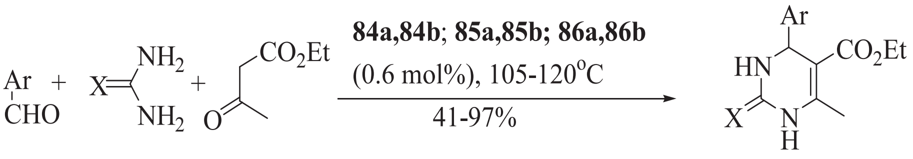
Imidazolium salts **86a,b,** important reagents with a number of potential synthetic uses can be prepared in other ways (scheme 33).

When imidazole **83** is treated with tert-butyl 2-bromoacetate, quaternization that is analogous to scheme 32 occurs. Deprotection gives a free carboxy- group of substance **86a**. A particularly mild method for the conversion of salt **86a** to imidazolium salt **86b** uses H_2SO_4 (scheme 33).



Scheme 33

3,4-Dihydropyrimidine-2(1*H*)-ones(thiones) **87a,b-92a,b** can be synthesized via one-pot reaction of ureas (thioureas), aldehydes with β-dicarbonyl compounds catalyzed by ionic liquids (scheme 34) [121,142].



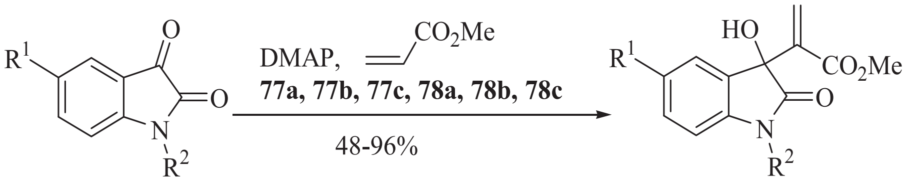
87a,b-92a,b

87 : Ar=Ph, X=O (a), S (b); **88** : Ar=3,4-$(MeO)_2C_6H_3$, X=O (a), S (b);
89 : Ar=2,4-$(MeO)_2C_6H_3$, X=O (a), S (b); **90** : Ar=2,4-$Cl_2C_6H_3$, X=O (a), S (b);
91 : Ar=4-$MeOC_6H_4$, X=O (a), S (b); **92** : Ar=4-$(Me_2N)C_6H_4$, X=O (a), S (b).

Scheme 34

It was established that using ionic liquids as organocatalysts of Biginelli reaction leads to the decrease of the reaction time and the increase of the product yields, as compared to the activity of other ionic liquids. It should be noted that in most cases, the yields of the 3,4-dihydropyrimidine-2(1*H*)-thiones are higher than those of their oxygen-containing analogues.

Considerable attention has recently been focused on the conversion of the simple starting materials into highly functionalized products such as α-hydroxy- or α-amino-alkyl activated olefins [1-6]. The 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-indolyl)acrylates sequence plays a very important part in organic as well as medicinal chemistry [143,144]. We established, that the two-component system consisting of ionic liquid and dimethylaminopyridine (1:8) is an efficient catalyst for obtaining 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylates **94a-h** (scheme 35)[145-147].



93a-h

94a-h

a) R^1=H, R^2=-Et; **b**) R^1=H, R^2=-C_3H_7; **c**) R^1=H, R^2=-CH_2CH=CCl-Me;
d) R^1=H, R^2=-CH_2-CH=CH_2; **e**) R^1=-Me, R^2=-CH_2-CH=CH_2;
f) R^1=H, R^2=-CH_2-CCH; **g**) R^1=H, R^2=-CH_2-C_6H_5; **h**) R^1=H, R^2=-C_4H_9

Scheme 35

The reaction was performed under stirring during 1 hour at room temperature of the mixture of isatines **93a-h**: methyl acrylate : dimethylaminopyridine : ionic liquid at a molar ratio of 1 : 1.56 : 0.5 : 0.06.

To conclude, it should be noted that due to the diversity and specificity of their characteristics, ionic liquids proved to be very attractive for catalysis and organic synthesis.

3. Conclusion

Up to date, low-temperature melting imidazole salts or ionic liquids were determined to be useful as alternative solvents, catalytic media and simply catalysts in various processes of organic synthesis.

In this paper we reviewed the available literature and our own data on the synthesis, physical and chemical properties, and future uses of imidazolic ionic liquids in such reactions as esterification, alkylation, epoxidation, acylation, isomerization, cycloaddition, etc. Ionic liquids form a two-phase system, which greatly facilitates the separation of products from the catalyst. In addition, they can be used repeatedly without any activity loss and without a need of regeneration. Another important advantage is represented by the strength (for some systems - superacidic) of metallochlorinated ionic liquids, a property that allows for the transformation process to occur at low temperatures. These properties permit ionic liquids to be full participants in “alternative” chemical processes, even if we don’t take into account the productivity and selectivity gains presented in this review.

We consider that electrochemical studies (using electrolytes of solar batteries, and so on.), electrocatalysis and complex metallic catalysis represent promising areas of further research for those interested.

Acknowledgements

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OPTICALLY ACTIVE CHRYSANTHEMIC ACID AND ITS ANALOGUES

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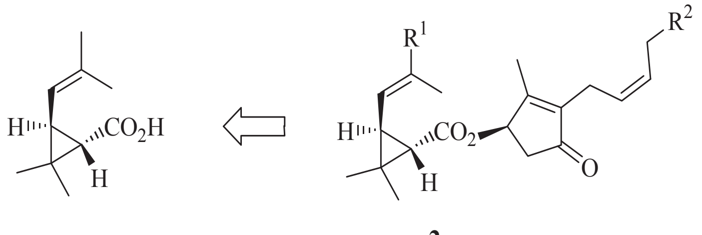
Dedicated to Professor Lupaşcu Tudor on his 60th birthday

Abstract: Optically active chrysanthemic acid and its analogues have received considerable attention in recent years due to their practical importance. This review will focus on describing the developments in the synthesis of optically active chrysanthemic acid and its analogues. The transformation that will be covered includes the chemistry of enantiomerically pure 2,2-dimethyl 1,3-disubstituted cyclopropanes derived from monoterpene (+)-3-carene.

Keywords: chrysanthemic acid, pyrethrins, pyrethroids, permetrin, cypermethrin, deltamethrin (decis), thigalotrin (cyhalothin), natural (+)-3-carene, organic synthesis.

1. Introduction

Optically active chrysanthemic acid **1** and its esters **2a-e** (pyrethrins) have been isolated from pyrethrum flowers (*Chrisanthemum cinerariaefolium*) [1-11]. For a long time pyrethrins have not found application as crop protection agents due to their photo lability and quick oxidization while in open air conditions.

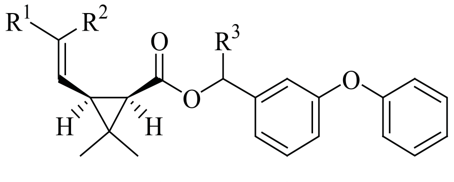


1 **2a-e**

2a R^1=-Me, R^2=-CH=CH$_2$; **2b** R^1=-CO$_2$Me, R^2=-CH=CH$_2$; **2c** R^1=-Me,R^2=-Me;
2d R^1=-CO$_2$Me,R^2=-Me; **2e** R^1=Me,R^2=-H;

Scheme 1

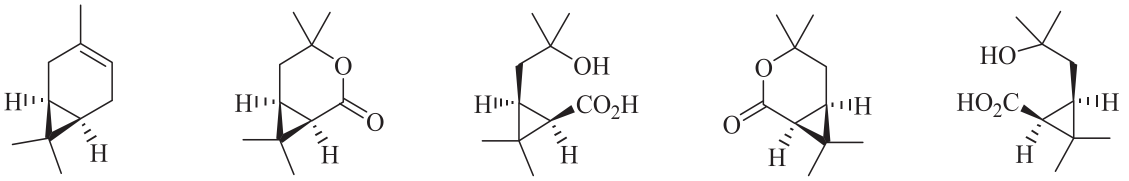
The synthesis of a stable and effective pyrethroid - permetrin **3a,** made in 1973 gave an impetus to the search for its structural analogues and, as a result, cypermethrin **3b**, deltamethrin (decis) **3c**, thigalotrin (cyhalothin) **3d** and several other compounds with higher insecticide activity were discovered [12-24].



3a R^1=R^2= CI, R^3= H;
3b R^1=R^2= CI, R^3= CN
3c R^1=R^2= Br, R^3= (*S*)CN
3d R^1= Cl, R^2= CF$_3$, R^3= (*S*)CN

Scheme 2

The present tendency of the pyrethroids chemistry developing is to carry out the guided synthesis of enantiomerically pure substances which, gradually, supplant the racemic ones. The syntheses of the optically active pyrethroids that represent ester are, in most cases, connected with the preparation of an enantiomerically pure acid component [25-29]. One of the ways of obtaining such acids is the using of the accessible natural (+)-3-carene **4** due to the renewable character of its sources, high enough optical purity, as well as the possibility for the synthesis of the products that belong to antipode series (see scheme 3).



4 **5a** **5b** **6a** **6b**

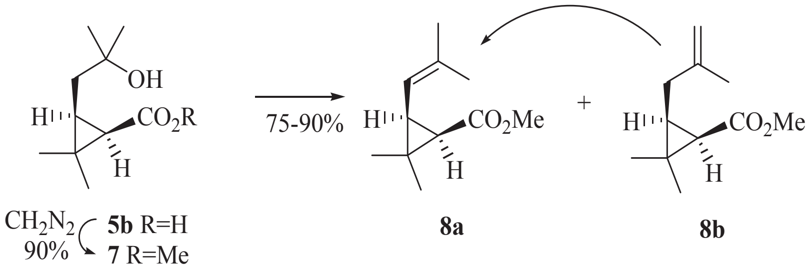
Scheme 3

The synthesis of pyrethroid acids from (+)-3-carene **4** has been thoroughly considered in [30-34]. Therefore, only the most important and newest data regarding the synthesis of chrysanthemic acid and its analogues from synthons on the basis of compound **4** will be dealt with in the review.

2. Synthesis, isomerization and separation of the chrysanthemic acid, its esters and analogues

Judging by the available data, more preferable initial substances in synthesizing these compounds are acid **5b** and lactone **5a**, as well as their antipodes **6a** and **6b**.

Dehydroxylation of alcohol **7** affords the mixture of methyl (1R,3S)-chrysanthemates **8a,b**.

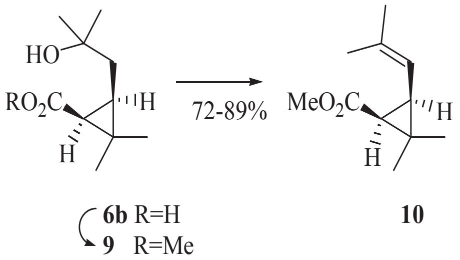


8a **8b**

Scheme 4

The transformation can be performed by refluxing with *p*-toluenesulfonic acid in toluene [28], xylene and benzene [35,36] or $POCl_3$ in Py [37]. Mixture **8a,b** can be separated only chromatographically on SiO_2 columns, impregnated with $AgNO_3$. However, during a prolonged heating of the reaction mixture, ester **8b** isomerizes into thermodynamically more stable ester **8a**.

Similarly, alcohol **9** has been converted into methyl (+)-(1S,3R)-chrysanthemate **10** [6,38].

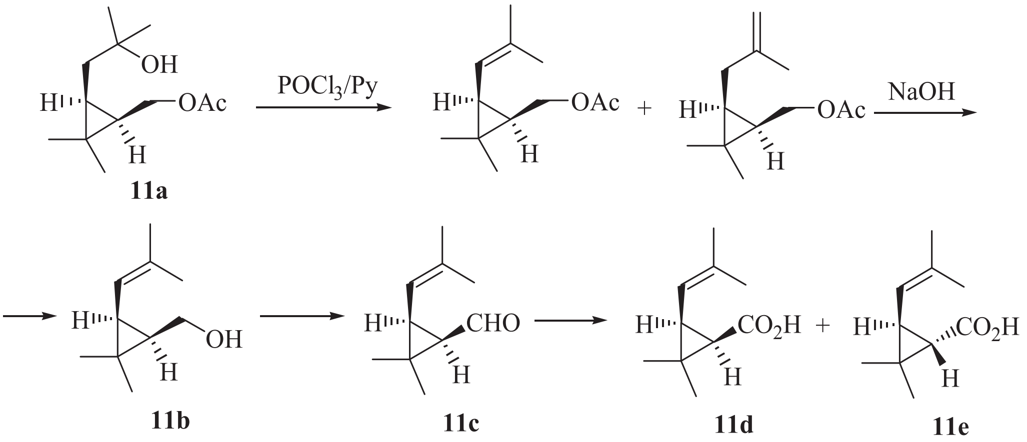


10

Scheme 5

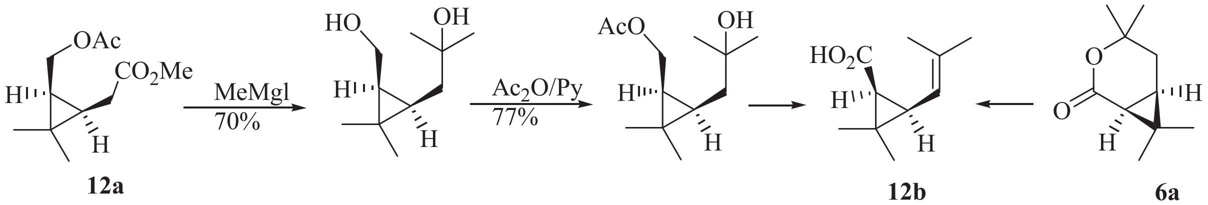
Acetate **11a** has served as initial compound for synthesizing the (-)-(1R,3S)-chrysanthemic acids **11d,e** [39].

It should be noted that dehydroxylation as well as oxidation proceeds non-specifically. Alcohol **11b** can be oxidized step-by-step, firstly in aldehyde **11c** by air oxygen on platinum catalysts [40] or CrO_3 [41]. In its turn, compound **11c** produces acid **11d,e** at the interaction with CrO_3 in pyridine [42,43], Jones's reagent [43] or silver oxide [40].



Scheme 6

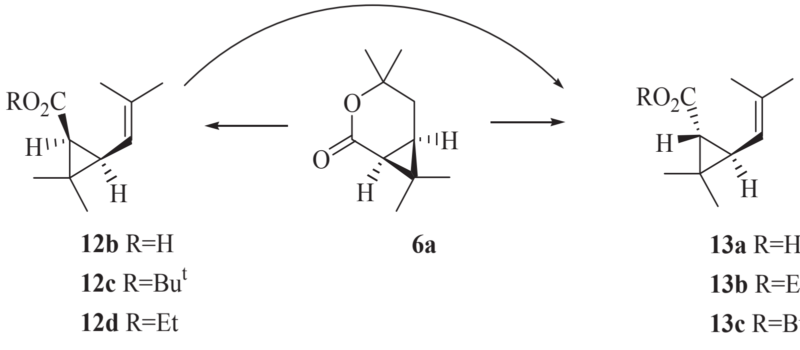
(-)-(1S)-*cis*-Chrysanthemic acid **12b** has been obtained from **12a** according to scheme **7** [44].



Scheme 7

As has been mentioned above, chrysanthemic acids can be obtained from dihydrochrysanthemolactone. Thus, (-)-lactone **6a** is easily converted into *cis*-chrysanthemic acid **12b** under the action of diluted H_2SO_4 [28,45,46], potassium *tert*-butoxide [28,45], potassium hydroxide [47] or SO_2Cl_2 [48]. This conversion, which ends the transformation of 3-carene **4** into acid **12b**, has served as a proof of its stereochemistry [49,50].

Compound **6a** with solution H_2SO_4 in *tert*-butanol affords ester **13a** (yield 95%) [51]. The authors [47] discovered that in more rigid condition (heating with sodium hydroxide in ethylene glycol at 225-230^{0}C for 5 hours) lactone **6a** immediately isomerizes into (+)-*trans*-acid **13a**.



Scheme 8

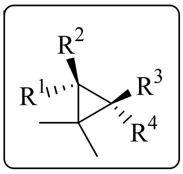
It should be noted that (-)-*cis*-acid **12b** can be also isomerized into (+)-*trans*-acid **13a** by heating its ethyl ester **12d** with NaOEt in ethanol in a soled tube followed by the saponification of **13b** with alkali [28,45]. A more convenient transformation of *cis*-esters into *trans*-esters under the action of potassium *tert*-butoxide is reported in patent [52].

Antipode **5a** can be turned into the corresponding (+)-*cis*-acid **11d** or (-)-*trans*-acid **11e** in the same way [28].

In the corresponding literature one can find a whole series of chrysanthemic acids and their esters analogues (see table). They have been mainly prepared by the schemes of the synthesis of chrysanthemic acids.

Table 1

Chrysanthemic acid esters and their analogues



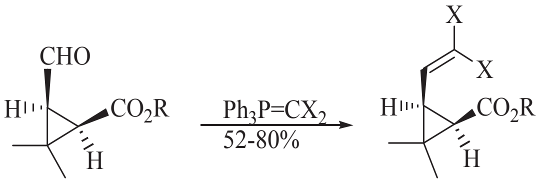
№	Substituents				Ref.
	R^1	R^2	R^3	R^4	
1.	H	CH=C(Ph)Me	H	H	35,60
2.	H	CO_2Me	CH=C(Ph)Me	H	53
3.	CO_2Me	H	CH=C(Ph)Me	H	54
4.	H	$CH=C(4\text{-}MeC_6H_4)Me$	CO_2Me	H	55
5.	CO_2Me	H	$CH=C(4\text{-}MeC_6H_4)Me$	H	55
6.	H	$CH=C\text{-}C_6H_4Me$	CO_2Me	H	56
7.	H	$CH=C\text{-}(4\text{-}ClC_6H_4)Me$	CO_2Me	H	56
8.	CO_2Me	H	$CH=C(4\text{-}Cl\text{-}C_6H_4)Me$	H	54
9.	CO_2Me	H	CH=C(CHO)Me	H	56, 57
10.	H	CH=C(CN)Me	CO_2Me	H	58
11.	H	CH=C(Cl)Me	CO_2Me	H	58
12.	CO_2Me	H	CH=C(Cl)Me	H	59
13.	H	CO_2Me	CH=C(Cl)Me	H	60
14.	CO_2Me	H	CH=C(Cl)Ph	H	61
15.	H	CH=C(Cl)Ph	CO_2Me	H	62
16.	H	CO_2Me	CH=C(Cl)Ph	H	63
17.	CO_2Me	H	$CH=C(4\text{-}ClC_6H_4)Ph$	H	64
18.	CO_2Me	H	$CHC\equiv CCl$	H	64
19.	H	$CH=C(Cl)CH_2OH$	CO_2Me	H	58
20.	H	CH=C(Cl)CHO	CO_2Me	H	58
21.	H	CO_2Me	C_2H_5	H	65
22.	H	CO_2Me	C_3H_7	H	66
23.	H	C_3H_7	CO_2Me	H	66
24.	H	CO_2Me	C_6H_{13}	H	65
25.	H	CO_2Me	$C_{10}H_{21}$	H	65
26.	CO_2Et	H	$CH=C(Cl)CF_3$	H	67,68
27.	CO_2Me	H	$CH=CC_5H_{11}$	H	52
28.	$CO_2{}^tBu$	H	CH=CHCl	H	54, 69,70
29.	CH=C(Me)Me	H	CO_2Me	H	69
30.	CH=C(Me)Et	H	CO_2Me	H	69
31.	$CH=C(Me)C_3H_7$	H	CO_2Me	H	69
32.	$CH=C(Me)C_4H_9$	H	CO_2Me	H	69
33.	$CH=C(Me)\text{-}CH=CH_2$	H	CO_2Me	H	69
34.	$CH=C(Me)\text{-}CH=CMe_2$	H	CO_2Me	H	69
35.	CH=C(Me)-CH=CHMe	H	CO_2Me	H	69
36.	$CH=CH_2$	H	CO_2Me	H	69
37.	CH=CHMe	H	CO_2Me	H	69
38.	$CH=CH\text{-}CH=CH_2$	H	CO_2Me	H	69
39.	CH=CH-C-CH=CHMe	H	CO_2Me	H	69

40.	CH=CH-CH=CMe_2	H	CO_2Me	H	69
41.	CH=C(Me)-CH=CH_2	H	CO_2Me	H	69
42.	CH=CH-CH=CH-CH_3	H	CO_2Me	H	69
43.	CH=C(Me)-C_2H_5	H	CO_2Me	H	69
44.	CO_2Me	H	CH=CPh_2	H	53
45.	CO_2Me	H	CH=CHPh	H	61

Two patents [70,71] also contained structural analogues, however, characteristic data were not given there.

Despite numerous analogues of chrysanthemic acids, 3-(2,2-dihalovinyl)-2,2-dimethylcyclopropanecarboxilic are the most important acids. Pyrethroids show the highest activity when *cis*-acid has 1*R*-configuration [30-34].

The interaction between aldehydes **14a,b,c** and dichloro- or dibromomethylene triphenylphosphoranes has been used for obtaining dihalovinyl-2,2-dimethylcyclopropanecarboxilic acids [26,33,34,69,71,72,75-80].

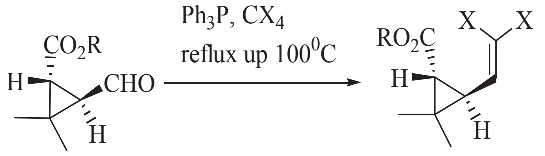


14a R=H
14b R=Me
14c R=^{t}Bu

15a R=H, X=Cl
15b R=Me, X=Cl
15c R=^{t}Bu, X=Cl
15d R=Me, X=Br
15e R=H, X=Br

Scheme 9

It is to be noted that phosphoranes can be obtained *in situ* from triphenylphosphine and CBr_4 or CCl_4 [72,76-79]. For example, the synthesis of *trans*-isomers **17a-e** from aldehydes **16a,b** has also been performed using Wittig reaction (scheme 10). In case of the synthesis of fluorinated analogues **17d**, sodium salt of chlorodifluoroneacetic acid [80] has been included in the reaction along with aldehyde **16a** and Ph_3P.



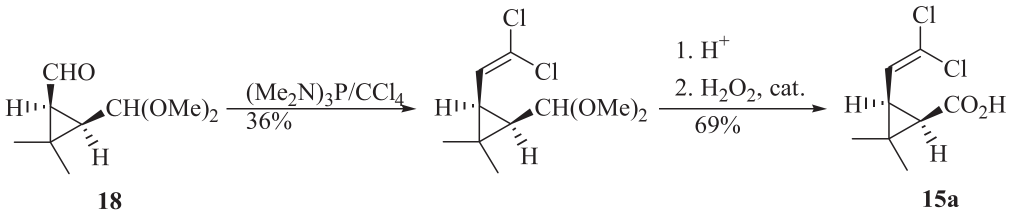
16a R=Me
16b R=^{t}Bu

17a R=^{t}Bu, X=Cl (61)%)
17b R=^{t}Bu, X=Br (60%)
17c R=^{t}Bu, X=I (54%)
17d R=Me, X=F (57%)
17e R=Et, X=Cl (80%)

Scheme 10

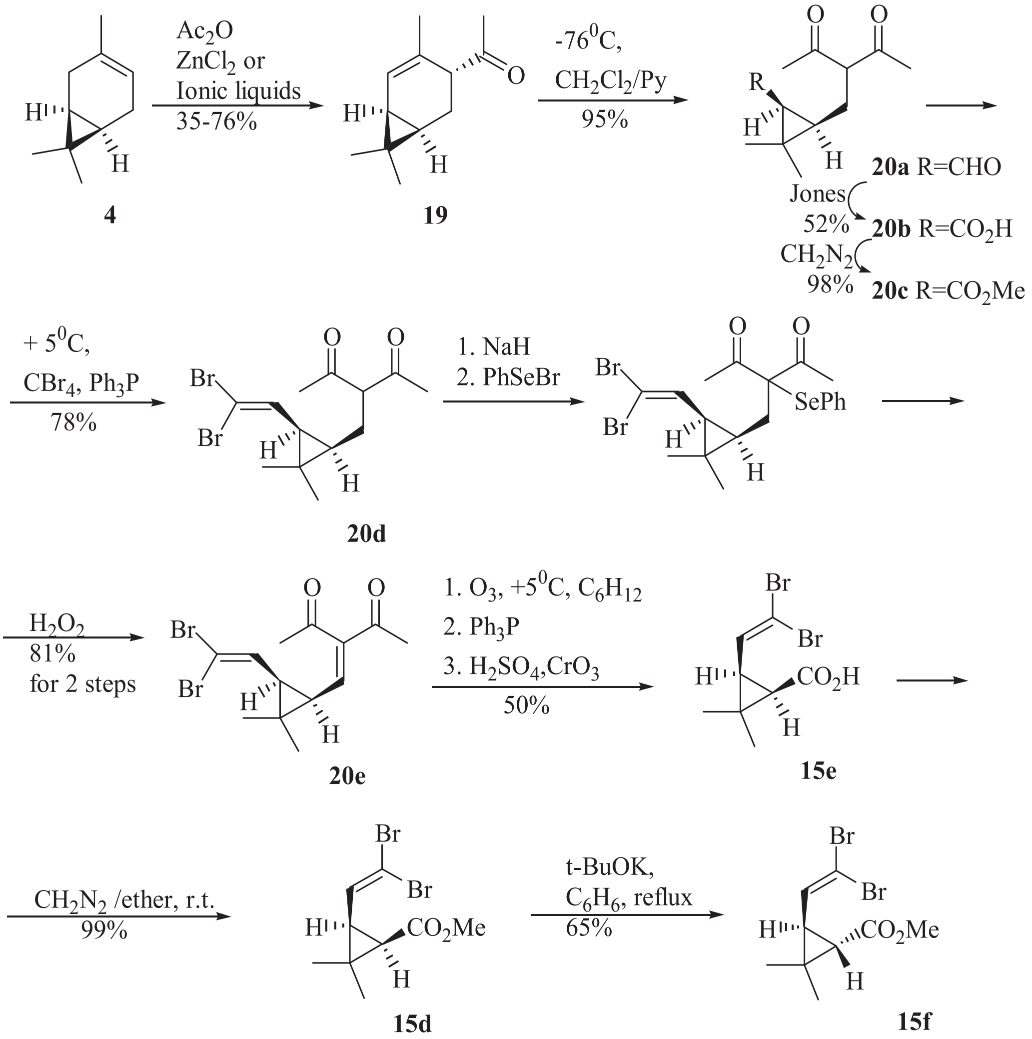
The afore-enumerated syntheses according to Wittig's reaction have several drawbacks: they offer a relatively low yield of products (about 60%), generate a partial epimerization of chiral centre at C_1 and partial cleavage of the cyclopropane ring. These drawbacks can be eliminated (unfortunately, only performing the reaction with small quantities of reagents), if *tris*-dimethylammoniumphosphine is used instead of Ph_3P and instead of CCl_4 – bromo(trichloro)methane [72,81]. The yield of *trans*-ester **17e** [81] and *cis*-esters **16b,c** has been about 80%.

It should be mentioned that the reaction of CCl_4 with *tris*-dimethylammoniumphosphine also proceeds. For example, ester **15b** [82,83] has been obtained by this way. The authors [84-87] have described another synthesis of *cis*-acid **15a** from aldehyde **18**.



Scheme 11

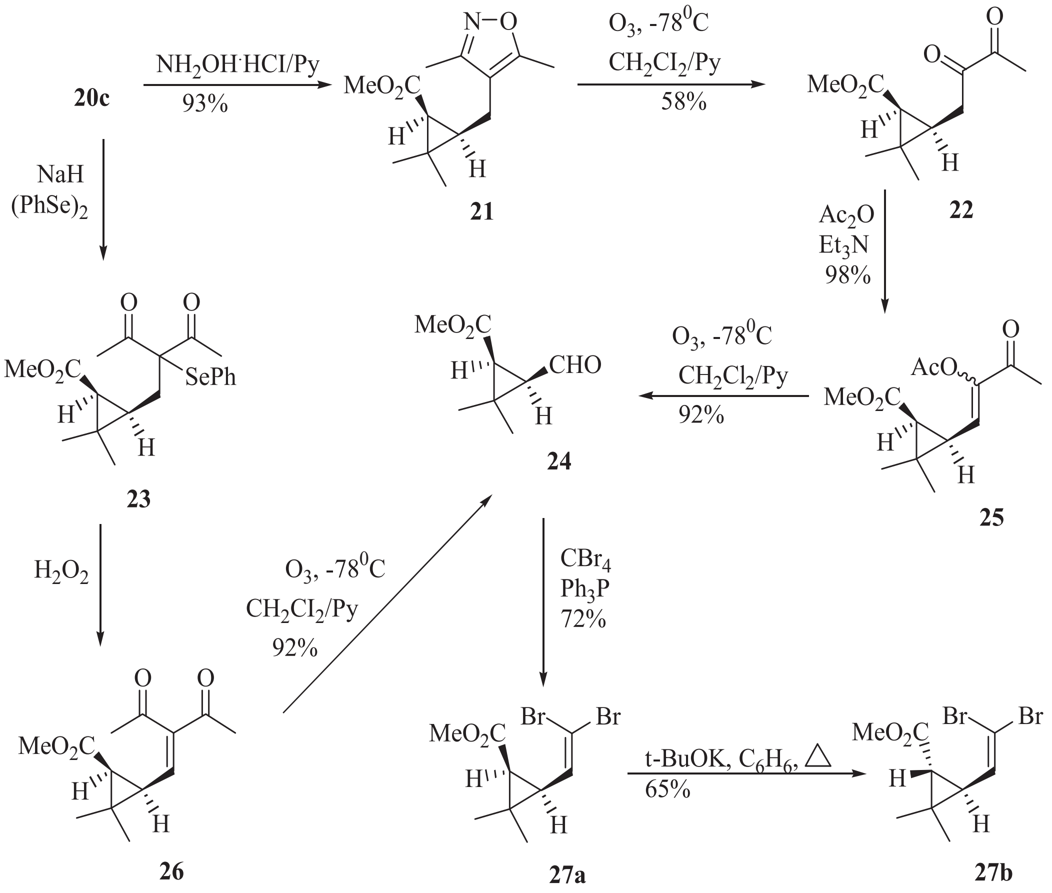
4α-Acetyl-2-carene **19** has been used for the synthesis of all four deltamethrinic acids (scheme 12) [76,77,87-89].



Scheme 12

Initial compound **19** has been converted into aldehyde **20a**, whose olefination produced dibromovinyl-2,2-dimethylcyclopropane **20d**. The preparation of diene **20e** includes a two-step dehydration. Ozonation of compound **20e** that followed oxidation has produced acid **15e**. Esterification of acid **15e** yielded (+)-1R-*cis*-ester **15d**. Product **15d** isomerizes rather smoothly into the thermodynamically more stable (+)-1S-*trans*-ester **15f**.

On the other hand, aldehyde **24**, is synthesized from β-diketone **20c** by two ways (scheme 13): **20c→21→22→25→24** and **20c→23→26→24** [90,91] has been used as intermediate in the synthesis of antipode **27a**.

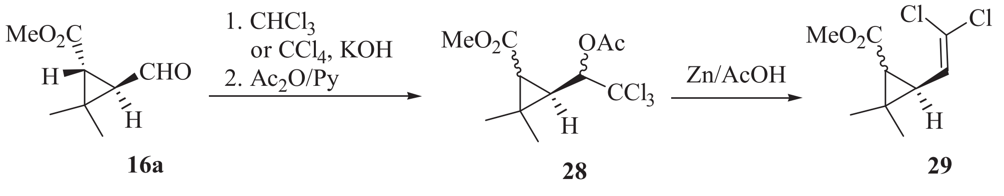


Scheme 13

cis-Product **27a** is formed at the interaction of aldehyde **24** with CBr_4 and Ph_3Ph. The enantiomer **27b** has been obtained from compound **27a** by boiling with potassium *tert*-butoxide in benzene.

Thus, enantiomeric 1*S*- and 1*R*-*trans*-2,2-dibromovinylcyclopropanes **15f** and **27b** have been obtained by epimerization of 1R- and 1S- *cis*-2,2-dibromvinylcyclopropanes **15d** and **27a**.

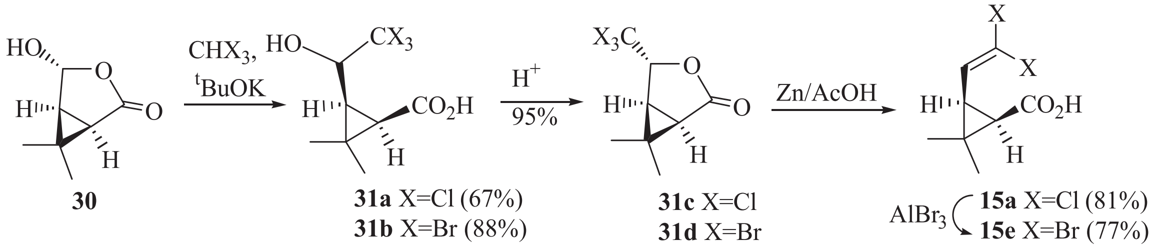
There has been worked out an alternative synthesis of dichlorovinyl-2,2-dimethylcyclopropanecarboxylic acid. For example, epimeric esters **29** have been obtained *via* the interaction of aldehyde **16a** with $CHCl_3$ or with CCl_4 in the presence of KOH in dimethoxyethane [92].



Scheme 14

The treatment of acetates **28** with zinc in acetic acid produces the epimers **29**. The total yield of the product reaction has been 29%.

Such a reaction has also been carried out with caronic aldehyde **30** (scheme 15) [93]. Caronic aldehyde **30** reacts with chloroform in DMF in the presence of potassium *tert*-butoxide generating the formation of hydroxyacid **31a** which is converted under the action of *p*-toluenesulfonic acid in lactone **31c**. At the interaction with zinc in acetic acid, lactone 31c turns into dichlorovinyl acid **15a**.

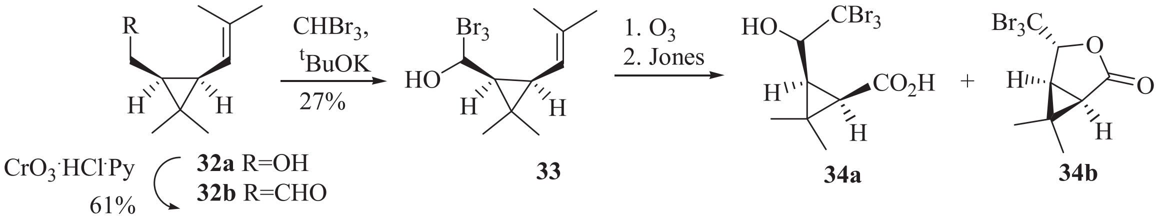


Scheme 15

Similarly, 1R-*cis*-acid **15e** has been obtained *via* substances **31b**, **31d** from acetal **30** [14,94,95].

The dibromovinyl acid **15e** can be obtained from dichlorovinyl acid **15a** when the latter is treated with AlBr$_3$ in 1,2-dibromomethane [88].

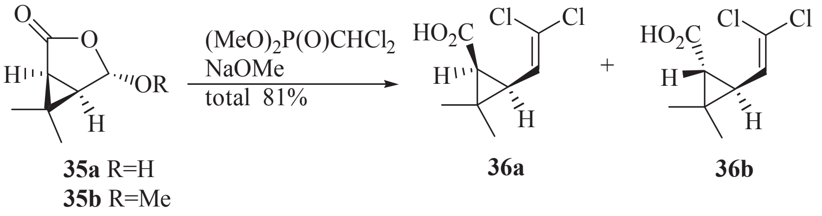
The Indian chemists [96] have described the synthesis of tribromoderivatives **34a**,**b** from alcohol **32a** by the scheme shown below.



Scheme 16

Alcohol **32a** is oxidized in aldehyde **32b**. Product **33** is ozonized and followed by transformation up to the mixture of acid **34a** (yield 15%) and lactone **34b** (yield 38%).

Permetrinic acids **36a,b** can be obtained from lactones **35a,b** also using the phosphate variant of Wittig's reaction [97].

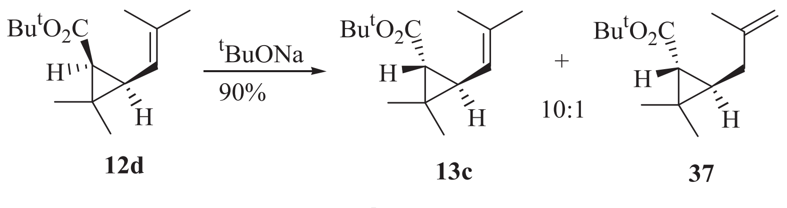


Scheme 17

It should be noted that patents [80,99] as well as the article [100] describe the isomerization of ester of 1*R*,3*R*-caronic aldehyde **16a** under the effect of NaOMe in methyl ester of 1*S*,3*R*-lactol **35b** which, when heated, easily hydrolyzes with aqueous 1,4-dioxane into semiacetal **35a**. Lactone **35b** has also been obtained from the same compound as a result of alkali saponification and the treatment of the product with acid in MeOH.

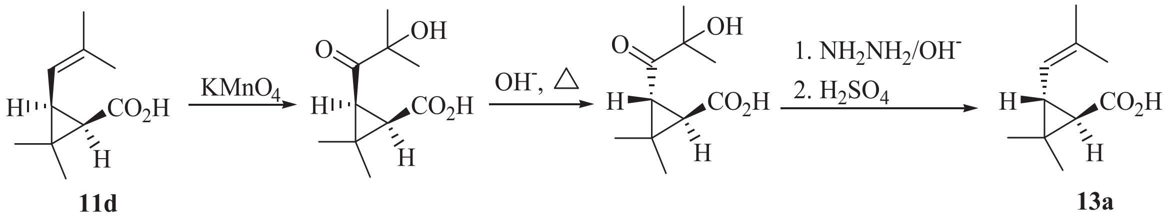
cis-Chrysanthemic acids, e.g. **12c,d** are isomerized into *trans*-isomer **13b,c** [28,34,52] under the action of alkali or when they are subjected to the action of Lewis's acids to chloro anhydride [95,101,102].

Dev S. has obtained ester (+)-*trans*-chrysanthemic acid **13c** in the mixture with its isomer **37** and the initial substance **12d** during the latter's isomerization with sodium *tert*-butoxide [47,51].



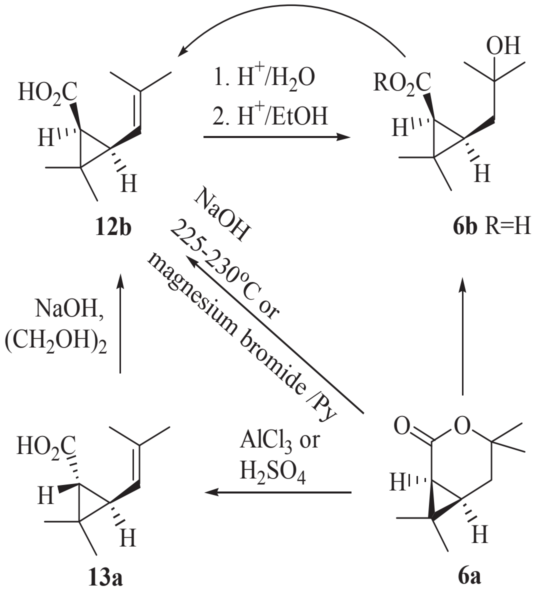
Scheme 18

cis-Acid **11d** can be isomerized into *trans*-isomer **13a** by scheme 19 [28,45].



Scheme 19

In this case epimerization occurs on the C_3 carbon atom. The transformation of *trans*-chrysanthemic acid **13a** into *cis*-isomer **12b** which can proceed by scheme 20 [43,48] is also possible.



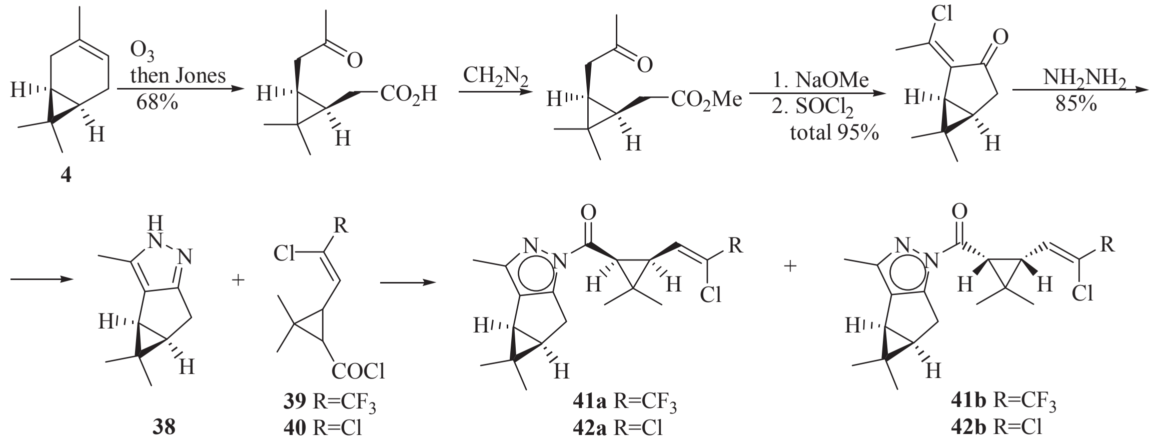
Scheme 20

Dihydrochrysanthemolactone **6a** can also be converted into *cis*-chrysanthemic acid **12b** by heating with magnesium bromide in pyridine [103]. If the above-mentioned conversion of lactone **6a** (heated with NaOH in diethylene glycol) into *trans*-acid **12b** is added, this scheme will be closed.

The set of modern crop protection agents is rather wide. Nevertheless, the investigations concerning the enlargement of their assortment and modernization of the methods of their obtaining are still under way. In the study of synthetic pyrethroids, a special emphasis is placed on the elaboration of new production technologies, including the isolation of diastereomers and enantiomers, which allows one to reduce the applied dozes and, thus, to decrease the chemical impact on the environment.

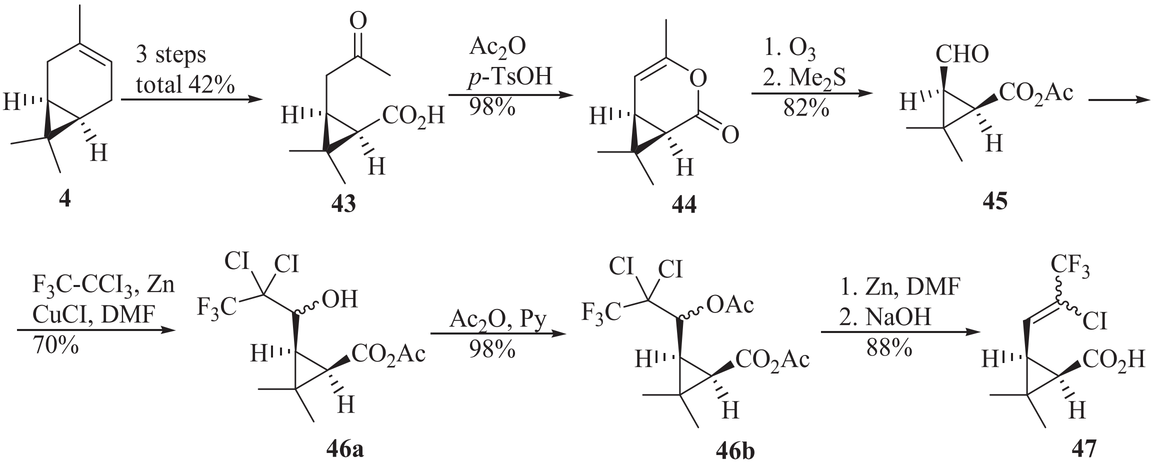
It is known that fluorine containing chrysanthemic acids analogues display a considerable insecticidal activity [67,68,104]. A variant for the separation of (±)-*cis*-thigalotrinic acid **39** and (±)-*cis*-permetrinic acid **40**, respectively, into antipodes *via* the acylation of chiral pyrazole **38** has been proposed [105-110].

In both cases 2*S*-derivatives **41a, 42a** have been completely separated from their antipodes by crystallization. Compounds **41b** as well as **42b** were obtained as oil.



Scheme 21

The mixture *E*- and *Z*- isomeric (-)-1*S*-*cis*-thigalotrinic acid **47** that constitutes an acid component of insecticide **3d** [111] can be obtained from (+)-3-carene **4** by scheme 22 [112,113].



Scheme 22

Acid **43** has been converted into anhydride **45** by the ozonation of lactone **44**. Aldehyde **45** interacts with F_3C-CCl_3 in the presence of zinc, producing a mixture of alcohols **46a** which, when treated with the mixture of acetic anhydride – pyridine, turns into a mixture of acetates **46b**. The reaction of the mixture of **46b** with zinc in DMF and the subsequent hydrolysis of the reaction product leads to the target mixture **47**.

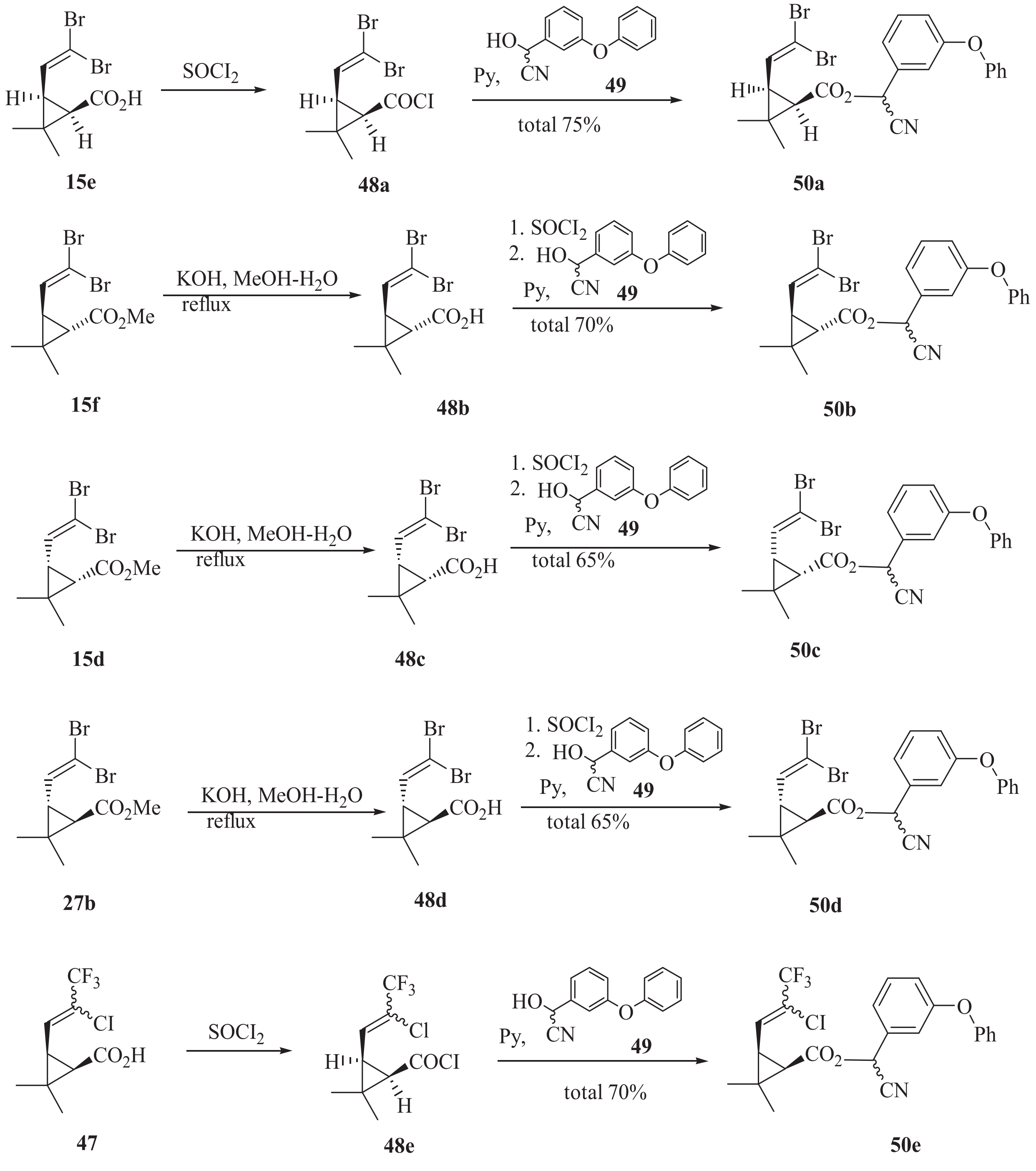
Esters **50a-e** have been synthesized for studying the relationship between stereochemistry and insecticide activity (scheme 23) [114].

Chloro anhydride **48a** has been directly treated with alcohol **49** in the presence of pyridine. Ester **50a** has been isolated with total yield 75%.

The reaction of anhydride **48e** with alcohol **49**, similar to the synthesis of ester **50b-d**, proceeds smoothly producing mixture **50e** with 16% yield from (+)-3-carene **4**.

The results of the laboratory tests on the insecticide impact upon the synthesized substances made against the room fly imago have shown that all synthetic products display a high insecticide activity. It has been established that the highest activity is displayed by product **50a** with 1*R*,3*S*- configuration of the cyclopropane ring carbon atoms. Further, the activity of stereoisomeric products decreases in the following order: 1*R*-*trans*- isomer **50d** > 1*S*-*trans*- isomer **50b** > 1*S*-*cis*- isomer **50c**. The insecticide activity of **49e** is lower than that of the standard – thigalotrin **3d**, however it takes the second place among the tested products.

The synthesis of 1*R*-*cis*-chrysanthemilamine **53** and azo-analogues **56a** of ciphenotrine **56b** was realized according to scheme 24 [115,116].

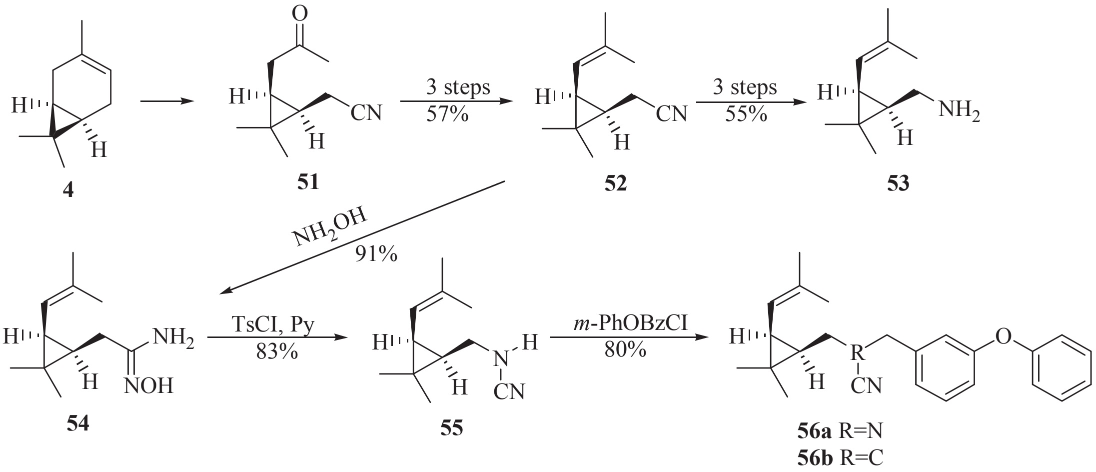


Scheme 23

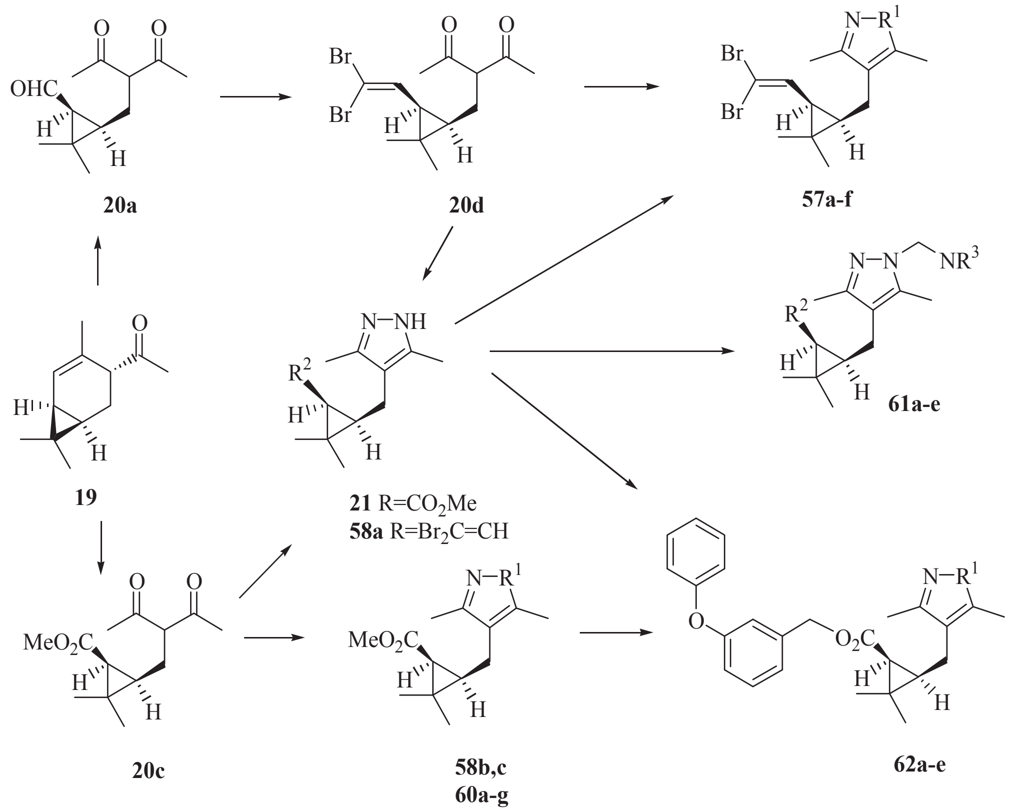
The reaction of nitrile **51** with MeMgI followed by dehydration yields nitrile **52**. The latter compound was converted into amine **53** with total yield 31%. Compound **52** interacts with NH_2OH forming amide oxime **54** which, through compound **55**, has been converted into azo-analogue **56a**.

(+)-4α-Acetyl-2-carene **19** is a convenient initial compound for the design of molecules, including fragments of various structural types with useful properties [117-125]. The assortment of the thus obtained products can be substituted and enlarged utilizing both the 1,3-disubstituted cyclopropanes **20a**, **20c**, and their transformation products **20d** and **21**.

The reaction of β-diketones **20c** with $NH_2OH{\cdot}HCl$ in aqueous solution Na_2CO_3 results in isoxazole **21** with 85% yield.



Scheme *24*



R^1=NEt (**58b**), (**57a**), (**62a**); R^1=O (**21**), (**57e**), (**62b**);
R^1=NPh (**57b**), (**60a**),(**62c**); R^1=CH_2Ph (**57f**);
R^1=2-MeC_6H_4(**57c**), (**60c**); R^1= 4-$MeC_6H_4SO_2$(**57d**), (**60e**);
R^1=4-$CO_2HC_6H_4$(**60d**); R^1= 4-$ClC_6H_4CH_2$(**60f**);
R^1=2-naphtyl (**60g**); R^1= 3-$PhOC_6H_4CH_2$(**60b**), (**62d**);
R^1= COPh (**60f**),(**62e**);
R^2=CO_2Me (**61a**), (**61b**), (**61c**);
R^2=Br_2C=CH (**57e**), (**61d**), (**61e**);
R^3=(-$(C_3H_7)_2$(**61a**); R_3=(-CH$(Me)_2)_2$(**61b**); R^3= morpholinyl (**61c**);
R^3=Et_2(**61d**); R^3=imidazolyl (**61e**).

Scheme 25

At the interaction of compound **20c** with NH_2NH_2 or ethyl hydrazine in boiling ethanol pyrazoles **58a,b** are formed with 80 and 71% yield, respectively. Condensation reaction proceeds more effectively in the presence of neutral Al_2O_3 without solvent increasing the yield up to 97% and 81%, respectively. The speed of the reaction almost doubles and the reaction finishes in 5 hours. However, if the condensation reaction in the presence of Al_2O_3 is performed under ultrasonic irradiation, then the reaction time decreases to 30 minutes, the reaction products yields remaining the same as shown above.

Chiral pyrazoles **60a-g** have been obtained in a similar way. It is worth noting that pyrazoles **58b** and **60b** have been also synthesized by alkylation of pyrazole **58a** with EtBr and 1-bromomethyl-3-phenoxybenzene, respectively.

When interacting with 1-benzenecarbohydrazine in the conditions described above for the synthesis of pyrazoles **58b,c**, diketone **20c** does not yield the heterocyclic derivative **60f**. However, when the formed adduct is heated in alcohol alkali followed by the treatment with 1-bromomethyl-3-phenoxybenzene, compound **60d** is obtained with 66% yield.

Aminoalkylation of **58a** with formaldehyde and dipropyl- and di-*iso*-propyl amines, as well as with morpholine, results in pyrazoles **61a-e**.

Finally, a series of heterocyclic analogues **62a-e** of permetrin **3a** has been synthesized. Esters **60a-c**, **57b** and **60b** have been saponified followed by the treatment with 1-bromomethyl-3-phenoxybenzene. It should be noted that in the case of the sodium salt of compound **58a**, the reaction of NH-group hydrogen substitution with the formation of product **62d** (yield 40%) proceeded simultaneously.

The investigation of anti-inflammatory effect and anti-microbic activity of compounds **58a-c**, **57f**, **60b,e** has shown that these compounds have a pronounced anti-inflammatory effect at reduced anti-microbic effect. The analysis of these compounds group testing results regarding the fungicide effect has shown that compounds **21b**, **60g** and **61e** display a considerable fungicide effect [126-128].

3. Conclusion

From the given data, it follows that chemists pay a rather great attention to the questions of obtaining, the intermediates suitable for synthesizing an optically active chrysanthemic acid and its analogues on the basis of natural careens. The primary products of the afore-enumerated intermediate transformations were the substances containing 1,3-disubstituted-2,2-dimethylcyclopropane fragment. These products were later utilized in selective synthesis of chrysanthemic acid and its analogues. The availability in the 3-carene **4** of the *gem*-dimethyl fragment as well as the reactive C=C-double bond has called forth the search for transition variants from cheap compound **4** to chrysanthemic acid and its analogues. The chemical transformations of enantiomerically pure 3-carene whose chemistry has been discussed in the review can serve as an alternative variant for synthesizing such kinds of substances.

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THIOCYANATE ION-SELECTIVE PVC MEMBRANE ELECTRODE

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Abstract A potentiometric selective sensor based on trinuclear chromium(III) complex as a novel ionophore for the thiocyanate-selective electrode is reported. The sensor displays a near Nernstian slope of 57 ± 2 mV per decade, over a wide pH range 3 - 11. The working concentration range of the electrode is $1 \cdot 10^{-5} – 1 \cdot 10^{-1}$ mol/L with a detection limit of $5 \cdot 10^{-6}$ mol/L. The sensor has a response time of 20 s and can be used for at least 6 months without any considerable fluctuation of the potential. The selectivity coefficients determined at using the fixed interference method indicate a good discriminating ability towards other anions. The prepared sensor was applied as an indicator electrode in the titration of thiocyanate with Ag^+.

Keywords: thiocyanate, potentiometric sensor, titration.

1. Introduction

The thiocyanate ion is usually present in low concentrations in human serum, saliva, and urine as a result of the digestion of some vegetables of the genus *Brassica* containing glucosinolates (cabbage, turnip, kale) or by intake of thiocyanate-containing foods such as milk and cheese [1]. Higher concentration of this ion, which is a metabolic product of cyanide, arises from tobacco smoke. In this respect, the concentration level of thiocyanate in human plasma is considered to be a good probe to distinguish between smokers and non-smokers. It has been found that there is a correlation among the blood cyanide, the plasma thiocyanate, and the salivary thiocyanate [1]. Saliva of non-smokers contains thiocyanate concentrations between 0,5 – 2 mM while in smokers, concentrations higher than 6 mM can be found. Chronically elevated levels of thiocyanate in body fluids are known to be toxic and its relation to local goiter, vertigo, or unconsciousness has been pointed out. Therefore, an accurate, simple, and rapid method for the determination of thiocyanate is significant in medicine and in the life sciences. Various methods, such as spectrophotometry, Raman spectroscopy, gas chromatography, electrochemistry and potentiometry based on ion-selective electrodes (ISE) [2-11] have been reported for the determination of thiocyanate concentration in various samples. Among these methods, carrier-based ISE have emerged as one of the most promising tools for this purpose because of their unique advantages such as simplicity, speed of analysis, fast response time, low cost, wide linear range, reasonable selectivity etc. These advantages of ISE have inevitably led to the development of potentiometric sensors for many inorganic and organic species and the list of available electrodes has grown substantially over the past years.

In this work, we describe the construction and characterization of a new thiocyanate selective electrode based on a trinuclear chromium (III) complex incorporated in a poly (vinyl chloride) (PVC) membrane.

2. Experimental

2.1. *Reagents*

All reagents used were of analytical grade. The solutions were prepared using twice distilled water. The pH adjustments were made with dilute sulphuric acid and sodium hydroxide solutions as required. A stock solution of thiocyanate was prepared by dissolving an appropriate amount of potassium thiocyanate in 100 ml of water. Working solutions were prepared by successive dilutions. H_2SO_4 and NaOH solutions having different concentrations were used to study the pH dependence of thiocyanate-selective electrode.

2.2. *Membrane preparation and sensor construction*

A mixture of PVC and a plasticizer (dictylphtalate (DOP), 2-nitrophenyl octyl ether (NE)) to give a total mass of 60 mg was dissolved in approximately 5 ml of tetrahydrofuran and 1ml of nitrobenzene. To this mixture was added the electroactive material - $[Cr_3O(C_5H_9O_2)_6(H_2O)_3]SCN$ and 4,4′-bipyridine in stoechiometric ration 2:3 (synthesis in situ [12-14]). The solution was poured onto a glass dish (ca. 5cm diameter) and allowed to dry at room temperature. A membrane (ca. 16 mm diameter) was cut and glued to the polished end of PVC tube by using a PVC (ca. 5%) – tetrahydrofuran solution. The Ag/AgCl electrode and 10^{-1}M of SCN^- + $5 \cdot 10^{-3}$M of KCl solution were used as reference electrode and the internal filing solution, respectively.

The electrode was conditioned for 12 h in a 10^{-1}M potassium thiocyanate solution, and stored in the same solution when is not in use. A silver/silver chloride electrode was used as an internal reference electrode.

2.3. Potential measurements

All measurement was made with a cell of the type:

Ag/AgCl, KCl ($5 \cdot 10^{-3}$ M) | internal filing solution (10^{-1}M SCN^-) | PVC membrane || tested solution || KCl satd. AgCl/Ag. The performance of each electrode was investigated by measuring its potential in potassium thiocyanate solutions in the concentration range $1\cdot10^{-1}$ to $1\cdot10^{-7}$M. Potential were measured using a 3310 JENWAY pH/mV – meter. The performance of the electrode was investigated by measuring its potential in potasium thiocyanate solutions prepared in the concentration range (10^{-1} – 10^{-7} mol/L) by gradual dilution of 0,1 mol/L KSCN stock standart solution. The solutions were stirred and potential readings recorded when they became stable. The data were plotted as observed potential versus the minus logarithm of the SCN^- concentration.

2.4. Sensor selectivity

Potentiometric selectivity coefficients ($K_{SCN,X}$) were evaluated using the mixed solution method. The potential was measured for solutions of constant activity of the interfering ion (X) and varying activity of the primary ion (SCN^-). The obtained electromotive force values were plotted vs. the logarithm of the primary ion activity. The intersection of the extrapolated linear portions of this plot indicates the a_{SCN} value that is to be used to calculate $K_{SCN,X}$ from the following equation: $K\text{SCN,X} = a_{SCN} / (a_X)^{ZSCN/ZX}$ where ZSCN and ZX are the charges on SCN^- and the interfering anion, respectively.

2.5. Potentiometric titration of thiocyanate

A thiocyanate membrane sensor based on the ionophore - trinuclear chromium(III) complex – as an indicator sensor and the Ag/AgCl double junction reference electrode were used for monitoring the titration of thiocyanate solution with $AgNO_3$. The sensor and reference electrode were immersed in an unknown SCN^- test solution in 20 ml beaker. The potential reading was recorded after each addition. The equivalence point was calculated from the sharp inflection at the equivalence point or from derivative curves.

3. Result and discussion

Recently trinuclear chromium(III) pivalates were investigated as ionophores in the membrane of the anionic sensors. The lipophilic complex cation can be combined with some inorganic and organic anions. We described electrodes selective to the presence of the perchlorate, salicylate and nitrate anions [12-14].

Therefore, using this type of chromium(III) complexes, we were prompted to study the response of a membrane to the presence of thiocyanate anions. The potentiometric response of ISE containing the ionophore $[Cr_3O(C_5H_9O_2)_6(C_{10}H_8N_2)_{1,5}]SCN$ synthesized *in situ*, was linear with a Nernstian slope of 57 ± 2 mV/-log a(SCN^-) and the detection limit, calculated as recommended by the IUPAC, was $5\cdot10^{-6}$ mol/L (fig. 1).

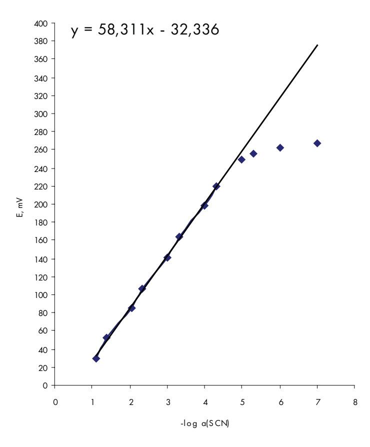

Fig. 1. Calibration graph for the electrode

The optimum equilibration time for the membrane electrode in the presense of 0,1 mol/L KSCN was 24 h, after which it generated stable potential in contact with thiocyanate solutions. The evolution of the thiocyanate selective electrode slopes in time is presented in fig.2.

There was a little slope decrease in time, but it still remains, after 6 months of intensive use, in the analitycal useful range of 56-59 mV/p(SCN). The effect of pH of the test solution on the membrane electrode response was tested in the pH range 2,0-12,0 at two SCN^- concentrations (10^{-2} and 10^{-3} mol/L). The results presented in fig. 3 show that the potentials remain constant within 4,0-11,0 pH range.

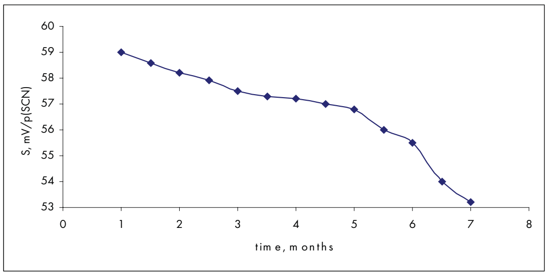

Fig. 2. Evolution of slope in time

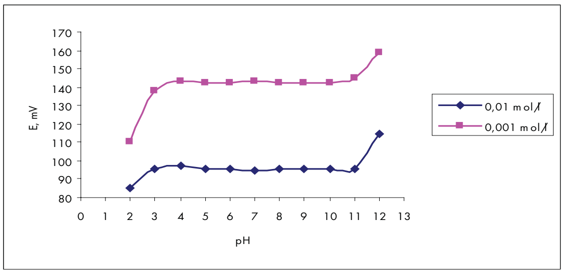

Fig. 3. The influence of the pH values on the electrode potential response

The variation of the potential at pH < 4 could be related to protonation of ionophore in the membrane phase which results in a loss of its ability to interact with SCN^- ions. At high pH value, the OH^- and SCN^- anions are in a strong competition, the hydroxyl concentration grows and the potentiometric answer of the electrode can deviate from linearity. Similar results have been reported for other sensors [6].

One of the most important characteristics of any ion-selective electrode is the relative response for the primary ion over other ions that may be present in solution, which is expressed in terms of potentiometric selectivity coefficients. Potentiometric selectivity coefficients describing the preference of the membrane for an interfering ion X^- relative to SCN^- were determined by the mixed solutions method. Table 1 lists the potentiometric selectivity coefficients data of the sensor for several anions relative to SCN^-.

Table 1

Electrode selectivity coefficients

X	I^-	ClO_4^-	NO_3^-	BF_4^-	CO_3^{2-}	HPO_4^{2-}	Br^-	F^-	Cl^-	CH_3COO^-	SO_4^{2-}
-logK SCN/X	1,58	2,04	2,16	2,53	3,23	3,47	3,80	4,07	4,10	4,18	4,55

It is clear that the proposed electrode is selective to SCN^-, and the selectivity sequence is: $SCN^- > I^- > ClO_4^- > NO_3^- > BF_4^- > CO_3^{2-} > HPO_4^{2-} > Br^- > F^- > Cl^- > CH_3COO^- > SO_4^{2-}$ - the main interfering anions were found to be iodide, perchlorate and nitrate.

The influense of the plasticizer nature on the parameters of the SCN^--senzor were studied. Table 2 reveals that the parameters, like the slope, detection limit and pH range, are not influenced by the nature of this plasticizer.

Table 2

Influence of the plasticizer nature on the parameters of the sensor

Plastisizer	Slope, mV/pa	Detection limit, M	pH range
NE	57-58	$(4\text{-}7)\cdot 10^{-6}$	3-11
DOP	57-59	$(4\text{-}7)10^{-6}$	3-11

The performances of a selection of different electrodes published in literature are shown in the Table 2. As it can be observed the parameters of the proposed electrode are comparable with of available thyocyanate-selective ones. Nevertheless the cost of electroactive material is chipper and it is more available that the complexes used in [2-11].

Table 3

Parameters of a selection of thiocyanate-selective electrodes

Ionophore	Concentration range, mol/L	Slope, mV/decade	Detection limit, mol/L	pH range	Lifetime	Reference
5,10,15,20-tetrakis-(4-methoxyphenyl)-porphyrin-Co(II)	$1\cdot 10^{-1} – 1\cdot 10^{-5}$	65,8	$6,0\cdot 10^{-6}$	3,0 – 9,5	6 weeks	[2]
(octabromotetraphenylporphyrinato)manganese(III) chloride	$1 – 4,8\cdot 10^{-7}$	58,3	$3,2\cdot 10^{-7}$		3 months	[3]
N, N′-ethylene-bis(4-methylsalicylidineiminato) nickel(II)	$1\cdot 10^{-1} – 1\cdot 10^{-6}$	58,9	$3,1\cdot 10^{-7}$	3,5 – 8,5	3 months	[4]

crown ether-cetyltrimethyl ammonium	$1\cdot10^{-1} – 1\cdot10^{-6}$	57,6	$3,0\cdot10^{-7}$	3,8 – 9,2	6 weeks	[5]
5,10,15,20-tetrakis(2,4,6-trimethylphenyl)-porphyrinatomanganese(III) chloride	$1\cdot10^{-1} – 2\cdot10^{-7}$	58,7	$1,3\cdot10^{-6}$	2,0–10,0	3 months	[6]
[Cobalt (Salpen) (PBu_3)] $ClO_4 \cdot H_2O$	$1\cdot10^{-1} – 1\cdot10^{-6}$	59,05	$8,0\cdot10^{-7}$	2,8-9,8	14 weeks	[7]
N,N′-bis-(benzaldehyde)-glycine metallic complexes	$1\cdot10^{-1} – 9\cdot10^{-7}$	57,6	$7,0\cdot10^{-7}$	4,0-7,0		[8]
macrotricyclic binuclear Cu(II)–Schiff base complex	$1\cdot10^{-1} – 1\cdot10^{-7}$	58,9	$3,1\cdot10^{-8}$	3,0-8,0	2 months	[9]
rhodium(II) phthalocyanine	$1\cdot10^{-1} – 1\cdot10^{-6}$	56,3	$7,9\cdot10^{-7}$	6,0	2 months	[10]
copper(II) bis(benzoylacetone) propylenediimine complex	$1\cdot10^{-1} – 8\cdot10^{-7}$	57,4	$7,4\cdot10^{-7}$	1,7-11,5		[11]

4. Analytical application

The proposed sensor was successfully used as an indicator electrode in the potentiometric titration of SCN^- solution with Ag^+. Results of the titration are shown, the amount of SCN^- ion in solution can be accurately determined with the electrode. A very good inflection point, showing perfect stoichiometry, was observed in the titration plot (fig. 4).

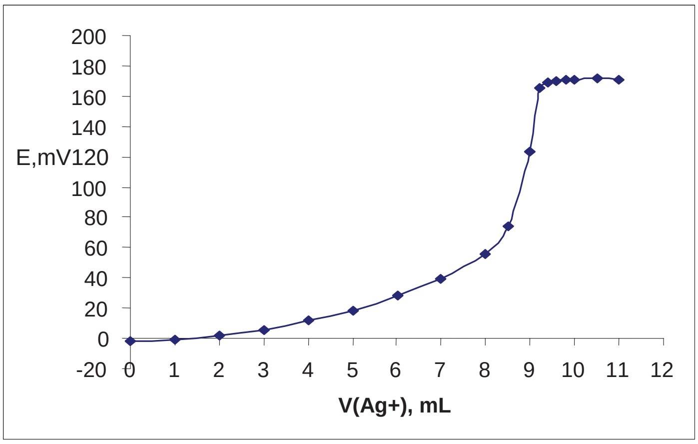

Fig. 4. Potentiometric titration curve of 10,0 ml 10^{-2} mol/l SCN^- with $1,08\cdot10^{-2}$ mol/l $AgNO_3$, using the SCN⁻–selective electrode based on trinuclear chromium(III) pivalate

This electrode was additionally applied to the direct determination of the SCN^- ions in different sample solutions. The resulting data of Table 4 indicate that the accuracy of the SCN^- ion detection in different sample solutions is almost quantitative.

Table 4

The SCN^- ions recovery from binary mixtures by the proposed electrode

SCN^-, mol/L	Added anion, mol/L	Recovery, mol/L
10^{-2}	SO_4^{2-}, 10^{-2}	$(1,03 \pm 0,03)\cdot10^{-2}$
10^{-2}	CH_3COO^-, 10^{-3}	$(0,99 \pm 0,04)\cdot10^{-2}$
10^{-2}	Cl^-, 10^{-3}	$(1,03 \pm 0,04)\cdot10^{-2}$
10^{-2}	HPO_4^{2-}, 10^{-4}	$(0,99 \pm 0,05)\cdot10^{-2}$
10^{-2}	HCO_3^{2-}, 10^{-4}	$(1,02 \pm 0,01)\cdot10^{-2}$
10^{-2}	NO_3^-, 10^{-4}	$(0,99 \pm 0,05)\cdot10^{-2}$

Results are based on three measurements

5. Conclusion

A novel electrode has been developed based on trinuclear chromium(III) pivalate as ionophore in dictylphtalate or 2-nitrophenyl octyl ether plasticized PVC membranes. The electrode exhibited good potentiometric response characteristics to thiocyanate and was applied as an indicator electrode in the potentiometric titration of the SCN^- solution with $AgNO_3$.

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THE EVOLUTION OF BIOCHEMICAL OXIDATION OF AMMONIA IONS IN SMALL RIVERS WATER

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Abstract: Nitrification is the oxidation of ammonia to nitrate, via nitrite and it occupies a central position within the global nitrogen cycle. Nitrifying bacteria are the organisms capable of converting the most reduced form of nitrogen, ammonia, to the most oxidised form, nitrate, but their activity is influenced by pollution level. Starting with the assumption that pollution of small internal water courses in the Republic of Moldova remained severe (phenols, detergents and copper regularly exceed the MACs) the work presented in the paper discusses the evolution of ammonia ions nitrification in the water of river Prut tributaries and its correlation with the content of pollutants in water: surface-active substances, Cu, BOD_5, COD and other compounds.

Keywords: biochemical oxidation, ammonia ions, nitrification, small rivers.

Introduction

Ammonia is produced by human activity. It occurs naturally from the breakdown of nitrogenous organic compounds in water, soil and the breakdown of biota, being an important source of nitrogen which is needed by plants and animals.

The presence of ammonium ions in natural waters is associated with pollution caused by livestock, intensive agriculture, and liberation of domestic sewage in courses of superficial waters. A statistically significant increase in ammonium concentration was detected in pond water exposed to artificial radiation resembling sunlight in the UV range of the highest absorbance after 5 h of irradiation. In sea and river water a corresponding increase (< 0.5 μM) was recorded after an exposure time of 25 hours [1]. Trace amounts of ammonia (NH_3) in unpolluted water are present from the reduction of atmospheric nitrogen by aquatic microorganisms. Ammonia is at equilibrium with ammonium ion (NH_4^+) and the equilibrium reaction between ammonia and ammonium ion is pH dependent.

$$NH_3(aq) + H^+(aq) \rightleftharpoons NH_4 + (aq) + OH^-(aq)$$

So Thus, total ammonia is the sum of the two forms. Natural unpolluted waters may contain 0 to 3 mg/l. Higher concentrations correspond to pollution and can be toxic to aquatic organisms. Sources of ammonia may be industrial discharges, particularly from the pulp and paper industry, fertilizer runoff, sewage releases into natural waters, and industrial releases.

Ammonia and ammonium salts are also found in small quantities in rainwater (ammonium chloride, sulfate and bicarbonate).

The plants (usually through their roots) consume ammonia taken up directly. Most of the ammonia is converted as a result of biochemical oxidation from a reduced to a more oxidized state, nitrate, by the Nitrifying bacteria. This is accomplished in two steps:

- Bacteria of the genus **Nitrosomonas** oxidize NH_4^+/NH_3 to **nitrites** (NO_2^-).

$$NH_4^+ + \frac{3}{2}O_2 \leftrightarrow NO_2^- + 2H^+ + H_2O$$

- Bacteria of the genus **Nitrobacter** oxidize nitrites to **nitrates** (NO_3^-).

$$NO_2^- + \frac{1}{2}O_2 \leftrightarrow NO_3^-$$

The oxidation of ammonia to nitrate by microorganisms is a key process in the nitrogen cycle, resulting in nitrogen loss from ecosystems, eutrophication of surface and ground waters. In aquatic ecosystems nitrifies compete with primary producers for ammonia and in all ecosystems nitrification results in the generation of reactive gases, in particular nitrous oxide, involved in the destruction of stratospheric ozone and global warming.

Effluents containing nitrogenous compounds must be treated in order to reduce the release of ammonium-N into natural waters, because this causes oxygen demand, is toxic to aquatic life, leads to eutrophication, modifying the biota and creating an ecological imbalance.

The First Step of the process ($NH_4^+ \rightarrow NO_2^-$, 66 kcal of energy are liberated per gram atom of ammonia oxidized) involved microorganisms called the ammonia oxidizers. The biochemical nitrite Oxidation ($NO_2^- + 1/2\ O_2 \rightarrow NO_3^-$, 18 kcal of energy is liberated per gram atom of nitrite oxidized) is the second step. Nitrate is the final product after completion of the biochemical oxidation. Nitrifying bacteria work either at full capacity or drift into a resting phase. Some substances will influence bacteria activity, such as phenol, surface-active compounds, heavy metals and others [2-8].

The nitrification process can have a direct impact on water quality. The end result of nitrification, nitrate (NO_3^-), is a form of nitrogen that is highly mobile and easily moves with water. When rainfall is heavy, nitrates can move downward in the soil and then in underground waters.

Start with the assumption that pollution of small internal water courses in the Republic of Moldova remained severe, recorded concentrations of ammonium, nitrite and other pollutants (BOD_5, oil products, phenols, and detergents) exceeded the maximum admissible concentration (MAC), the evolution of biochemical oxidation of ammonia ions in small rivers water was evaluated in this work.

To surface waters loads of pollution contributes the runoff from residential and industrial areas, domestic wastewater discharges from non-sewered population. The animal waste is not anymore concentrated in a limited number of sites; it is spread everywhere, on both private and public lands, threatening the drinking water sources and the surface waters. This major pollution source became more diffuse and less manageable. Another source of surface waters pollution is the non-observance of protection strips along the water courses. Within the settlements, these are transformed into domestic waste dumps.

Materials and Methods

It was used aA combination of laboratory and field studies was used to elucidate the factors controlling the growth, activity and survival of nitrifies in natural waters.

Nitrification capacity of small rivers water was investigated by means of laboratory modelling with employment of natural waters [9]. Analytical settlement of the problem was realized by controlling NH_4^+, NO_2^-, NO_3^-, O_2 and pH.

In small rivers water, were determined the concentrations of macro-, nitrogen and organic compounds. Samples (3 000 ml) of different aquatic environments were enriched with $(NH_4)_2SO_4$ to concentrations of 2**.0 – 6,0** mg/dm^3 and incubated on natural conditions at 20-22^{0}C. The content of NH_4^+, NO_2^- and NO_3^-, and the pH were determined after the liquid was filtrated. This replacement procedure was repeated every 2-5 days.

Ammonia ions were determined by using the Nessler reactive [10]. Nitrite was estimated by the procedure with the Griess reagent, and the reduction method with the Zn-$MnSO_4$ mixture [11] was used to measure nitrate [12] and other compounds [13-16].

Results and discursions

The nitrification process can have a direct impact on water quality. The end result of nitrification, nitrate (NO_3^-), is a form of nitrogen that is highly mobile and easily moves with water. When rainfall is heavy, nitrates can move downward in the soil.

The river network in the Republic of Moldova is the final receptor of most runoff and wastewater, either household or industrial, as in any other country; the treatment level of wastewaters is insufficient and about 1/3 of pollutants, including ammonia compounds, pesticides, detergents, some heavy metals still persist after treatment, being discharged into natural waters. The concentrations of ammonium, nitrites, phenols, detergents and copper regularly exceed the MACs. For example, ammonium concentrations were found of 17,0 mg/dm^3 as N (43,6 MAC) up to 46,5 mg/dm^3 as N (119 MAC) in the Bic river, downstream Chisinau (wastewater treatment station, WWTS), maintaining their high values up to the confluence with the Nistru river [17].

Out by experimental obtained results it was established that $NH_4^+ \rightarrow NO_2^-$ process in modeling of small rivers Ciuhur, Larga, Draghiste, Lopatnic, Calanjir, Racovat, Vilia, Bogda, Camenca water it takes place in the same way as river Nistru water and lasts 6-10 days, whereas in river Racovat water, only 40-77% of ammonium ions are oxidizes. Even after 15-20 days, 7-20% of NH_4^+ remained in solutions. $NH_4^+ \rightarrow NO_2^-$ transformation in model with Vilia, Lopatnic (Lopatnic), Racovat (Grajdiesti) water take place in 15 days. In rivers Draghiste (Burlanesti), Bogda, Garla Mica, Bac, Racovat (Hadarauti), Raut (downstream Balti, Floresti, Orhei) and Cainari, the process lasts about 20-21 days, but in the case of r. Racovat (Clocusna), Lopatnic (Gremencauti), Draghiste (Bulboaca), Larga samples - 25 and more days (fig. 1, a-f). Process takes place for 21-25 days in the waters of r. Cainar (Gura Cainari), Ichel (Ratus), Isnovat (Ialoveni) and Camenca (Gura Camenca).

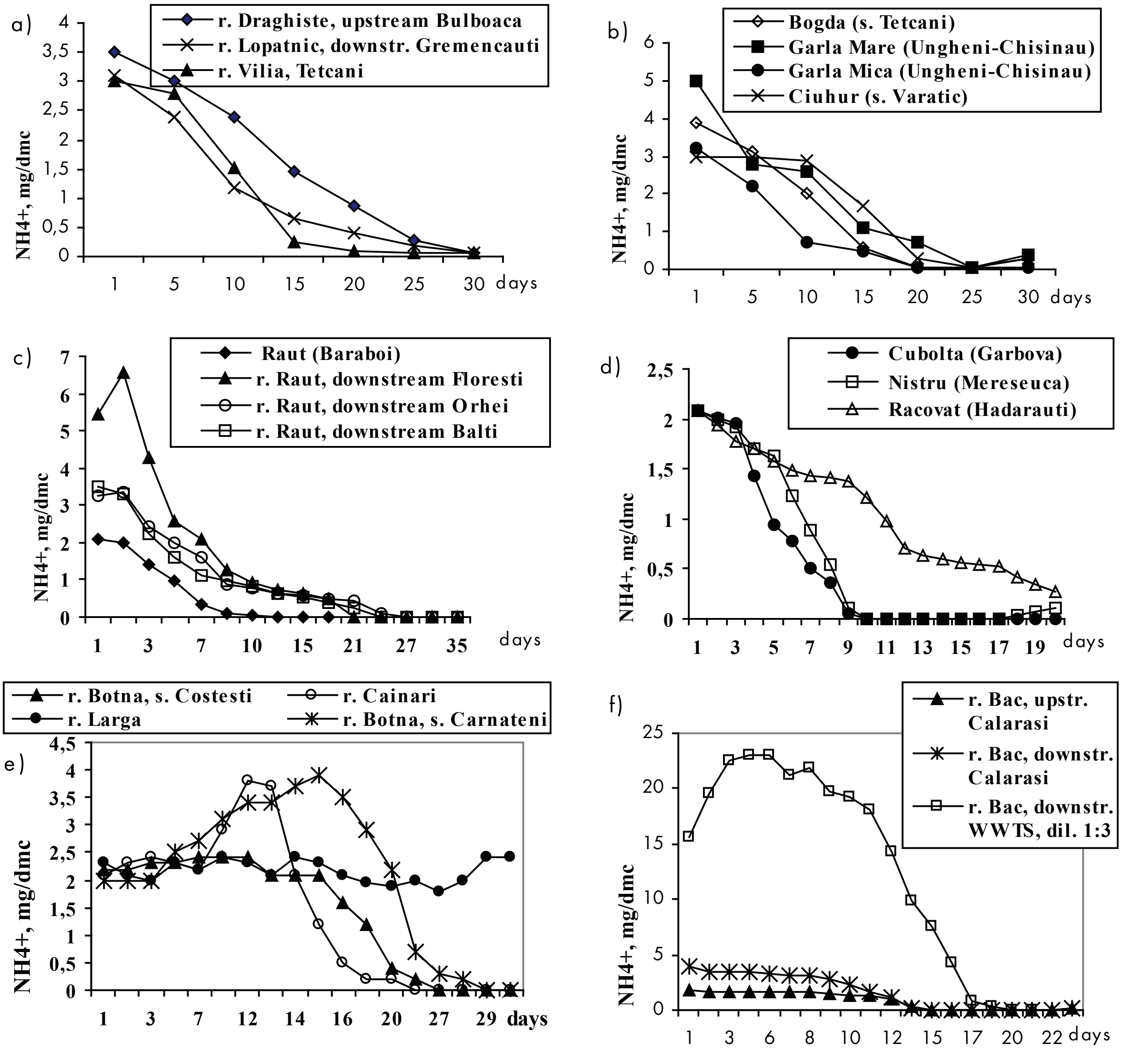
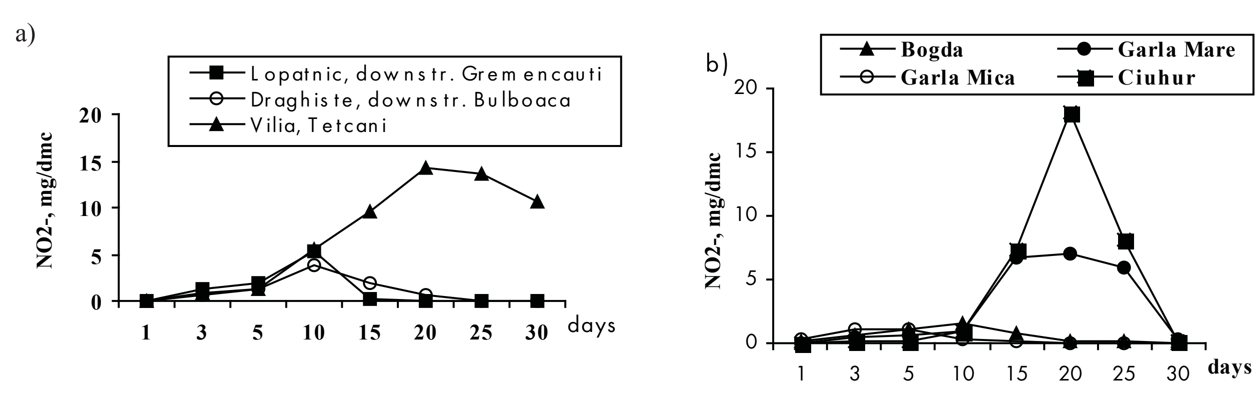


Figure 1. Evolution of NH4$^+$ → NO_2^- process in small rivers water.

The second stage of nitrification (NO_2^- → NO_3^-) lasts 15 days in Garla Mica, Lopatnic (Lopatnic), Racovaț (Grajdiesti) rivers water; in r. Draghiste, Lopatnic (Gremencauti), r. Vilia (Cotiugeni) and Bogda – 25 days; r. Racovat (Clocusna), r. Draghiste (Burlanesti), r. Vilia (Tetcani) and r. Ciuhur (Varatic) the transformation NO_2^- → NO_3^- was developed during 30 and more days. The time of nitrification correlates with the content of pollutants in water: surface-active substances, Cu, BOD_5, COD and other compounds.



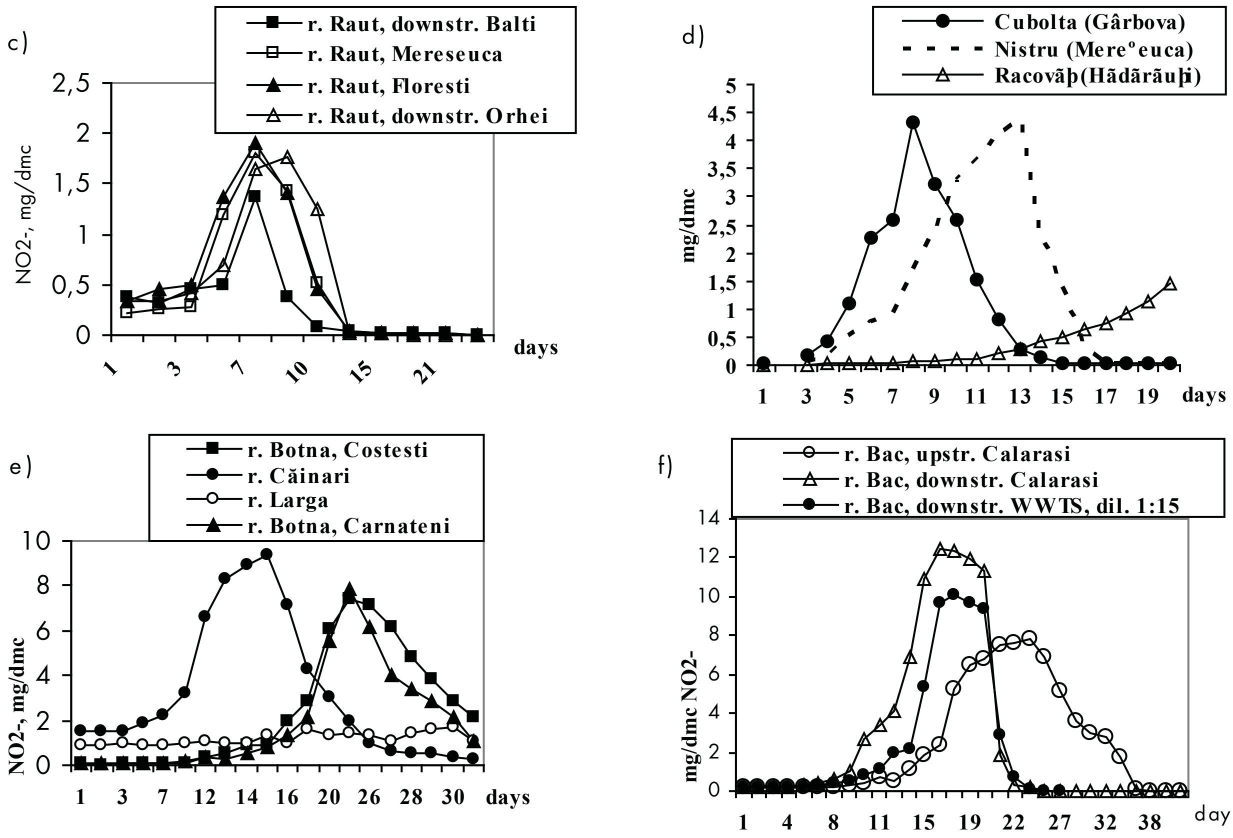


Figure 2. Evolution of the second stage of nitrification ($NO_2^- \rightarrow NO_3^-$) in rivers water.

The rate of ammonia oxidation exceeded the similar of nitrite process. Differences in oxidation rates can be attributed to ammonia-oxidizing bacteria out competing nitrite-oxidizing bacteria due to a number of factors, including free ammonia inhibition, dissolved oxygen concentration, heavy metals, organic matter, temperature and pH [18-20].

The study of nitrification in natural waters with high suspended-solid (SS) content indicated that the presence of SS could accelerate the nitrification process. The nitrification rate would increase non-linearly with the increase of suspended-solid content [21].

High suspended-solid content has useful implications for nitrogen removal from river systems in the Republic of Moldova: rivers Raut, Lopatnic, Cubolta, Cainari, Bac.

The time passing on ammonia ions oxidation is conditioned in natural small rivers water by organic and inorganic pollutants content, which influenced the activity of Nitrifying microorganisms, and correlated (fig. 2) with biological (BOD) and chemical oxygen demand (COD-Mn, COD-Cr).

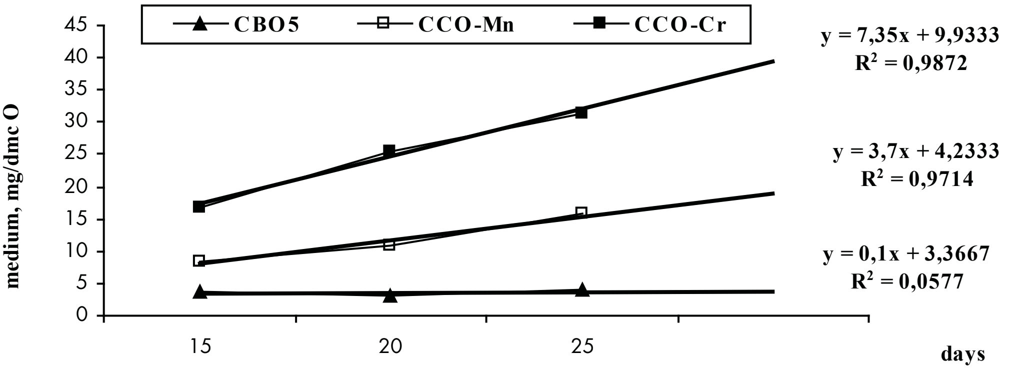


Figure 3. The correlation between the time of ammonia biochemical oxidation and BOD, COD-Mn and COD-Cr.

It is noticed that the improvement of natural waters state (quality, self purification, nitrification) depends on the implementation of water protection measures as soon as possible.

Conclusions:

1. Effluents containing nitrogenous compounds must be treated in order to reduce the release of ammonium-N into natural waters, because this causes oxygen demand, is toxic to aquatic life, leads to eutrophication, modifying the biota and creating an ecological imbalance.
2. The concentrations of ammonium regularly exceed the MACs (17,0 - 46,5 mg/dm^3 as N, 43,6-119 MACs, in Bac river, downstream Chisinau, maintaining their high values up to the confluence with the Nistru river).
3. $NH_4^+ \rightarrow NO_2^-$ process in modeling of small rivers lasts from 6-10 till 21-25 days in dependence of pollutants content.
4. The second stage of nitrification ($NO_2^- \rightarrow NO_3^-$) lsasts 15 - 30 and more days.
5. The time of nitrification correlates with the content of pollutants in water: BOD$_5$, COD and other indicators.
6. High suspended-solid content has useful implications for nitrogen removal from Raut, Lopatnic, Cubolta, Cainari, Bac river systems.

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Chemistry Journal of Moldova. General, Industrial and Ecological Chemistry. 2010, 5 (1), 84-89

STUDY OF SPRINGS WATER QUALITY AS SOURCES OF POTABLE WATER AND FOR IRRIGATION IN REZINA DISTRICT

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Abstract. A spring is a component of the hydrosphere, where water flows on to the surface of the earth from below the surface. Thus it is where the aquifer surface meets the ground surface. It may be the result of karsts topography where surface water has infiltrated the Earth's surface, becoming part of the area groundwater. As sources of water supply in the Republic of Moldova underground waters constitute 15,2% (bore holes, springs and wells). The present work includes water quality investigations and aims to reveal local sources in river Nistru hydrographic basin (Rezina district) for drinking water provision in villages. Chemical composition of investigated spring's water shows that in Rezina district 19% of springs are polluted with nitrogen compounds. Water of only 9% of springs is in conformity with the standard for drinking water. Water from 102 springs meets the requirements of irrigation that doesn't present the risk of soil salinization (K > 18) – 1 383 L/min.

Keywords: Spring, Groundwater, Water quality, Magnitude discharge, Water Types, Irrigation coefficients, Correlation coefficient.

Introduction

Groundwater from wells and springs is an important source of water supply and moves very slowly and follows the least resistive (most permeable) pathway from the point of recharge (where water enters the aquifer) to the point of discharge (where water leaves the aquifer).

In addition to wells, springs provide a source of water supply from aquifers and form the headwaters of many streams and wads. Springs occur where the water table intersects the surface topography and are common where geologic structures, such as faults, provide an outlet for groundwater discharge. Springs represent visible discharge from aquifers; invisible or concealed discharges include seepages, evaporation, transpiration to plants, and hidden springs. Under natural conditions, aquifers discharge water in an amount proportional to the total annual infiltration (recharge).

A spring is a place on the earth's surface where groundwater emerges naturally. The water source of most springs is rainfall that seeps into the ground uphill from the spring outlet. Groundwater obtained from springs is similar to water pumped from shallow wells. Like shallow wells, springs may be contaminated by surface water or other sources on or below the ground surface. The range of natural and man-induced pollutants includes nitrates, pesticides, sulfates, etc. [1]. Water hardness often exceeds the sanitary-hygienic standards by 2-5 times and more. The water quality in wells does not comply in the Republic of Moldova with the national standard for potable water: 87% of the shallow groundwater samples exceed the MAC for nitrate, but as sources of water supply underground waters constitute 15,2% (bore holes, springs and wells). Shallow aquifers are used for non-centralized water supply and the share of shallow groundwater in rural area reaches 95-100% from all water used [2].

Earlier it was investigate springs water quality in Briceni, Edinet, Rascani, Nisporeni Falesti and Glodeni districts [3-5].

The object of this work is to evaluate springs water quality as sources of potable water and for irrigation in Rezina district and to classify spring's magnitude based on the summer value of discharge.

Materials and Methods

Sampling of water: several expeditions were organized to assess the springs water pollution and to collect samples in conditions to exclude water composition changes.

Sample preparation: water samples were analyzed without preventive storing using conventional methods of analysis. In springs water were determined the concentrations of macro- and nitrogen compounds, pH and other compounds. Ammonia ions were determined using the Nessler reagent [6-8]. Nitrite was estimated by the procedure with the Griess reagent and the reduction method with Zn-$MnSO_4$ mixture was used to measure nitrate ions [9,10]. In territory, were determined the location, temperature, flow, water odor and color. Reliability of analytical work has been checked using the internal standard.

Apparatus: DR/2500 spectrophotometer, pH meter, analytical balance, centrifuge.

Assessment of change in ions concentration was performed using mathematical statistics.

Particularly important is the evaluation of the correlation between the basic components of water. Rank correlation coefficient r Spearmen [6] is the most commonly used statistical characterization of the correlation between 2 sets of data because it is dimensionless and is not a relative size, it depends on the size of comparable values, but the report change.

Results and discussions

On 30.12.2005, in decision nr. 1406, the Government approved a „New Program of water supply and wastewater treatment for the settlements of the Republic of Moldova until 2015". Upon the implementation of the Program nearly half of the population will have access to centralized water services. As a priority of the Program, is mentioned the development of water distribution network, including and public wells/springs, recording and liquidation of pollution of water sources and prevent their pollution.

Springs have been used for thousands of years as an important source of water supply in the world and are places where groundwater discharges through natural openings in the ground. Springs flowing from water-table aquifers tend to have small, extremely variable flows and are influenced greatly by climatic conditions. There are some types of spring outlets: filtration springs with small flow rates in which the source water has filtered into permeable earth; fracture springs, discharge from faults, joints, or fissures in the earth and tubular springs which create underground channels, basically cave systems.

A spring flow is determined by the "spring's" recharge basin. Factors include the size of the area in which groundwater is captured, the amount of precipitation, the size of capture points, and the size of the spring outlet. Water may leak into the underground system from many sources including permeable earth, sinkholes, and losing streams.

Groundwater obtained from springs is similar to water pumped from shallow wells. Like shallow wells, springs may be contaminated by surface water or other sources on or below the ground surface. The groundwater is highly vulnerable to anthropoid impacts. Its quality is largely influenced by the geologic and geochemical conditions. While springs may seem to be good water supply, they need to be selected with care, developed properly, and tested periodically for contamination.

Today we face the challenge of protecting the springs from disappearing. Elevated nitrates content are a common and growing problem in springs. A steady rise in nitrate levels has been observed in springs over the past thirty years or so [11].

Contamination of groundwater from point and non-point sources is one of the major problems of water resources [12, 13]. Altogether one hundred and nineteen groundwater samples were collected and investigated from Rezina district.

Water Quality. Groundwater quality can be affected by both natural and anthropogenic activities. In aquifers unaffected by human activity, the quality of groundwater results from geochemical reactions between the water and rock matrix as the water moves along flow paths from areas of recharge to areas of discharge. In general, the longer the groundwater remains in contact with soluble materials, the greater the concentrations of dissolved materials in the water [14]. The quality of groundwater also may be changed as the result of the mixing of waters from different aquifers. In aquifers influenced by human activity, the quality of water can be directly affected by the infiltration of anthropogenic compounds or indirectly - by the alteration of flow paths or geochemical conditions. The quality of water discharged by springs vary greatly because of factors such as the quality of the water that recharges the aquifer and the type of rocks with which the ground water is in contact. The rate of flow and the length of the flow path through the aquifer affect the amount of time the water is in contact with the rock, and thus, the amount of minerals that the water can dissolve.

Physical parameters. The measured pH values of the water in the present study range from 7,25 to 8,3, thus classified as low alkaline. Spring-water temperatures range from 10 to 17^{0}C. It has not odor and color.

Chemical parameters. Spring water quality represents the general state of ground-water system. Most spring water in Rezina district is of good quality. The specific hardness generally is of 5 to 24,2 mmol/L: eleven springs with hardness less than 7 mmol/L, sixty six – hardness of 7 to 10 and nineteen springs have very hard water (more than 10 mmol/L) (fig. 1). The mineralization (total dissolved salts - TDS) ranges between of 356 to 1860 mg/L indicating that amounts of minerals are dissolved in the water. The minimum value of magnesium is about 10 mg/L (in Slobozia Horodiste) and the maximum about 168 mg/l (Meseni village). The concentration of $Na^+ + K^+$ ranges from 14 mg/L (in Cineseuti) to 221mg/L (in Gordinesti). The concentration of chloride in the study area is of 14-148 mg/L and 345 mg/L in Gordinesti. The highest concentration of sulfate was found in Meseni spring (446 mg/L), while the lowest concentration was 11 mg/L found in Echimauti. Water from only eleven (9%) springs in Rezina district corresponds to the standard for drinking water (table 1).

Table 1

Water springs in Rezina district corresponding to the drinking water standard

	Village	Ecological state	Geographical coordinations			Debit (L/min)
			N	E	h (m)	
1	Pereni	Equipped, clean	47˚39.481	028˚46.384	160	11,5
2	Pripiceni Razasi	Equipped, clean	47˚41.103	028˚45.643	164	3,3
3	Pripiceni Razasi	Muddy	47˚41.192	028˚44.561	157	14,6
4	Pripiceni Razasi	Non equipped	47˚41.558	028˚45.392	190	17,6
5	Hartop	Equipped, clean	47˚43.291	028˚43.464	233	6,4
6	Hartop	Equipped, clean	47˚43.291	028˚43.465	200	5,4
7	Cineseuti	Need restoration	47˚41.323	028˚50.926	188	1,4
8	Mateuti	Equipped, muddy	47˚48.264	028˚56.492	166	37,5
9	Solonceni	Clean	47˚48.005	028˚59.407	42	7,9
10	Lipceni	Equipped, need restoration	47˚48.426	028˚52.690	173	13,0
11	Lipceni	Equipped, need restoration	47˚48.422	028˚48.242	170	8,2
Total						**≈ 130**

The nitrate concentrations in the study area range from 2 mg/L (in Trifesti village) to 314 mg/L (in Otac). Sixty nine springs (58%) had nitrate concentrations exceeding the threshold value of 20 mg/L, and 23 springs (19%) from Buseuca, Otac, Cuizauca, Ignatei, Meseni, Cineseuti, Gordinesti, Tareuca, Mateuti, Mincenii de Sus, Echimauti villages had nitrate concentrations higher than 50 mg/L, the maximum acceptable concentration (MAC) of nitrates for drinking water (exceeding MAC of one to five times) (fig. 1). There is a wide spatial variation in the nitrate concentration in spring water. Untreated domestic wastewater is most probably the major source of nitrate in the spring water. Moreover, in the area under consideration there are no major industries or intensive agricultural activities. The results of this study are useful to highlight one of the most important environmental problems, namely the degradation of water quality, and may serve to alert and encourage local and national authorities to take substantial steps and actions to protect and manage water quality.

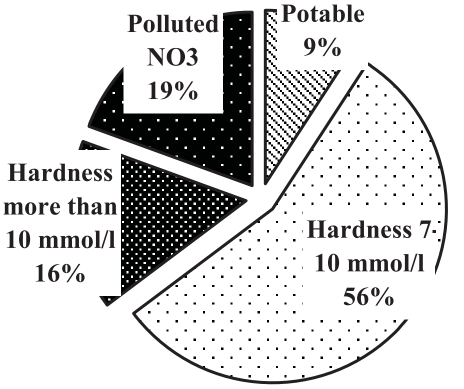
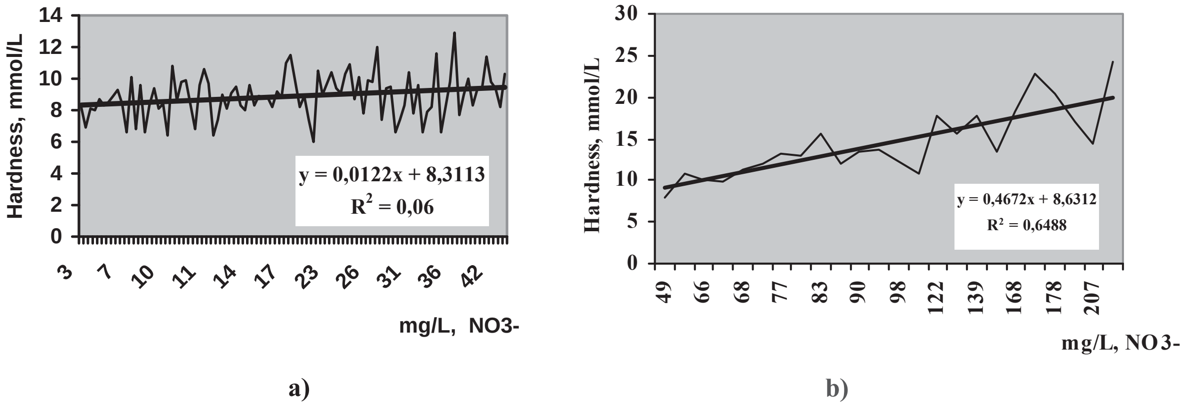


Fig. 1. Quota number of water springs: 1 – potable (9%); 2 – hardness 7 – 10 mmol/L (56%); 3 - hardness > 10 mmol/L (16%) and 4 - polluted with NO_3^- (19%).

Correlation coefficients. The correlation coefficient between any two variables is an important measure because it helps in identifying the strength and degree of relationship between them. Though much work has been done in developing different correlation measures, most of these are suitable only for crisp numbers.

Calcium, the most abundant dissolved cationic constituent of groundwater and responsible for water temporal hardness, ranges from 72 mg/L (in Pereni, Slobozia Horodiste villages) to 259 mg/L (in Otac village). The correlation coefficient of Ca^{2+} versus HCO_3^- and Cl^-, is 0,33, and 0,11, respectively. The content of Ca^{2+} has also high positive correlation coefficient with NO_3^- (0,21); it can be attributed to association of its compound in soil and utilized fertilizers or/and wastes non regularly deposits.

It is to mention that the content of nitrate ions correlated with hardness [15, 16]. The values of correlation coefficient constitutes $R^2 = 0,6488$ (fig. 2) that confirms the observed trend and indicates a clear influence of nitrogenous compounds (especially ammonia) on calcareous elements of the earth [17, 18]. The coefficient for springs water with the content of NO_3^- less than MAC is very small (0,06). Was established an insignificant correlation of the NO_3^- content with waters mineralization ($R^2 = 0,1704$) and practically absence with chloride and sulfate concentrations.



a) b)

Fig. 2. Correlation between water hardness and nitrates content. Regression equation and the credibility correlation coefficient (R^2): a) less than MAC; b) more than MAC nitrates content.

Water Types. In some cases, the ground water may exit from multiple vents. One vent may exhibit different water chemistry than another vent. These differences are sometime referred to as water types. The water type can be determined from the chemical content of a sample. Were established the following types of water springs in Rezina district on the basis of anions: 33% of HCO_3, 29% - HCO_3-SO_4/Cl, 23% - HCO_3-SO_4, 5% - HCO_3/Cl-SO_4 and about 10% of springs water is of nitrate type (HCO_3 – SO_4 - Cl – NO_3; HCO_3 – NO_3 – Cl – SO_4; HCO_3 – NO_3 – Cl) (fig. 3). Cations content in studied waters conditioned the presence of Ca-Mg/Na (88%), Mg-Ca/Na (9%) and Na-Ca/Mg (3%) types of water.

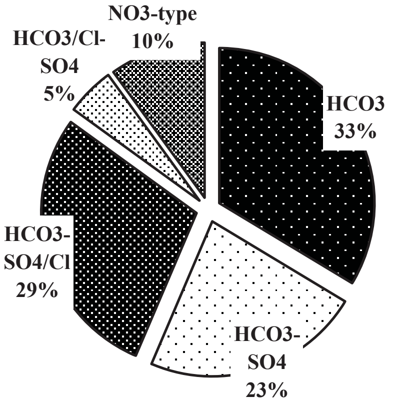


Fig. 3. Quota number of springs grouping on water type: HCO_3 (33%); HCO_3-SO_4/Cl (29%); HCO_3-SO_4 (23%); HCO_3-Cl (5%); and 10% nitrate type of springs water.

Classification of springs

Springs are classified by magnitude (from 1 to 8) on the basis of their volume of flow, or discharge of water [19].

First, second, third and fours magnitude springs discharge the greatest amount of water but are absent in the studied territory. There are eight 5th magnitude springs, seventy seven 6th magnitude springs, thirty-one 7th magnitude springs, plus another three springs classified as 8th magnitude. The following is a summary of spring classification by volume in Rezina district (table 2).

Table 2

The summary of spring classification by volume

Magnitude	Flow L/min	Number of springs in Rezina district
1 st Magnitude	>168 000	0
2 nd Magnitude	16 800 to 168 000	0
3 rd Magnitude	1 680 to 16 800	0
4 th Magnitude	378 to 1680	0
5 th Magnitude	37,8 to 378	8
6 th Magnitude	3,78 to 37,8	77
7 th Magnitude	0,48 to 3,78	31
8 th Magnitude	< 0,48	3

Irrigation Water Criteria. Irrigation is an artificial application of water to the soil and is used to assist in the growing of agricultural crops, maintenance of landscapes, and revegetation of disturbed soils in dry areas and during periods of inadequate rainfall. Sources of irrigation water can be groundwater extracted from springs or by using wells, surface water withdrawn from rivers, lakes or reservoirs or non-conventional sources etc. Numerous parameters are used to define irrigation water quality. One criteria was used in this study for evaluating irrigation water quality – the Stebler irrigation coefficients [20]. All ionic concentrations (Na^+, Cl^-, SO_4^{2-}) are expressed in milliequivalent per liter.

The calculated irrigation coefficients for the water of 17 springs in Rezina district (s. Echimauti, Lipceni, Solonceni, Pereni, Otac, Pripiceni Razasi, Hartop, Peciste, Ignatei, Meseni – by one, Sarcova, Tareuca, Gordinesti – by two, Buseuca – by three) don't correspond to irrigation conditions (K < 18). As for the rest of the springs (102) it doesn't present any danger of soil salinization (K > 18) and water may be used with the purpose of irrigation.

Conclusions

The study shows the following results:

- The quality of water discharged by springs vary greatly because of factors such as the quality of the water that recharges the aquifer and the type of rocks with which the ground water is in contact. The rate of flow and the length of the flow path through the aquifer affect the amount of time the water is in contact with the rock, and thus, the amount of minerals that the water can dissolve.
- The measured pH values of the water in the present study range from 7,25 to 8,3, thus classified as low alkaline. Spring-water temperatures range from 10 to 17^0C. It has not odor and color.
- The groundwater in the study area falls under fresh (TDS<1,000 mg/l) to brackish (TDS> 1,000 mg/l) type of water.
- Water from eleven (9%) springs corresponds to the standard for drinking water.
- Most of the waters are unfit as drinking ones because of the NO_3^-(19%), hardness and TDS contents are as well high (72%).
- Quota number of springs grouping on water type constitutes 33% for HCO_3; 29% - HCO_3-SO_4/Cl; 23% - HCO_3-SO_4; 5% - HCO_3-Cl and 10% nitrate type of springs water.
- As calculated, irrigation coefficients water for 17 springs in Rezina district (14%) don't correspond to irrigation conditions (K < 18). The rest of the springs (102) don't present danger of soil salinization (K > 18) and water may be utilized for irrigation.

Recommendations

Contamination sources of springs include livestock, wildlife, crop fields, forestry activities, septic systems, and fuel tanks located upslope from the spring outlet. To protect springs it is necessary to take the following measures.

1. As the quality of groundwater is a general problem, the government authorities are strongly advised to protect water supply over the long term.
2. The groundwater quality management should be attempted in the study area.
3. Prohibit flooding near the spring.
4. Construct a U-shaped surface drainage diversion ditch to divert any surface runoff away from the spring, but not to dig deep enough to uncover flowing groundwater.
5. Fence an area in all directions around the spring box to prevent contamination by animals and people who are unaware of the spring's location.
6. Avoid heavy vehicle traffic over the uphill water bearing layer to prevent compaction that may reduce water flow.

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COBALT SALTS PRODUCTION BY USING SOLVENT EXTRACTION

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Abstract: The paper deals with the extracting cobalt salts by using mixtures on the basis of tertiary amine from multicomponent solutions from the process of hydrochloride leaching of cobalt concentrate. The optimal composition for the extraction mixture, the relationship between the cobalt distribution coefficients and modifier's nature and concentration, and the salting-out agent type have been determined. A hydrochloride extraction technology of cobalt concentrate yielding a purified concentrated cobalt solution for the production of pure cobalt salts has been developed and introduced at Severonikel combine.

Keywords: cobalt, solvent extraction, tertiary amines, salting-out, octanoic acid.

Introduction

Cobalt is a strategic element widely applied both in the form of a high-quality metal and pure salts. In Russia, cobalt is produced from cobalt concentrates resulting from the copper-nickel ore processing [1]. One of the major producers of cobalt in Russia is Severonikel combine of the Kola Mining and Metallurgical Company, where the cobalt concentrates contain, w/o: Co – 45-46; Ni – 2-4; Fe – 3.5-5; Cu – 0.1-1.0; Mn – 0.1-0.3; Pb – 0.1-0.5; SO_4 – 5-10, and also trace amounts of As, Pb, Zn, SiO_2.

Separating cobalt from impurities involves preliminary dissolution of cobalt concentrate in, for instance, hydrochloric acid. The peculiar feature of this reaction is that dissolving of Co(III) and Ni(III) hydrate concentrates is accompanied by evolution of gaseous chlorine:

$2Co(OH)_3 + 6HCl \rightarrow 2CoCl_2 + 6H_2O + Cl_2$;

$2Ni(OH)_3 + 6HCl \rightarrow 2NiCl_2 + 6H_2O + Cl_2$.

Since the reactive gaseous chlorine has to be utilized, this complicates the process.

The solvent extraction hydrochloride technology of cobalt concentrates developed and introduced at the Institute of Chemistry KSC RAS and introduced at Severonikel Combine, incorporates digestion of the concentrate in the presence of a solid-phase reducer, preventing chlorine evolution at the leaching stage and providing a fast and safe transition of cobalt and impurity elements to solution [2]. The resulting concentrated multicomponent chloride solutions can be effectively processed by an advanced, easily controllable and automated method, i.e. solvent extraction. The non-ferrous metals and iron, contained in solution, form complex $MeCl_2^-$, $MeCl_3^-$, $MeCl_4^{2-}$ anions of varying stability and, consequently, can be extracted by anion-exchanging extracting agents, for instance, by tertiary amines Fig.1 [3].

This work discusses cobalt extraction by mixtures based on tertiary amine from multicomponent solutions resulting from hydrochloride leaching of cobalt concentrate of a quality sufficient for producing pure cobalt salts.

Result and discussion

Creating of an efficient pattern enabling to process multicomponent solutions after cobalt concentrate digesting has involved a quest for the optimal composition of the extraction mixture and studying of the effect of the salt background nature and concentration on cobalt extraction.

In many cases, extracting elements with tertiary amines makes one resort to modifiers enhancing the solubility of extracted components in the extracting phase, facilitating phase stratification, and reducing the amine viscosity (spirits, ketones, tributylphosphate, etc.) [4].

In practice, the easiest commercial available modifiers are synthetic fatty alcohols. It is known, however, that alongside with increasing the metal complex solubility in the organic phase, alcohols inhibit extraction due to the process of salvation. Quite the reverse with ketones, which facilitate the extracting agent interaction with the metal anion complex, thus increasing the extraction degree. Notwithstanding the fact that ketone modifiers contribute to achieving higher cobalt distributions coefficients, their application is limited due to their high solubility in solution. Therefore we recommend octyl alcohol as modifier for the organic mixture based on tertiary amine.

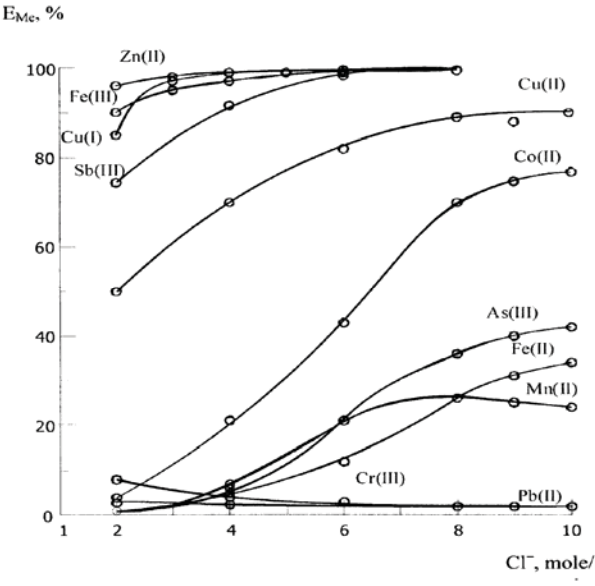

Fig. 1. Plots of metals recovery level vs. $[Cl^-]$ concentration.

Our experiments, taking into account the time of phases mixing and separation, and distribution coefficients, have led us to propose an organic mixture of the following composition, % v/v: (30-35) TAA + (10-20) long-chain aliphatic alcohol, the rest being a diluent.

During the solvent extraction from multi-component solutions of the target component (cobalt in our case) its extraction may be affected by different metal salts. Sometimes the components proper of the salt background are not extracted but, nevertheless, seriously affect the extraction of other elements. This is due to the fact that the activity of both water and other solution components may be changing due to the nature and concentration of the salting-out agent. The process may be occurring either way: increasing of the element distribution coefficient (salting-out) or decreasing one (salting-in) [5, 6]. In this connection, we have studied the impact of the nature and concentration of a large number of metal chlorides on cobalt extraction by organic mixtures based on tertiary amines.

It has been found that the cobalt distribution coefficient is affected both by salting-out agent concentration and nature or, to be more exact, the cation radius and its charge [7]. This is due to the cation ability to bind various water quantities in their hydrate shells, which changes the share of water able to solvate the metal compound being extracted.

The desalinating action of cations can be formulated thus: the lower the level of salting-out agent hydration, the greater the water activity and the lower the active concentration of dissolved substance. So, hydrating of salting-out agent ions will be diminishing the quantity of free water and increasing the activity of $CoCl_2$ ions. To put it differently, the diminishing free water concentration will promote the growth of chlorine ions concentration, facilitating the formation of an anion, readily extractable complex, $CoCl_4^{2-}$. Comparing the chlorides investigated according to their salting-out ability, it is evident that they can be arranged in the following series:

$$LiCl>AlCl_3>MgCl_2>CaCl_2>NiCl_2>CrCl_3>LaCl_3/NdCl_3>>FeCl_2/NaCl>NH_4Cl$$

Notwithstanding the fact that H^+ is also highly hydrated in aqueous solutions, the degree of cobalt extraction from HCl is considerably lower than from most of the salt solutions. The reason for it is that the tertiary amine chlorides can additionally extract hydrochloric acid inhibiting the $CoCl_4^{2-}$ extraction. At a later stage, the nickel-containing cobalt solutions were processed using nickel chloride, in which case no extra reagents are needed.

The research has resulted in developing, large-scale testing and introducing of a solvent extraction hydrochloride technology of cobalt concentrate at Severonikel Combine Fig.2.

After starting the plant, we solved the problem of separating cobalt from the bulk of impurities and produce fairly pure chloride solutions from which cobalt carbonate was further precipitated.

At the first stage, by precipitating cobalt carbonate from re-extracts, products containing less than 0.1% of impurity non-ferrous metals and iron were obtained. However, their quality was inferior because of the presence of 0.5% residual sodium and chlorine, unremovable by washing with water. Therefore we looked into the impact exerted by the nature of precipitator and precipitation conditions on the level of sodium and chlorine ions' entering into the structure of carbonate precipitates.

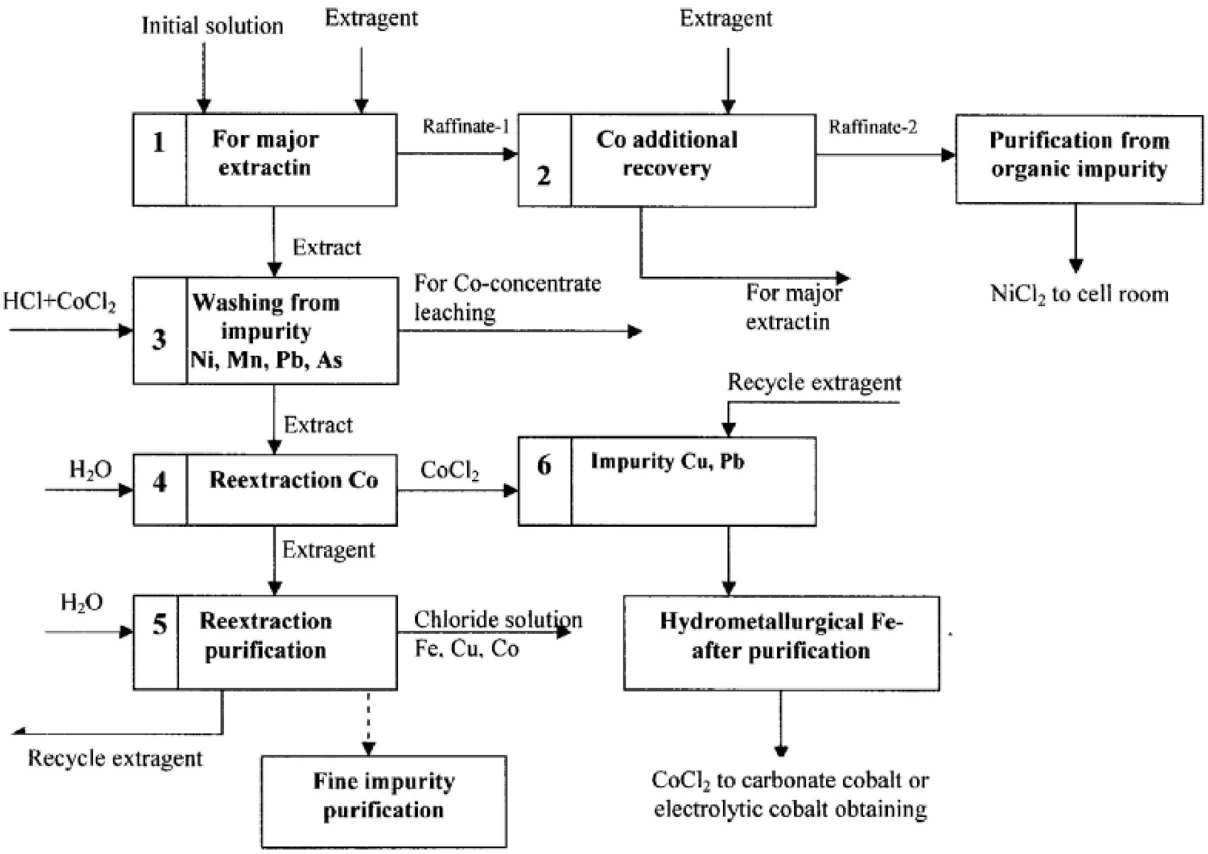

Fig. 2. Principle diagram of Co extraction at Severonikel combine.

In particular, the first parameters to be investigated were the effect of the ratio between the precipitator (Na_2CO_3, $NaHCO_3$ and $CoCl_2$), initial $CoCl_2$ concentration, temperature, duration and order of reagent feeding, and also exposure of the precipitate formed in the mother liquor, and the structure and composition of forming precipitates. It was discovered that the main prerequisite for minimizing the chlorine content in precipitates (0.01% w/o) is duration and order of reagent feeding.

Slow feeding of soda solution to cobalt chloride solution creates a stable deficit of CO_3^{2-} ions with resulting precipitates containing up to 4.6% of structural chlorine unremovable by water. In the case of reverse slow adding of cobalt chloride solution to a vigorously stirred Na_2CO_3 solution, the process occurs under an excess of carbonate ions preventing the chlorine from entering into the structure.

At the same time, the excess of carbonate ions in solutions should not be too high, since it may promote the formation of $[Co(CO_3)]^{2-}$ anion complexes interacting with sodium cations to form a hardly soluble salt, $Na_2[Co(CO_3)]$, which explains why a part of sodium can be removed from cobalt carbonate.

Based on these studies, we developed a method [8] for the production of basic cobalt carbonate, yielding a salt containing not less than 0.05% of sodium and chlorine. Currently the Severonikel Combine has manufactured several thousand tons of paste and dry cobalt carbonate.

Besides the basic cobalt concentrate, the chloride solutions with limited impurity contents can be used in the production of other cobalt salts such as acetate, nitrate and sulphate. From the viewpoint of economic and technological efficiency, an attractive method is that of extraction conversion, which consists in extracting of cobalt from chloride solution using a cation-exchange extracting agent followed by re-extracting with respective acids to target salts.

Table 1

Composition of high-purity cobalt salts obtained from cobalt chloride solutions

Element	Content, ppm			
	hydroxide	dichloride	acetate	carbonate
Co	base	base	base	Base
Ni	20	20	30	30
Cu	0.6	0.9	1	0.8
Fe	10	10	10	20
Mn	0.5	2	1	0.9
Si	<7	5	<2	5
Bi	<0.1	<0.1	<0.1	<0.1
Sb	<0.5	<0.5	<0.5	1
Sn	<0.1	<0.1	<0.1	0.5
Pb	0.2	0.1	0.1	0.1
Zn	1	0.5	0.2	2
P	<0.5	<0.5	<0.5	-
Mg	2	1	0.5	5
Te	<0.1	<0.1	<0.1	<0.1
Tl	<0.01	<0.01	<0.01	<0.01
Na	15	10	2	100
Ca	15	10	2	200

The possibility of carrying out the method of cation-exchange solvent extraction conversion in continuous regime was tested at a laboratory cascade, when cobalt was extracted from a chloride solution of the following composition, g/l: Co – 112; Ni – 0.01; Fe, Mn, Cu <0.005 with ammonium form of n-octanoic acid in Escaid 100 at four stages followed by a two-stage re-extraction with a 2 mole/l vinegar acid solution. The pattern of the experiment on the production of cobalt acetate solution at an extractor cascade with ammonium form of n-octanoic acid is presented in Fig. 3.

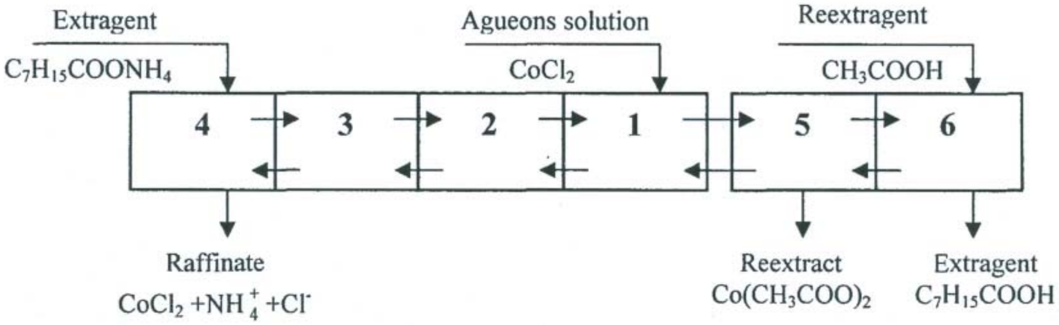

Fig. 3. Pattern of cobalt chloride extraction conversion to acetate at an extractor cascade.

The obtained cobalt acetate solution was filtered and evaporated. After cooling, the crystals were separated at a nutsch filter and dried under vacuum by gradually increasing the temperature to 100ºC. The content of impurities in the salt is given in Table 1.

The impurity elements were determined by mass spectrometry in induction-bound argon plasma (MS IBP) on ELAN 9000 DRG-e (Perkin Elmer, USA). The method was developed at the Institute of Chemistry Laboratory of chemical and optic methods of analysis.

The same method is applied to cation-exchange extraction conversion of cobalt chloride to nitrate, sulphate and other cobalt salts, which are important intermediate products for the synthesis of highly effective catalysts, solid electrolytes and capacitors. So, the method allows expanding the range of cobalt products.

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THE EFFECT OF SULPHURIC ACID CONCENTRATION ON SOLVENT EXTRACTION OF ReO_4^- BY THE LONG-CHAIN ALIPHATIC TERTIARY AMINES AND ALCOHOLS

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Abstract: The effect of sulphuric acid concentration on solvent extraction of ReO_4^- by the long-chain aliphatic tertiary amines and alcohols in a wide range of H_2SO_4 concentrations in initial solutions is discussed. It has been established that the influence of the sulphuric acid concentration on rhenium solvent extraction is largely due to the extraction process mechanism. In the case of the anion-exchange mechanism, ReO_4^- is best extracted from weakly acidic solutions, whereas when the hydrate-solvate mechanism takes place – from solutions containing 4-7 mole/l H_2SO_4.

Keywords: Rhenium, solvent extraction, long-chain aliphatic tertiary amine and alcohols, sulphuric acid media.

Introduction

Rhenium is one of the rarest trace metals. The rhenium clark is $7\cdot10^{-8}$ %; rhenium compounds commonly occur in nature as an isomorphous impurity in molybdenite, in sulfide copper ores and, still rarer, in polymetallic ores.

Depending on the kind of raw material and equipment used, pyrometallurgical processing of rhenium-bearing concentrates can yield up to 96% of rhenium sublimated to the gaseous phase, next captured and concentrated in the wet scrubbing system. Wet scrubbing sulfuric solutions (wash sulphuric acid) from copper and copper-molybdenum plants is the main industrial source of the metal and may contain 60 to 700 g/l H_2SO_4 and more, and up to 1.5 g/l rhenium. Up to date, rhenium has been recovered from such solutions by solvent extraction technologies with tertiary amine-type extragents [1-3].

The extraction of rhenium by tertiary amines has been extensively described in the literature. However, the available data on the impact of acidity are fairly contradictory [1-7]. Knowing that acidity is a major factor controlling the process efficiency, we undertook studying the effect of H_2SO_4 concentration on rhenium distribution coefficients during the extraction by tertiary amines and high-molecular aliphatic alcohols usually employed as a modifier in tertiary-amine based extraction mixtures.

Experimental

In the experiments on Re(VII) extraction we used the following organic reagents of the amine type: commercially pure tri-iso-octylamine (TIOA) of Hostarex A 324 brand (no less than 95% main substance and up to 5% primary and secondary amines), pure tri-n-octylamine obtained from “Vekton” (St.Petersburg, Russia) and commercially pure trialkylamine produced in Lermontov (Russia); and the reagents belonging to long-chain alcohols: 1-heptanol, 2-heptanol, 1-octanol, 2-octanol, 1- nonanol and 2-nonanol of “pure” grade, produced by “Viking” company (Voronezh, Russia) or by “Vekton” (St.Petersburg, Russia).

In the case of amine-type extraction, the extracting agents were the solutions containing 5-30% v/v of the amine in an Escaid 100 diluent with addition of 20% v/v isomeric aliphatic alcohols (1-octanol or 2-ethyl-hexanol-1 of “pure” grade). The extracting agent was preliminarily converted into the salt form via the contact with a H_2SO_4 solution of the same concentration as a solution of rhenium, from which the extraction was performed.

The extraction was performed in separatory funnels at a volume ratio of the organic to aqueous phase equal to 1:25 at room temperature in the course of 5 min, which provided attaining the equilibrium by the system.

The experiments on the temperature effect on the extraction were carried out in a constant-temperature round-bottomed flask with a volume of 0.25 ml supplied with a mechanical stirrer.

In the case of long-chain alcohols, the extracting agent was undiluted reagent. Since aliphatic alcohols are able to extract mineral acids [8], the extracting agents were preliminarily saturated with H_2SO_4 to prevent additional extraction of the mineral acid from concentrated acid media.

The extraction experiments were carried out at room temperature in 50-100 ml volumetric cylinders for 5 min at 1:1 organic to aqueous phase ratio.

Model rhenium-containing solutions were prepared by dissolution of pure-grade ammonium perrhenate in distilled water, with addition of a necessary amount of chemically pure sulfuric acid. The concentration of rhenium(VII) was about 0.001 mole/l (186.2 mg/l), and that of sulfuric acid, from 0.1 to 9 mole/l.

The content of rhenium(VII) in the aqueous phase was determined spectrophotometrically from the coloration intensity of the thiourea complex of rhenium(IV), formed in the presence of Sn(II) as reducing agent. The light absorption was measured with a KFK-3 photoelectric colorimeter at a wavelength λ=390 nm [9] or by the atomic-emission method on a "Plazma 400" spectrometer. The content of rhenium in the organic phase was calculated as the difference of its contents in the aqueous phase before and after extraction.

The sulfuric acid concentration in the aqueous phase was determined by titration.

Result and discussion

The obtained data are presented in Figures 1 and 2. It follows from Fig. 1 that irrespectively of the amine type, its concentration and process temperature, increasing of the acid concentration in the aqueous phase only causes the rhenium distribution to diminish (Fig.1), which is due to the anion-exchange mechanism of ReO_4^- extraction with amines:

$(R_3NH)_2SO_4 + 2ReO_4^- \leftrightarrow 2R_3NHReO_4 + SO_4^{2-}$.

Apparently, any attempt to increase the sulphuric acid concentration will only decrease the rhenium concentration.

Both in weakly acidic (up to 2-3 mole/l H_2SO_4) and strongly acidic (>7.5 mole/l H_2SO_4) areas, the decline of rhenium distribution coefficients is more pronounced, which is due to changing forms of the extracting agent and the metal under these conditions. Thus, it is known that increasing the acidity to 2-3 mole/l H_2SO_4 converts practically the entire of $(R_3NH)_2SO_4$ into the organic phase to a bisulphate form – $[(R_3NH)HSO_4]_4$ [10], whereas at high H_2SO_4 concentrations a complex rhenium anion $[ReO_2(SO_4)_2]^-$ is formed [11], which undoubtedly tells on the extractional characteristics of the system.

Interestingly, we have failed to detect the numerously reported maxima on the $C(H_2SO_4)$-D(Re) curve of rhenium extraction with amines. Apparently, the low D(Re) values were obtained in a weakly acidic region due to analytical errors of spectrophotometric analysis [1-3, 6, 7]. We have noted that during the analysis of weakly-acidic samples by the spectrophotometric method [9] there appears a hardly noticeable colloid suspension (probably, SnO_2), which gives a higher value of the sample optic density, thus increasing the rhenium content in raffinates analyzed resulting in incorrect data. By applying atom-emission spectroscopy with inductive-bonded plasma (AAS ICP) to the weakly acidic raffinates, we eliminated this error and obtained reliable data on the acidity effect on rhenium extraction by tertiary amines.

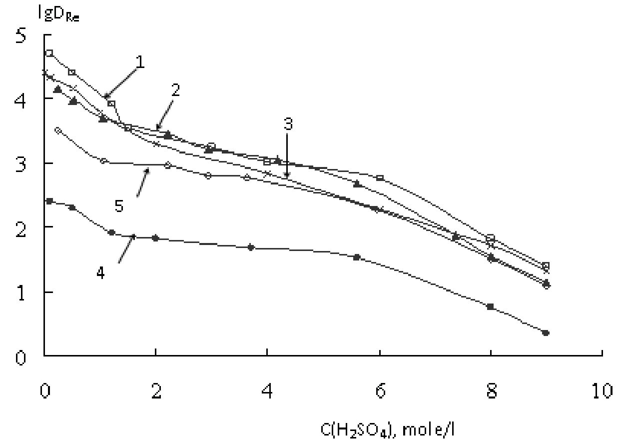

Fig. 1. The effect of H_2SO_4 concentration in the aqueous phase on lgD_{Re} during the rhenium (VII) extraction by tertiary amines, v/v: 30% ТиОА (1), 30% ТОА (2), 30% ТАА (3), 5% ТиОА at t=20°C (4), 30% ТиОА at t=55°C (5). O:W = 1:25, τ=5 min., $C(Re)_{init.}$ ~10^{-3} mole/l (0,2 g/l).

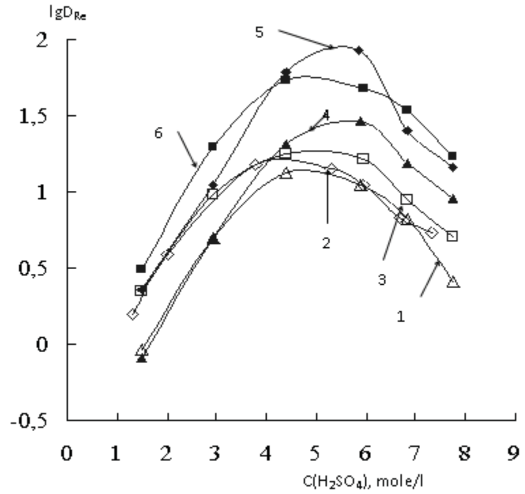

Fig. 2. The effect of H_2SO_4 concentration in the aqueous phase on D_{Re} during rhenium (VII) extraction by isomeric aliphatic alcohols C_7-C_9: 1-nonanol (1), 1-octanol (2), 1-heptanol (3), 2-nonanol (4), 2-octanol (5), 2-heptanol (6). O:W = 1:1, τ=5 min., $C(Re)_{init.}$~10^{-3} mole/l (0,2 g/l), t=20°C.

High-molecular aliphatic alcohols are predominantly used in rhenium technology as modifying additives in amine-containing extractive compositions. However, recent attention has been focused on the extractive properties of the alcohols proper [10].

Aliphatic alcohols, containing 7-9 carbon atoms in the chain, meet the principal requirements to industrial extracting agents being able to extract rhenium from acidic solutions, although not as efficiently as tertiary-amine based agents. Since the extraction process with alcohols proceeds by the hydrate-solvate mechanism, according to the pattern:

$$ReO_4^- + H_3O^+ + nH_2O + qROH \leftrightarrow [H_3O(H_2O)_n\ (ROH)_q]^+ReO_4^-,$$

an increase in the metal extraction to the organic phase is observed at $C(H_2SO_4) \geq 1$-2 mole/l. As can be seen from Figure 2, the curves of $C(H_2SO_4)$-lgD(Re) dependences for all alcohol isomers C_7-C_9 pass through a maximum at $C(H_2SO_4)$ from 4 to 7 mole/l depending on their structure. On the one hand, this behavior of the curves is caused by increasing rhenium(VII) extraction by alcohols as acidity in the area of low and medium acid concentrations grows due to a shift in equilibrium towards the formation of a hydrate-solvate complex. On the other hand, this occurs due to inhibition of the rhenium(VII) extraction in the strongly acidic region as the competing process of H_2SO_4 extraction enhances.

Conclusion

Thus, it has been established that the effect of the sulphuric acid concentration on rhenium solvent extraction is largely due to the extraction process mechanism. In the case of the anion-exchange mechanism, ReO_4^- is best extracted from weakly acidic solutions, whereas when the hydrate-solvate mechanism is used – from solutions containing 4-7 mole/l H_2SO_4.

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The authors wish to thank researcher Serba N.V., Lab. of chem. and optic methods of analysis of ICTREMRM KSC RAS, for AAS ICP analyzing.

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VOLTAMMETRIC CHARACTERIZATION OF THE IRON BEHAVIOUR FROM STEELS IN DIFFERENT ELECTROLYTIC MEDIA

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Abstract. The dissolution of the iron from steel was observed by drawing the cyclic voltammetry (CV) for the systems consisting of the solution resulted when the alloy sample was immersed in HNO_3, H_2SO_4, and HCl, aqueous solutions on platinum disk electrode (PtDE). The presence of some redox processes can be observed only in HNO_3 which confirms the complexity of the mechanism of Fe dissolution in this acid. On the other hand, there were manufactured electrodes of steel samples taken into experiment achieving the corrosion characteristics in the media mentioned above.

Keywords: corrosion, cyclic voltammetry, peak potential, polarization curves, steel.

Introduction

In the characterization of the behaviour of metals and alloys, a main role belongs to the electrochemical approaches, and among them the voltammetry is frequently used [1-4].

The necessity of these studies appeared due to the frequent practical implications such as the electrolytic extraction and treating of metals, the change of the metal surfaces through deposit or electrochemical polishing and electroplating, corrosion, current electrochemical sources, electrochemical syntheses, sensors.

Within the electrochemical corrosion of metals, which is in fact an anodic dissolution, free metal ions or insoluble products can be appeared, which are characteristic to the passive state [5]. Generally these processes imply the interaction between the surface of the metal and that of the electrolyte, the transfer of the electrons, the electrochemical reaction, and the diffusion of the ions or the molecules. For a more accurate comprehension of the mechanisms of anodic dissolution it is necessary to know the state of the surface of the metal, the chemistry of the interface solid–liquid and of the electrochemical processes [6].

The anodic dissolution processes led to relatively small electric potentials, in which the determinant step rate is the charge transfer or concomitantly the charge transfer and diffusion, results in kinetic rate and mix respectively [7-8]. The behaviour of metals in different electrolytic mediums can be estimated by the help of Pourbaix diagrams [9].

The significance of these diagrams is limited because it refers to ideal electrolyte solutions, to pure metal and not to alloys. These diagrams do not take into consideration the nature of the acid or of the base which modify pH value. It does not modify the risk of the cathode corrosion in immunity either, where the potential is strongly electronegative and the drawing of the diagram is based on the thermodynamic data, without taking into consideration the kinetic calculations [10].

Experimental

Electrodes and electrolytes

In Table 1 the composition of the five alloy samples, which followed two ways of study is given:

a) the steel dissolution in H_2SO_4, HCl and HNO_3 aqueous solutions as well as in NaOH alkaline solution and the drawing of the cyclic voltammogram (CV), using as a work electrode (WE) an platinum disk electrode (PtDE), 2mm in diameter, an auxiliary electrode (AE) – a Pt wire 1mm in diameter and 10mm long, and as reference electrode (RE) the saturated calomel electrode (SCE);

b) the constitution of work electrodes from each of the alloy samples and their coupling with AE of Pt and the reference electrode SCE for the voltammetric studies.

Table 1

The composition of the alloy samples considered in the study

Sample	Fe	C	Mn	Si	Cu	Sn	Ni	Mo	Cr	Pb	< 0.1%
1	98.10	0.13	0.71	0.35	-	-	-	0.07	0.09	0.110	S, B, Zn,Pb,V, Al
2	98.00	0.23	0.84	0.24	0.11	0.083	0.05	0.02	0.13	0.090	S, Sb, Nb, Al, Ti
3	98.90	0.11	0.33	0.02	0.12	0.160	0.08	0.02	0.10	0.090	S, Nb, V, Ti
4	97.30	0.23	-	0.25	-	-	0.24	0.16	0.63	0.009	S, B, As, Ti
5	98.10	0.20	0.66	0.24	0.30	0.146	0.10	0.02	0.06	0.010	S, Nb, Al

For the determination of some parameters characteristic to Fe corrosion, out of each alloy sample there were made disk-shaped work electrodes with Φ=5mm, introduced in a polymeric matrixt. As a reference electrode the saturated calomel electrode (SCE) was used and Pt plan electrode (1 x 1cm) as an auxiliary electrode was employed.

The solutions used as electrolytic media were prepared of highly pure analytic substances and the bidistillated water, and, before the drawing of the voltammogram, the oxygen was eliminated through bubbling with nitrogen for 10 minutes.

The equipment and the working manner

For the drawing of the polarization diagrams of the systems studied in a), there was used the electrochemical device VoltaLab 32 (Radiometer Copenhagen), which has among its components a DEA-332 Potentiostat (Digital Electrochemical Analyzer), an electrochemical cell with the three electrodes mentioned above, which is equipped with a thermostating matrix, a nitrogen bubbling system for the elimination of the oxygen dissolved in the solution, a data interface IMT 102, connected to a computer with Volta Master 2 software.

At certain moments from the immersion, out of the solutions in which the alloy sample was introduced there were taken volumes of 1mL each in the electrochemical cell and there were diluted with bidistillated water at 30mL for the drawing of the CV. Regarding the considered system, there were drawn CV on domain 1000 ÷ -100mV (on domain -100 ÷ 1000mV a much higher initial cathode current was found, due to the formation of hydrogen, reason for which it was chosen this order of sweeping the potential), at 100mV/s.

For the studies in b) before each series of determination, WE was grinded with emery of different granulosities (from 200 to 2000msh), ungreased and cleaned with bidistillated water. The voltammetric behaviour of WE prepared in this way was studied using the Potentiostat PG STAT 302N Autolab (Netherlands – Eco Chemie), which has among its components GPES software for taking and processing the findings.

Results and discussions

The experimental data relieved the fact that at the anodic dissolution of Fe an important role belongs to the water molecules and to the anions adsorbed on the surface. The following simplified mechanism was suggested [11]:

$$Fe + H_2O \rightarrow Fe(OH)_{ads} + H^+ + e^- \quad (1)$$
$$Fe(OH)_{ads} \rightarrow FeOH^+ + e^- \quad (2)$$
$$FeOH^+ \rightarrow Fe^{2+} + HO^- \quad (3)$$

and the presence of chloride anion will generate the following processes:

$$Fe + Cl^- \rightarrow FeCl_{ads} + 1e \quad (4)$$
$$FeCl_{ads} \rightarrow FeCl^+ + 1e \quad (5)$$
$$FeCl^+ \rightarrow Fe^{2+} + 1e \quad (6)$$

The mechanism of the hydroxide implies as intermediates adsorbed hydroxyl ions, which catalyzes the iron dissolution to produce hydrated ferrous hydroxide. This kind of mechanism, which implies the adsorbed hydroxyl ion, leads to the passivity of metals through the increase of the anodic polarization.

In the presence of the chloride ion, which is also active on the surface of the electrode, there is a competition between the adsorption of the chloride ion and hydroxyl respectively. In the case of the mechanism suggested for the chloride ion there will not take place the passivity of iron, this one preventing the formation of the oxide layer on the surface of iron. There were proposed two mechanisms for the formation of iron oxide layer on the surface of iron.

$Fe(OH)_2$ can also formed during these processes based the electrocoagulation approach when the insoluble iron(II) hydroxides keeps away the pollutants as some possible complex compounds or through the electrostatics attraction [12].

The anodic dissolution of pure iron constituted the task of many studies regarding the corrosion phenomenon, concluded through the treatments given by Bockris and Koch [13]. They do not assert that the stage of the dissolution of the iron either in pure iron or in alloys would be the main stage of the anodic process which takes place in the iron dissolution. A minute presentation of the mechanism of the anodic iron dissolution was presented by Despic and co. [14].

In Fig. 1 – 3, is shown CV diagram obtained for the solution resulted from the total dissolution of sample 1 in HNO_3 – 4M, in which there appear a cathode peak and two anodic peaks.

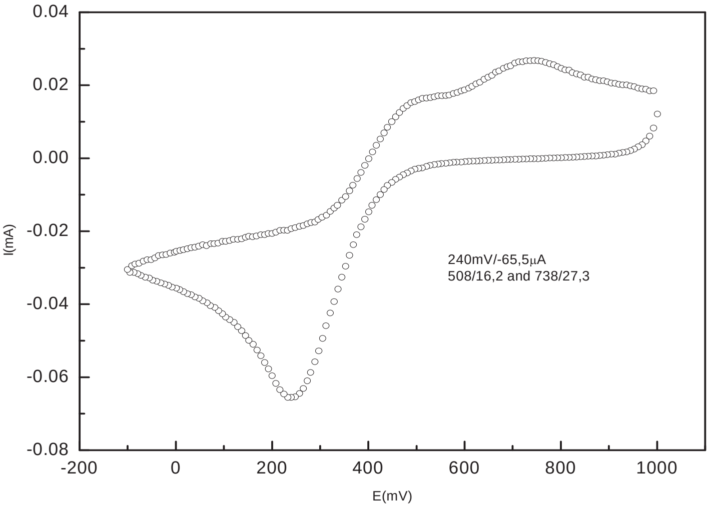


Fig. 1. CV obtained for the solution resulted from the total dissolution of sample 1 in HNO_3 – 4M.

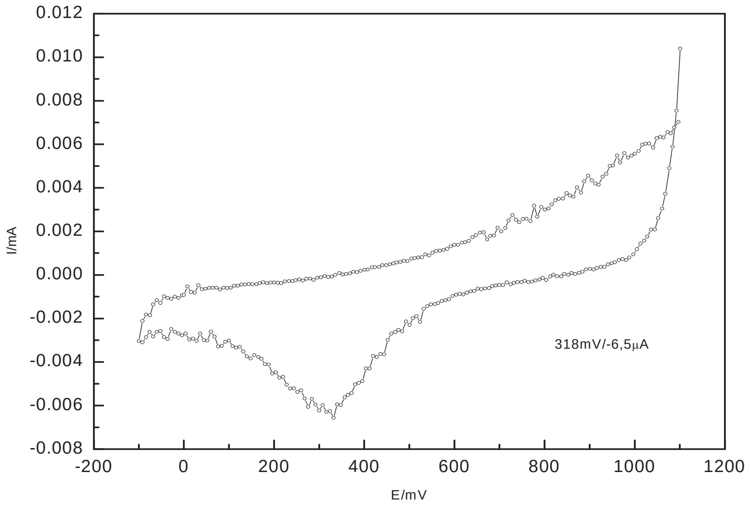


Fig. 2. CV of HNO_3 -4M on EDPt, 100mV/s.

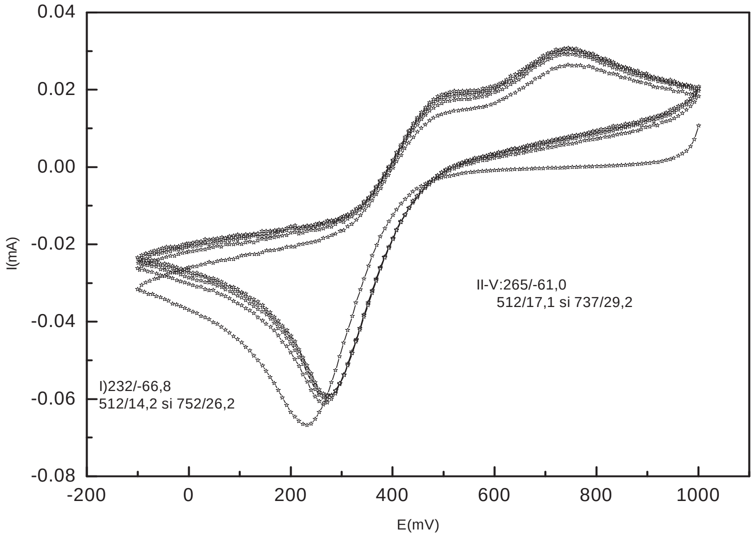


Fig. 3. CV of multiple cycling (n=5) for the dissolution of sample 1 in HNO_3 4M.

Comparing with the CV curves drawn under the same conditions only for the solution HNO_3 4M, presented in Fig. 2, there can be observed that the cathode peak is much smaller and shifted to the right side, while no other anodic peaks appear. In Fig. 3 the CV curves obtained for the sample 1 in HNO_3 4M, under the conditions of multiple cycling, in which there can be noticed a slight shift of the diagram in the first cycle of sweep, in the following ones the difference between the plats being very small, a proof that the reduction – oxidation process can be considered quasi – reversible.

The reduction peak corresponds to NO_3^- and to the existing species in the solution at the iron dissolution, considering the modification within time of the cathode peak intensity, for sample 4 in HNO_3 4M and in HNO_3 2M, determining the following dependence:

a) in HNO_3 4M solution:
$I(\mu A) = 34,44 - 3,83\ t + 4,4 \cdot 10^{-2}\ t^2 – 1,577 \cdot 10^{-4}\ t^3$;
corellation coefficient R = 0.98355

b) in HNO_3 2M solution:
$I(\mu A) = - 4,78 + 2,08 \cdot 10^{-2}\ t – 1,98 \cdot 10^{-3} t^2$;
corellation coefficient R = 0.995, where t is the time in minutes.

The dissolution of the alloy samples took place in HNO_3 solution of (0.25 ÷ 4M) concentration, the drawing of CV achieving with the dilution of each concentrations from which the alloy dissolved, in Table 2 being presented the characteristics of the reduction peak to five concentrations in the absence of the alloy. There can be noticed that the peak intensity does not depend on the concentration of the acid, and the modification of the peak potential can be attributed to the adsorption processes which take place on PtDE.

Table 2

The peak characteristic in HNO_3 solutions of different concentrations

HNO_3 (mol/L) concentration	**0.136**	**0.067**	**0.033**	**0.016**	**0.008**
E_C(mV)	364	252	318	300	316
- I_C(μA)	5.52	7.62	6.5	6.67	7.16

Irrespective of the concentration of the acid in the samples, there was obtained no anodic peaks in CV, what proves that the reduction of nitrogen group is an irreversible process in the conditions of CV drawing.

The drawing of CVs for HNO_3 solutions which contain dissolved Fe lead to two anodic peaks, and the intensity of the cathode peak is higher, which proves that beside the reduction of NO_3^- group there are also electrochemical species, which resulted at the iron dissolution and reduce within the same domain.

The formation of water in the neighbouring of the electrode accelerates the reaction of the iron dissolution and the current becomes higher than the current of limit diffusion; $Fe(II)_{sol}$ so formed is the promoter of the reaction of the reduction of $(NO_2)_{ads}$. Based on the data presented above, there concludes that the mechanism of the dissolution of Fe in aqueous solution of nitric acid is complex, and the voltammetric approach allows to make only a series of qualitative statements.

On 0.25 ÷ 4.00M concentration domain there were dissolved alloy samples in H_2SO_4, HCl or NaOH aqueous solutions, but CVs drawn gave no signs, the same thing being observed also for the alloy samples dissolved in much diluted HNO_3 (10^{-5}M) solutions.

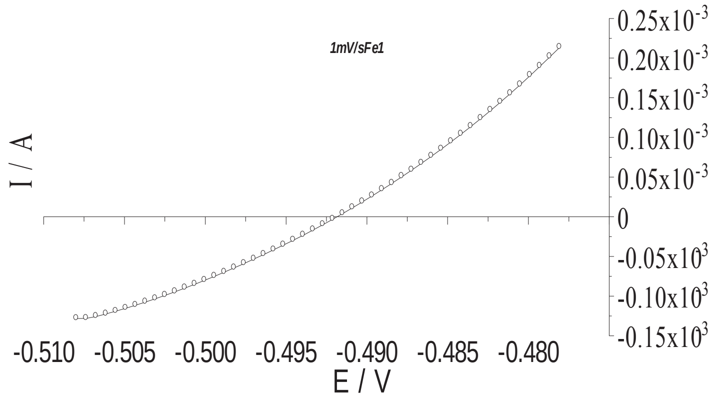


Fig. 4. The polarization diagram for the calculation of R_p in 4M H_2SO_4 of sample 1.

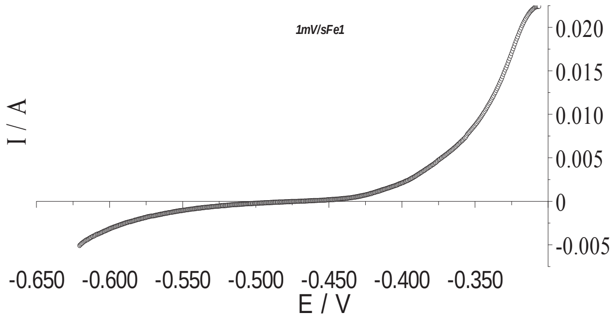
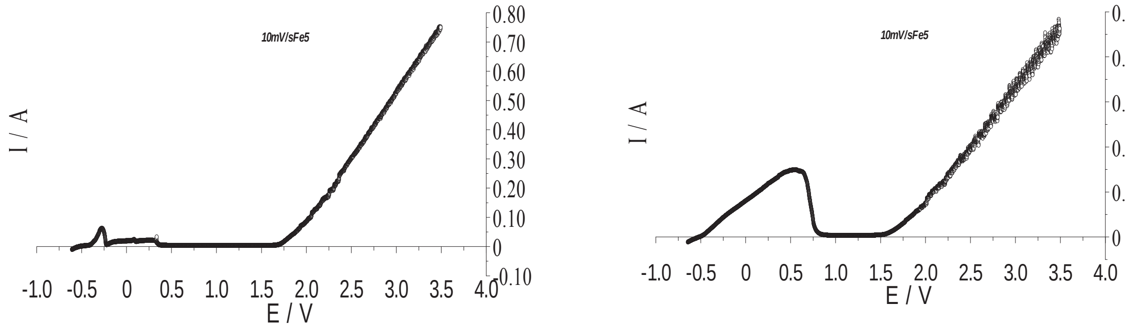


Fig. 5. The diagram of the polarization for the determination of Tafel parameters in 4M H_2SO_4, sample 1.



a)

b)

Fig. 6. The diagrams of polarization of sample 5 in H_2SO_4 4M (a) and in H_2SO_4 0.25M (b).

Following the latter direction of the study (b), the evaluation of the corrosion phenomenon was achieved by the polarizing resistance approach, by the measurement of the current in the corrosion potential domain, as it is presented in Fig. 4, and the slope at the corrosion potential will be:

$$\frac{1}{R_p} = \left(\frac{dI}{dE}\right) \qquad (7)$$

R_p being the polarization resistance, the sweep rate of the giving potential 1mV/s, and the sweep domain very narrow (±15mV regarding the corrosion potential).

The polarization resistance can be calculated with Stern–Geary relation [15-16]:

$$R_p = \frac{b_a|b_c|}{2{,}303 I_{cor}\left(b_a + |b_c|\right)} \qquad (8)$$

where b_a and b_c are the slopes of Tafel line, which will be obtained through the drawing of the voltammogram on an anodic and cathode domain compared to 150mV corrosion potential, as it is presented in Fig. 5, on the base of which E = f(log j) semi-logarithm representation leads to the obtaining of b_a and b_c [17-18].

To characterize the rate of the dissolution process of the iron in the steel, taken in the experiment the rate of the puncture defined by the equation was calculated:

$$V_{cor} = \frac{\delta}{t} = \frac{M}{zF\rho} j_{cor} \qquad (9)$$

where:

δ – the thickness dissolved in the analyzed sample;
T – time;
M/z – the equivalent molar mass (considered z = 2);
F – Faraday constant (96485C/mol);
ρ – the density of the analyzed sample;
j_{cor} – the corrosion current density.

Out of the diagrams of polarization a first image of the behaviour of the alloy at corrosion in a medium given under well précised conditions can be taken out. The potentiodynamic plats are obtained through the continuous polarization of WE at a certain sweep rate of the potential with the recording of the value of the current. With these plates it may be obtained the most important parameters of the corrosion process: the critic polarization potential (E_{pc}), the potential of passivity or Flade potential (E_F), the break potential (E_{str}) with corresponding values of the current as well as the possibility of establishing the domains: active (D_{active}), pre-passive ($D_{pre\text{-}passive}$), passive ($D_{passive}$).

Fig. 6 presents the polarization diagram on an extended potential range (-0.6 ÷ 3.5V) for sample 5 in H_2SO_4 4M (a) and 0.25M (b), obtaining in the case of concentrate H_2SO_4 solution also a pre-passive domain while in the diluted solution E_{pc} (critic polarization potential) it is much shifted towards the right side (at positive values of the potential) and no pre-passive domain appears. Similar diagrams were also obtained for the other alloy samples, the results being presented in Table 3.

Table 3

The characteristics of the polarization curves of the iron alloys in different electrolytic mediums

<table>
<tr><td colspan="9">a) H_2SO_4 4M</td></tr>
<tr><th>No. sample</th><th>$-E_{cor}$ (V)</th><th>$+E_{pc}$ (V)</th><th>I_{pc} (A)</th><th>E_F (V)</th><th>E_{Str} (V)</th><th>D_{activ} (V)</th><th>$D_{prepasiv}$ (V)</th><th>D_{pasiv} (V)</th></tr>
<tr><td>1</td><td>0.454</td><td>-0.243</td><td>$5.478 \cdot 10^{-2}$</td><td>-0.204</td><td>1.696</td><td>-0.454÷-0.247</td><td>-214÷0.347</td><td>0.347÷1.696</td></tr>
<tr><td>2</td><td>0.453</td><td>-0.256</td><td>$5.91 \cdot 10^{-2}$</td><td>-0.209</td><td>1.675</td><td>-0.453÷-0.256</td><td>-0.256÷0.341</td><td>0.341÷1.675</td></tr>
<tr><td>3</td><td>0.450</td><td>-0.224</td><td>$4.61 \cdot 10^{-2}$</td><td>-0.189</td><td>1.664</td><td>-0.450÷-0.224</td><td>-0.189÷0.333</td><td>0.362÷1.664</td></tr>
<tr><td>4</td><td>0.426</td><td>-0.259</td><td>$4.96 \cdot 10^{-2}$</td><td>-0.206</td><td>1.685</td><td>-0.426÷-0.259</td><td>-0.206÷0.337</td><td>0.368÷1.685</td></tr>
<tr><td>5</td><td>0.431</td><td>-0.266</td><td>$5.82 \cdot 10^{-2}$</td><td>-0.220</td><td>1.698</td><td>-0.431÷-0.220</td><td>-0.220÷0.339</td><td>0.379÷1.698</td></tr>
<tr><td colspan="9">b) H_2SO_4 0.25 M</td></tr>
<tr><td>1</td><td>0.510</td><td>0.711</td><td>$6.9 \cdot 10^{-2}$</td><td>0.905</td><td>1.532</td><td>-0.510÷-0.711</td><td>-</td><td>0.905÷1.532</td></tr>
<tr><td>2</td><td>0.503</td><td>0.643</td><td>$7.06 \cdot 10^{-2}$</td><td>0.870</td><td>1.534</td><td>-0.503÷-0.643</td><td>-</td><td>0.870÷1.534</td></tr>
<tr><td>3</td><td>0.462</td><td>0.541</td><td>$5.44 \cdot 10^{-2}$</td><td>0.862</td><td>1.503</td><td>-0.462÷-0.541</td><td>-</td><td>0.862÷1.503</td></tr>
<tr><td>4</td><td>0.462</td><td>0.540</td><td>$5.44 \cdot 10^{-2}$</td><td>0.808</td><td>1.535</td><td>-0.462÷-0.540</td><td>-</td><td>0.808÷1.535</td></tr>
<tr><td>5</td><td>0.485</td><td>0.566</td><td>$7.37 \cdot 10^{-2}$</td><td>0.819</td><td>1.536</td><td>-0.485÷-0.566</td><td>-</td><td>0.819÷1.536</td></tr>
<tr><td colspan="9">c) HCl 4M</td></tr>
<tr><td>3</td><td>0.482</td><td>0.132</td><td>$1.88 \cdot 10^{-1}$</td><td>0.236</td><td>1.934</td><td>-0.482÷0.132</td><td>-</td><td>0.236÷1.934</td></tr>
<tr><td colspan="9">d) HCl 0.1M</td></tr>
<tr><td>3</td><td>0.505</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-0.505÷2.869</td><td>-</td><td>-</td></tr>
<tr><td colspan="9">e) HNO_3 4M</td></tr>
<tr><td>5</td><td>0.280</td><td>0.452</td><td>$4.91 \cdot 10^{-2}$</td><td>0.870</td><td>1.691</td><td>-0.280÷0.452</td><td>-</td><td>0.870÷1.691</td></tr>
<tr><td colspan="9">f) HNO_3 0.1 M</td></tr>
<tr><td>5</td><td>0.492</td><td>1.757</td><td>$3.58 \cdot 10^{-2}$</td><td>1.846</td><td>1.915</td><td>-0.492÷1.757</td><td>-</td><td>1.846÷1.915</td></tr>
</table>

The data in Table 3 point out a slight shift of E_{cor} of iron towards negative values in H_2SO_4 solution, E_{pc} for diluted solutions shifts at positive values regarding the concentrated solution with almost 1.00V, while the intensity corresponding to each alloy sample is higher in the diluted solution. For diluted solutions, E_F shifts to positive values with more than 1.00V, too. The trans-passivity of the sample in the diluted solution appears earlier than in the concentrated solution ($E_{str.4M} < E_{str.0.25M}$). The active domain of the corrosion of the samples is strongly diminished in the concentrated solution as compared to the diluted one, in which the pre-passive domain does not appear any longer as in the case of the concentrated H_2SO_4 solutions. The passive domain of the alloy samples is larger in the concentrated solution than in the diluted one [19-21]. The data obtained from the analysis of the polarization diagrams confirm that the five Fe alloy samples are very close not only from the composition point of view but also from the structural one, and the different additions do not lead to different voltammetric behaviour.

Since the behaviour of the five samples in HCl, H_2SO_4, and NaOH aqueous solutions media is characterized by very close values of the parameters of the polarization plat, in Table 3 are given the parameters obtained for a single sample.

Table 4

The parameters of the corrosion of iron in alloys in different electrolytic mediums 4.00M H_2SO_4

No. sample	R_p Ω	$10^3 j_{cor}$ A/cm^2	Tafel $\lvert b_c \rvert$ V	Tafel b_a V	R_p (Tafel)	$\overline{R_p}$ Ω	v_{cor} mm/year
1	22.4	1.629	0.095	0.079	15.5	20.45	19.80
2	38.2	1.524	0.101	0.088	16.7	27.45	16.67
3	29.1	1.076	0.092	0.032	46.3	37.70	15.6
4	62.3	0.896	0.104	0.041	51.5	56.90	11.01
5	78.2	0.142	0.071	0.106	59.6	68.9	9.17
0.25 M H_2SO_4							
1	82.8	1.989	0.143	0.081	80.9	81.7	0.989
2	28.1	3.751	0.136	0.159	24.2	26.15	3.839
3	17.1	0.150	0.118	0.024	16.3	16.7	0.154
4	16.7	4.750	0.156	0.186	13.5	15.1	4.864
5	28.7	0.963	0.150	0.151	19.6	24.15	2.036
HCl 0.25M							
2	91.16	0.197	0.240	0.046	24.55	57.85	10.27
HCl 4M							
3	315.9	0.22	0.104	0.102	106.8	211.35	2.263
HNO_3 4M							
4	2.78	48.81	0.131	0.257	1.54	2.16	49.9
5	1.72	76.78	0.162	0.208	0.97	1.34	89.6

In the case of the diluted HCl (0.1M) solution, the corrosion is continuous distinguished but no passive or prepassive domain can be deduced. The nitric acid solution, both diluted and concentrated higher than 2V, there appear oscillations of the current in CV. Such oscillations appear also for the samples introduced in alkaline NaOH solutions, where the modification of the potential takes place continuously from the introduction of the alloy sample, without the possibility of establishing an accurate value of the corrosion potential. In 0.25M solution a significant increase of the current to 0.400V appear, and at 1.00V there start the current oscillations which lead to a maximum of about 2.500V. The polarization curves were drawn out on the potential domain $E_{cor} \div 3.500$V, at a 10mV/s rate. E_{cor} was established by immersing WE in the solution following the potential in open circuit.

The steels dissolution in diluted aqueous solution is electrochemical characterized by the calculation of the corrosion currents corresponding to these systems and by measuring the polarization diagrams on a large potential range when the rate stages determining the dissolution process corresponding to the investigated potential domain are shown.

Conclusions

In present paper the corrosion of five steel samples having the iron content 97.3 ÷ 98.90% through the dissolution in HNO_3, H_2SO_4, and HCl aqueous solutions in the range of 0.25 ÷ 4M concentration, by voltammetric method, have been studied. There were revealed electrochemical processes in CV of the samples dissolved in HNO_3 solutions, confirming the complexity of the mechanism of iron dissolution in HNO_3 solutions.

To characterize the anodic dissolution of iron there were made WEs from steels taken in the study, to drown out the cyclic voltammograms for the determination of the polarization resistance of Tafel parameters and of the corrosion characteristics.

Out of the polarization curves for the more concentrated solutions (4M) there was defined a pre-passive domain, which is not met at the diluted solutions (0.25M), and at higher potentials there appeared oscillations of the current as well.

For the same steel sample the corrosion potential is higher for the lower acid concentration. Therefore, a possible passivation effect would be stronger for the more concentration acids, which favors the appearance of some protective chemical compounds as oxides, hydroxides or insoluble salts on the contact surface steel sample - corrosion medium.

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C15 FUNCTIONALIZED DERIVATIVES OF *ent*-KAUR-16-EN-19-OIC ACID: ISOLATION FROM THE SUNFLOWER *HELIANTHUS ANNUUS* L. AND SYNTHESIS

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Abstract. The known diterpenic ester – 15α-angeloyl-*ent*-kaur-16-en-19-oic (angeloylgrandifloric) acid has been isolated from the dry wastes of *Helianthus annuus* L. The synthesis of 15α-hydroxy- and 15-oxo-*ent*-kaur-16-en-19-oic acids starting from *ent*-kaur-16-en-19-oic acid has been performed.

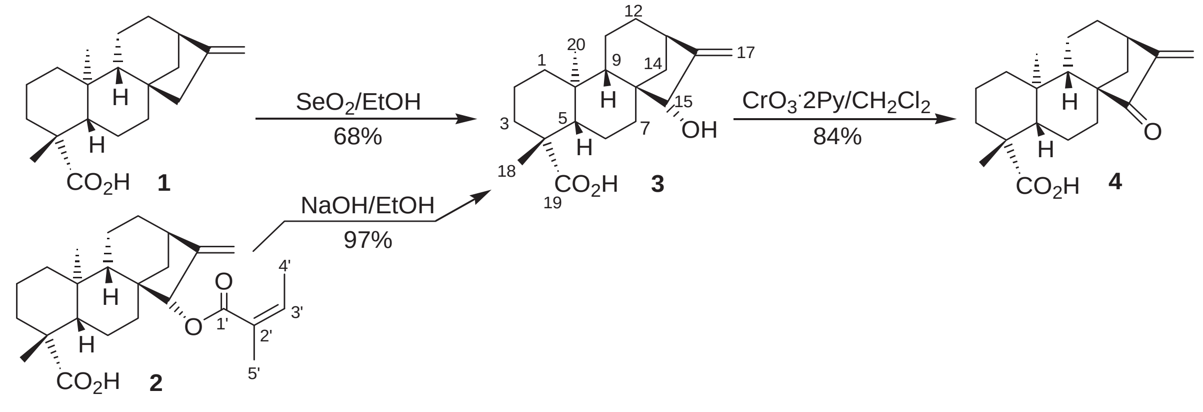
Keywords: diterpene, isolation, synthesis, 15α-angeloyl-*ent*-kaur-16-en-19-oic acid, 15α-hydroxy-*ent*-kaur-19-oic acid, 15-oxo-*ent*-kaur-16-en-19-oic acid.

1. Introduction

Kaurenic compounds possessing a broad spectrum of biological activities have been isolated from different natural sources [1, 2]. An encreasing interest towards this class of diterpenoids has been observed in the recent years [3, 4], due to potential applications, especially, in the field of pharmacological research. We have reported previously a new procedure for isolation of *ent*-kaur-16-en-19-oic acid (**1**) from the dry wastes of sunflower (*Helianthus annuus L.*) [5], that made the *ent*-kaurenic acid (**1**) readily available from renewable local raw material.

2. Results and discussion

In line with our continuous interest in the synthesis of functionalized terpenes, we present in this paper our results on the synthesis of some derivatives of *ent*-kaur-16-en-19-oic acid (**1**) which possess additional functional groups at C15 position. It is known, that a high degree of functionalization represents a prerequisite of a relevant biological activity. Following this idea, a similar C15 functionalized analog has been isolated from the same source, and its structure was proved both on the basis of spectral data, as well as of chemical transformations.



Following a simple procedure of extraction and chromatographical separation, a minor crystaline product was isolated along with previously reported *ent*-kaur-16-en-19-oic acid (**1**). It was identified on the basis of its spectral data (IR, ^{1}H and ^{13}C NMR) as 15α-angeloyl-*ent*-kaur-16-en-19-oic (**2**). This compound was indentical in all respects to the previously published data [6, 7].

The 15α-angeloyl-*ent*-kaur-16-en-19-oic acid (**2**) was isolated previously from the South American *Wedelia grandiflora* [8], from leaves of *Helianthus debilis* [6] and *Helianthus sp*. [9], from *Viguiera dentata* (Cav) [10], from *Montanoa tomentosa* ssp [11] and recently from leaves of *Helianthus annuus L*. [7].

On the saponification of the ester (**2**) with an ethanolic solution of potassium hydroxide, the 15α-hydroxy-*ent*-kaur-16-en-19-oic acid (**3**) was obtained in a 97% yield. It was identified on comparison of its spectral data with those published [12-15].

It is noteworthy mentioning that the hydroxyacid (**3**) is also a natural compound isolated previously from different plant material (*Helianthus niveus* subspecies *Canescens* [12], *Viguiera ladibractate* [16], *Viguiera potosina* [17], *Espeletia timotensis* [14]).

Due to the availability of the *ent*-kaur-16-en-19-oic acid (**1**), we have used it as starting material for the synthesis of other C-15 functionalized *ent*-kauranic derivatives. Accordingly, the oxidation of (**1**) with selenium dioxide in ethanol the corresponding allylic alcohol (**3**) was obtained in a good yield (68%). It was identical in all respects with the authentic sample of 15α-hydroxy-*ent*-kaur-16-en-19-oic acid (**3**), obtained from acid (**2**) as described above.

Following oxidation of the hydroxyacid (**3**) with the Collins reagent [18] in dichloromethane led to the formation of the 15-oxo-*ent*-kaur-16-en-19-oic acid (**4**) with a 84% yield. The obtained product was identified on the basis of its spectral data and comparison with the literature data [15, 19, 20]. We should mention, that the ketone (**4**) is a natural compound isolated from *Pteris longipes Don* [19] and *Espeletia grandiflora* and posess a relevant cytotoxic activity [21]. It was also shown to have a proapoptotic effect on the human prostate carcinoma epithelial cell line PC-3 [21].

3. Conclusion

The 15α-angeloyl-*ent*-kaur-16-en-19-oic acid (**2**) was isolated from the dry wastes of sunflower. A synthetic scheme for the synthesis of two C15-functionalized derivatives of *ent*-kaurenoic acid was elaborated, basing on readily available *ent*-kaur-16-en-19-oic acid (**1**).

4. Experimental

IR spectra were recorded on a Bio-Rad FTS 7 spectrophotometer.^{1}H and ^{13}C NMR spectra were recorded in $CDCl_3$ on Bruker 400 AVANCE III (400 MHz) spectrometer; chemical shifts are given in ppm and are referenced to chloroform ($CHCl_3$) as internal standard (δ = 7.26 ppm for proton and δ = 77.0 ppm for carbon). Optical rotations were measured in chloroform on a Jasco P 2000 polarimeter, using a 10 cm cell. Commercial Merck Si gel 60 (70–230 mesh ASTM) was used for flash chromatography, and Merck pre-coated SiO_2 gel plates were used for TLC. The chromatograms were sprayed with 0.1% solution of cerium (IV) sulfate in 2*N* sulfuric acid, and heated at 80 °C for 5 min to detect the spots. Treatment of reaction mixtures in organic solvents included the extraction by diethyl ether, washing of the extract with water up to neutral reaction, drying over anhydrous Na_2SO_4, filtering, and solvent removal in vacuum.

Obtaining of the extract from dry wastes of sunflower. Dry wastes of sunflower (500 g) have been preliminarily crumbled up and extracted in the soxhlet by diethyl ether during 2 hours. After evaporation of the solvent, the 65 g of extract was obtained in the form of a hard brown mass which, when heated at ~50°C, melts. The obtained extract is dissolved readily in diethyl ether, benzene, chloroform, but poorly in petrol ether. A part of the extract (7.2 g) has been dissolved in diethyl ether and treated with aqueous solution of alkali KOH (5% solution, 40 mL). The aqueous phase has been separated, acidified with 10% solution of H_2SO_4 (20 mL), extracted with ether, washed with brine up to the neutral reaction and concentrated in the vacuum, giving 6.3 g of yellow oil. A portion of the extract (4.1 g) has been separated on column with silica gel (120 g) by gradient elution with the mixture of petroleum ether and ethylacetate, affording 2.8 g of the mixture of *ent*-trachiloban-19-oic, *ent*-kaur-16-en-19-oic (**1**) and 15α-angeloyl-*ent*-kaur-16-en-19-oic (angeloylgrandifloric) (**2**) acids.

Chromatographic isolation of 15α-angeloyl-*ent*-kaur-16-en-19-oic (angeloylgrandifloric) acid (2). The mixture of acids (460 mg) has been separated on the column with $SiO_2/AgNO_3$ (25 g). Elution with ethylacetate - petroleum ether mixture (1:49) resulted in obtaining of 52 mg (11%) mixture of *ent*-trachyloban-19-oic and *ent*-kaur-16-en-19-oic acid (**1**), 262 mg (57%) of *ent*-kaur-16-en-19-oic acid (**1**) [5] and 123 mg (27%) 15α-angeloyl-*ent*-kaur-16-en-19-oic (angeloylgrandifloric) acid (**2**): colorless crystals, mp 195–197°C (from EtOAc). IR liquid film, (ν, cm^{-1}): 3206-2450, 1705, 1255, 1040, 1010, 890. ^{1}H NMR (400 MHz, δ_H): 0.95 (s, 3H), 1.25 (s, 3H), 1.88 (4, 3H, *J* = 1.0 Hz), 1.96 (dq, 1H, *J* = 8, 1.0 Hz), 2.78 (m, 1H), 5.42 (m, 1H), 5.09 (bs, 1H), 5.20 (bs, 1H) and 6.08 (qq, 1H, *J* = 8, 1.0 Hz). ^{13}C NMR (100 MHz, δ_C): 40.4 (t, C-1), 18.9 (t, C-2), 35.3 (t, C-3), 43.7 (s, C-4), 56.5 (d, C-5), 20.6 (t, C-6), 37.3 (t, C-7), 47.8 (s, C-8), 53.1 (d, C-9), 39.7 (s, C-10), 20.7 (t, C-11), 32.5 (t, C-12), 42.7 (d, C-13), 37.9 (t, C-14), 82.5 (d, C-15), 155.8 (s, C-16), 110.3 (t, C-17), 28.7 (q, C-18), 185.2 (s, C-19), 15.9 (q, C-20), 168.3 (s, C-1'), 128.6 (s, C-2'), 137.4 (d, C-3'), 15.9 (q, C-4'), 18.6 (q, C-5'). Compound (**2**) showed spectral data (IR, ^{1}H and ^{13}C NMR) identical with those of described [6, 7].

15α-Hydroxy-*ent*-kaur-19-oic acid (3). a) 15α-Angeloyl-*ent*-kaur-16-en-19-oic (**2**) (115 mg, 0.287 mmol) was dissolved in 2.0 mL of EtOH and 1.4 mL of 10% KOH/EtOH solution were added. The reaction mixture was refluxed for 2 h. After the usual workup, 98 mg of a crude residue was obtained which was purified on a silica gel column (2 g) (petroleum ether–ethylacetate, 4:1) to give 89.2 mg (97%) of 15α-hydroxy-*ent*-kaur-19-oic acid (**3**), a white solid which was crystallized from MeOH yielding 48.2 mg of colorless needles, mp 219-221 °C, $[\alpha]_D^{25}$ -103° (c, 0.50, $CHCl_3$). IR liquid film, (ν, cm^{-1}): 3415-2725, 1690, 1620, 895. ^{1}H NMR (400 MHz, δ_H): 0.96 (3H, s, H_3-20), 1.25 (3H, s, H_3-18), 2.75 (1H, bd. s, H-13), 3.80 (1H, bd. s, H-15), 5.08 (1H, s, H_A-17), 5.22 (1H, s, H_B-17). ^{13}C NMR (100 MHz, δ_C): 40.6 (t, C-1), 19.1 (t, C-2), 37.8 (t, C-3), 43.5 (s, C-4), 57.3 (d, C-5), 21.0 (t, C-6), 35.5 (t, C-7), 47.7 (s, C-8), 53.4 (d, C-9), 40.1 (s, C-10), 18.4 (t, C-11), 32.8 (t, C-12), 42.3 (d, C-13), 36.2 (t, C-14), 82.7 (d, C-15), 160.4 (s, C-16), 108.3 (t, C-17), 29.1 (q, C-18), 183.7 (s, C-19), 15.9 (q, C-20). Compound (**3**) showed spectral data (IR, ^{1}H and ^{13}C NMR) identical with those of described [6, 12, 14, 15].

b) To a solution of selenium dioxide 23 mg (0.207 mmol) in ethanol (1.5 mL), was added the solution of *ent*-kaur-

16-en-19-oic acid (**1**), (125 mg, 0.414 mmol) in ethanol (1.5 mL) and the mixture was refluxed for 4 h. After the mixture was cooled to 0°C and added $NaBH_4$ (7.8 mg, 0.207 mmol) and the mixture were stirred for 0.5 h at r.t. After the usual workup, 92 mg of a crude residue was obtained and purified on a silica gel (2 g) column (petroleum ether–ethylacetate, 4:1) to give 89.2 mg (68%) of 15α-hydroxy-*ent*-kaur-16-en-19-oic acid (**3**), identical with authentic sample.

15-Oxo-*ent*-kaur-16-en-19-oic acid (**4**). Complex $CrO_3 \cdot 2C_5H_5N$ (85 mg, 0.33 mmol) was added to a solution of alcohol (**3**) (35 mg, 0.11 mmol) in dry CH_2Cl_2 (4 mL). The reaction mixture was stirred at room temperature for 24 h, and then filtered on silica gel to give 31.5 mg of a crude product, which was chromatographed on a silica gel (0.5 g) column (petroleum ether-EtOAc, 17:3) to give 29.2 mg (84%) of a crystalline 15-oxo-*ent*-kaur-16-en-19-oic acid (**4**): mp 196-198°C (from EtOAc), $[\alpha]_D$ -176° (c 0.15, $CHCl_3$). IR liquid film, (ν, cm^{-1}): 1718, 1680, 1637, 896. ^{1}H NMR (400 MHz, δ_H): 0.97 (3H, s, H_3-20), 1.25 (3H, s, H_3-18), 2.93 (1H, bd. s, H-13), 5.22 (1H, s, H_A-17), 5.88 (1H, s, H_B-17). ^{13}C NMR (100 MHz, δ_C): 39.8 (t, C-1), 18.9 (t, C-2), 37.9 (t, C-3), 43.5 (s, C-4), 57.0 (d, C-5), 20.9 (t, C-6), 32.4 (t, C-7), 52.3 (s, C-8), 51.4 (d, C-9), 40.3 (s, C-10), 18.5 (t, C-11), 33.6 (t, C-12), 38.4 (d, C-13), 36.7 (t, C-14), 210.8 (s, C-15), 149.8 (s, C-16), 114.7 (t, C-17), 29.1 (q, C-18), 192.5 (s, C-19), 15.7 (q, C-20). Compound (**4**) showed spectral data (IR, ^{1}H and ^{13}C NMR) identical with those of described [15, 18, 20].

5. Acknowledgements

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NEW CATALYTIC SYSTEM FOR PREPARATION OF METHYL 2-(3-HYDROXY-2-OXO-2,3-DIHYDRO-1*H*-3-INDOLYL)ACRYLATES

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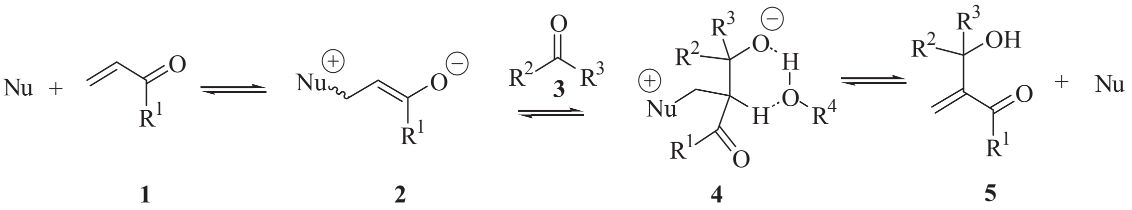
Abstract: A novel catalyst derived from the nitrile functionalized ionic liquids and DMAP promoted the Morita-Baylis-Hillman reaction of N-substituted isatines and the methyl acrylate with moderate up to high yields.

Keywords: catalyst, cocatalyst, functionalized ionic liquids, DMAP, 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-indolyl) acrylates, Morita-Baylis-Hillman reaction.

1. Introduction

Considerable attention has recently been focused on the conversion of the simple starting materials into highly functionalized products such as α-hydroxy- or α-amino-alkyl activated olefins [1-6]. The 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-indolyl)acrylates sequence plays a very important part in organic as well as medicinal chemistry [7-10]. The method for preparing such substances consists in the condensation of acrylic ester with isatine or its derivatives using the Morita-Baylis-Hillman (MBH) reaction [11]. The reaction is mediated by tertiary amines or phosphines, however DABCO is the most common catalyst employed. Reversible Michael addition of the nucleophilic base to the activated alkene **1** gives zwitterionic enolate **2**. It is well documented that the rate determining the step of the MBH reaction is not the 1,2-addition of the reactive carbonyls **3**, as was previously reported, but rather the proton abstraction followed by the elimination of the catalyst from intermediate **4** [12-21]. This fact points to the proton-donor ability of the catalyst and has a major consequence in the catalyst design.



Scheme 1

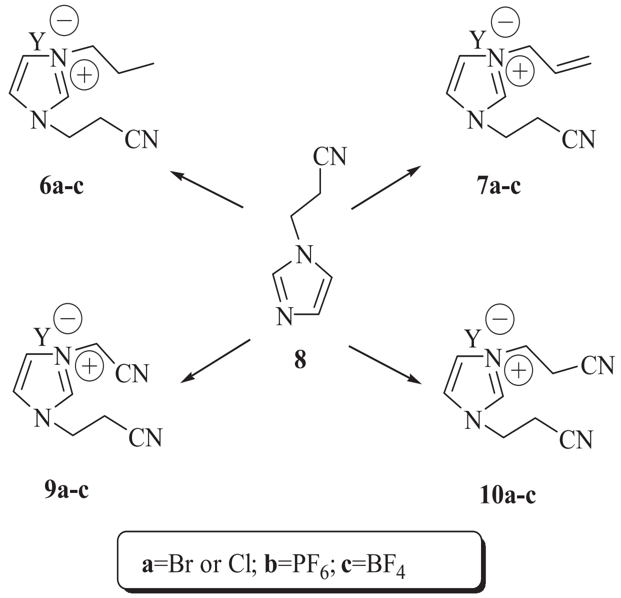
Lin reported the use of ionic liquids as catalysts of the MBH reaction [22-24]. Earlier we also reported the synthesis of new ionic liquids as new generation of solvents/catalysts for "green chemistry" [25]. For example, we published a one step procedure to effect the selective Biginelli, Kondakov, Prince reactions catalyzed by new mono-nitrile (carboxy) functionalized ionic liquids [26-28]. Moreover, there has been proposed a new approach for particularly attractive liquid/liquid metal ion extraction processes by using a carboxy-functionalized imidazolinium salt [29].

2.1. Design and Development of the nitrile functionalized ionic liquids

It was reported earlier that in the key step of the MBH reaction, the addition of the N,N-(dimethylamino)pyridine-activated enone to aldehyde forming the C-C bond, both the aldehyde and enolate are bound and are activated by bis-thiourea cocatalyst [30,31]. It should be noted that DMAP itself may promote the self-aldol reaction of reactive carbonyls. In order to avoid this secondary reaction, we considered that may be use the nitriles group in this case will help to form the complex DMAP-imidazolium ionic liquid. This substance will promote conjugate addition by binding to the zwitterionic enolate and stabilizing these intermediates. Moreover, it remains hydrogen-bonded to the resulting enolate in the enolate-addition step to reactive carbonyls, and finally efficient proton transfer in the rate determining proton abstraction step [19, 32]. Such a model explains the autocatalytic effect of the product **5,** as well.

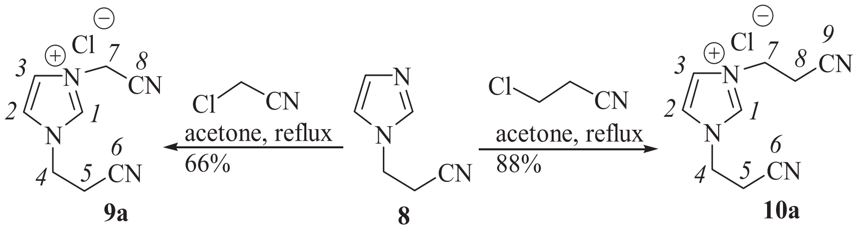
This hypothesis was completely verified and we report in the present paper that the mixture of DMAP with bis-nitrile functionalized ionic liquids catalyzed the MBH reaction under mild conditions.

We began by designing solvents/catalysts which would be prepared from 2-(1*H*-1-Imidazolyl)ethilcarbonitrile **8**. Earlier was published that the quaternization of **8** with alkyl halides to give imidazolium halide salts **6a** (Y=Br)**, 7a** (Y=Br). The next step of the metathesis of **6a, 7a** with the appropriate inorganic salt ($NaBF_4$ or KPF_6) in water or acetone leads to ionic liquids **6b** (Y=PF_6), **6c** (Y=BF_4) as well as to **7b** (Y=PF_6), **7c** (Y=BF_4) [25,26].



Scheme 2

We began with an investigation of the preparation of salts **9a, 10a** from **8** with 2-chloroacetonitrile. As was expected, the reaction of **8** with 2-chloroacetonitrile at room temperature proceeded smoothly (longer than for 48 hours), that is why the synthesis of new imidazole derivatives was realized by refluxing equimolar quantities of imidazole **8** and 2-chloroacetonitrile in acetone solution.



Scheme 3

The reaction product is solid, its composition and structure are confirmed by elemental analysis, IR- and NMR spectra. In the IR spectrum of compound **9a,** the characteristic bands at 620 см$^{-1}$ (C–Cl); 740 cm^{-1} (-CH=CH-); 1170 cm^{-1} (N-Cl); 1565 cm^{-1} (NH_3^+); 1620 cm^{-1} (C=N); 2090 cm^{-1} (C=C); 2250 cm^{-1} ($C\equiv N$) and 2800 cm^{-1} (CH_2) appear. In comparison with ^{1}H NMR spectrum initial **8** [25] the signals of imidazole as well as propylnitrile groups are located in the downfield region (3.33 ppm, 4.58 ppm, 7.99 ppm, 8.04 ppm). Additionally, the signal of the ^{5}C methylene group was observed at 5.75 ppm.

The changing of 2-chloroacetonitrile on 3-chloropropanenitrile has not affected the time of the reaction, whereas the yield of a homologue **10a** has increased up to 88 %.

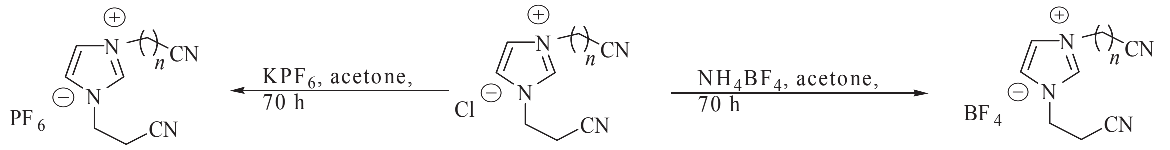
According to the spectral data, the molecule **10a** represents a symmetric product with heterocyclic and alkylnitrile fragments.

The specific feature of ^{1}H NMR spectrum of the investigated compound **10a** in comparison with that of a product **9a**, is the absence of a singlet two-proton signal at 5.75 ppm and the presence of only two triplet signals of methylene group in a combination with singlet signals of the imidazole ring. It is to be mentioned that there are insignificant signals of the mentioned group in a stronger region. Worth pointing out these data are supported by the IR-spectrum of **10a** having characteristic bands at 1168 cm^{-1} (Cl), 2249 cm^{-1} (CN), 2945 cm^{-1} (CH_2), 3368 cm^{-1} (-N=), 3393 cm^{-1} (=N^+=). These data in combination with the results of the elemental analysis confirm the structure **10a**. It is necessary to note that the product **10a** is by itself a lower-melting material than **9a**.

The next step of our investigation was the selection of optimal conditions for an exchange of chloride synthesized salts on anions PF6$^-$ and BF4$^-$.

Carrying out the reaction with the appropriate salt ($NaBF_4$ or KPF_6) in acetone at room temperature leads to obtaining target compounds with yields up to 97%.

The specific feature of **9b** from its precursor **9a** is the lowering of the melting point from 122-123^{0}C to 84-85^{0}C. In the IR-spectrum of **10b,** characteristic bands at 822 cm^{-1} (P-F) appear. In the spectrum ^{1}H NMR of **9b** there are signals of the ethylene, methylene, nitrile and heterocyclic fragments as well. The change of anion has resulted in an insignificant shift of signals of propylnitrile substances in stronger field with changing of coupling constants from *J*=6.48 Hz up to *J*=6.0 Hz, whereas the signal $^7CH_2$ is observed at 5.75 ppm.



9b *n*=1 (93%)
10b *n*=2 (97%)

9a *n*=1
10a *n*=2

9c *n*=1 (93%)
10c *n*=2 (97%)

Scheme 4

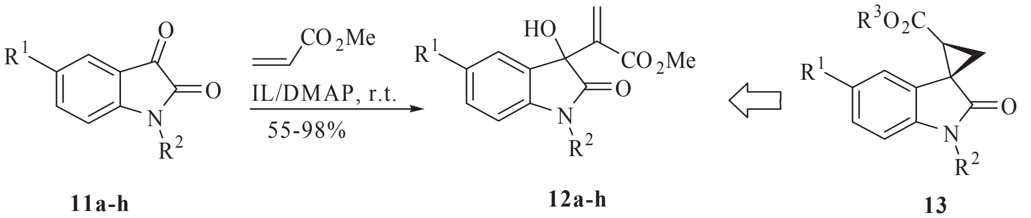
The composition and chemical structure of the product **9c** is confirmed by the data of the elemental analysis, IR - and ^{1}H NMR spectroscopy. The comparative analysis of the ^{1}H NMR spectrum of **9c** from its analogues **9a,b** specifies a shift of the position of aliphatic groups and imidazole ring.

It is necessary to point out, that substances **9c,b** are low temperature crystalline products and so is even the initial **9a**. Changing the methylenenitrile for a propylenenitrile fragment did not essentially influence the yields of products **10b,c**. ^{1}H NMR-spectra of structurally simple salts **10b,10c** were not considerably different from those of **10a**, either (see experimental part). A small difference position of carbonitrile group in IR-spectrum was observed: for **10a** at 2249 cm^{-1}, for **10b** at 2259 cm^{-1} and for **10c** at 2258cm^{-1}. These data in the combination with maximums at 1168 (Cl), 822 (P-F), 1037 (B-F) confirmed the structures of products. The discussed data are supplemented by the results of the elemental analysis.

2.2. Catalytic reaction of N-substituted isatine with methyl acrylate

We therefore focused our attention on preparing a novel catalytic system. We believed that we could increase the activity of DMAP by the application of nitrile-functionalized imidazolinum ionic liquid. Consideration of the transition state suggests that any cocatalyst must be capable of simultaneous associating, and hence, stabilizing both the enolate oxygen arising from the adduct formed between methyl acrylate and DMAP and the partial δ^- charge located on the carbonyl oxygen atom. The nitrile-functionalized imidazolinum ionic liquid has anion-cation aggregates due to the electron-withdrawing effect of the CN group, which makes the aliphatic hydrogen atoms more acidic so that hydrogen bonding between the cation and anion is enhanced, and/or head-to-tail interaction of the CN group with the target atoms is increased.

That is why a new cocatalyst design was generated by placing two CN groups at the locations required to recognize the two oxygen atoms in the intermediate, like **4** (see scheme 1).



11a-h **12a-h** **13**

Ionic Liquids = **9a, 9b, 9c, 10a, 10b, 10c**

a) R^1=H, R^2=-Et; **b**) R^1=H, R^2=-C_3H_7; **c**) R^1=H, R^2=-CH_2CH=CCl-Me;
d) R^1=H, R^2=-CH_2-CH=CH_2; **e**) R^1=-Me, R^2=-CH_2-CH=CH_2;
f) R^1=H, R^2=-CH_2-CCH; **g**) R^1=H, R^2=CH_2-C_6H_5; **h**) R^1=H, R^2=-C_4H_9

Scheme 5

The ability of the six catalysts **9a,b,c** and **10a,b,c** to accelerate the reaction between the methyl acrylate and isatine **11a** was assessed using a standard set of reaction conditions - in the absence of solvent. However, in all cases it resulted in near-quantitative recovery of starting materials. After that a number of mixtures from our ionic liquids and DMAP have been prepared. For each of the six cocatalysts **9a,b,c** and **10a,b,c**, five different cocatalyst loadings were investigated – 2 mol %, 4 mol %, 6 mol %, 8 mol % or 10 mol %. The ratio of isatines to DMAP was held constant and was always 1.0: 0.5. The reaction mixture contained 1.5 equiv of methyl acrylate and 1.0 equiv **11a**.

The progress of the reaction was monitored by TLC over a period of several days, during which the formation of a polar, colorless product and the solubilisation of isatin were observed.

We found that the highest selectivity was obtained at room temperature via mixing isatin **11a**, methyl acrylate, DMAP and salt **10a** in molar ratios of 1: 1.56: 0.5: 0.06. The alcohol **12a** (yield 84 %) appeared as the main product. As expected the reactions proceed smoothly to give target product, indicating that the self-aldol reaction of isatine was avoided. Its IR-spectrum contains absorption bands characteristic of a carbonyl bond at 1700 cm^{-1} and hydroxy group at 1040, 3340 cm^{-1}. In the ^{1}H NMR spectrum of this compound three-proton signals of both methyl groups are presented at 1.16 ppm and 3.46 ppm., two-proton signals of the methylene group at 3.63-3.73 ppm and vinylic protons at 6.46 ppm. In the highest and medium fields of its ^{13}C NMR spectrum, the signals of eleven carbon atoms (see experiment) are supplemented by three signals in the lowest field at 172.30, 164.25 and 144.85 ppm. These data, in combination with the data of elemental analysis specify the structure **12a**. If the condensation is carried out by using chloride **9a**, the reaction product is also the allylic alcohol **12a**, however the yield decreases to 7 %.

We also examined the catalytic activity of hexafluorophosphates **9b** and **10b**. In the reaction catalyzed by **10b**, the highest yield of **12a** (up to 89 %) was achieved. Then, we have tested the influence of **9c, 10c** on the interaction between **11a** and methyl acrylate. The highest yield 77 % was registered in the case of using **10c**.

The relationship between the nature of anion/cation and optimal yield of the allylic alcohols **12a-h** is depicted in table 1.

These results suggests that small changes in structure of the cocatalyst cause a drastic change in the yield of 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-indolyl)acrylates. The difference in activity between **9a,9b,9c** or **10a,10b,10c** is intriguing. Despite their structural similarities, in most experiments, cocatalysts **10a,10b,10c** outperforms cocatalysts **9a,9b,9c** significantly. The difference in activity can be found by the examination of the sizes of the side chain to each cocatalyst. This change in size imposed by the cocatalyst in order to satisfy the steric and electronic requirements of binding results in an increase stabilizing both the enolate oxygen arising from the adduct formed between methyl acrylate and DMAP resulting in the highest activity. It should be mentioned that there was no relation between the nature of alkyl substitution of isatine on yield as well as time reaction. As shown in table, hindered substituted isatines are effective generating of 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-indolyl)acrylate.

The reason for positive effects of the mixture DMAP-imidazolium ionic liquid is not yet clear. Nevertheless, introduction of imidazolium ionic liquid suppresses undesired direction of reaction. It is necessary to point out, that in the absence of at least one of the components reactions do not take place. We believed that use the nitrile-functionalized imidazolinum ionic liquid helped to form the complex DMAP-ionic liquid. This substance promoted conjugate addition by binding to the zwitterionic enolate and stabilizing these intermediates as well. This chemical phenomenon was brought to our attention by the following observation: although an excess of imidazolium ionic liquid up to 10 mol % is in general required for efficient reactions, in all case 6 mol % of ionic liquid is sufficient. Additionally, the observed experimental results suggest that hexafluorophosphates **9b,10b** were more active in most reactions. However, the undesired cocatalyst exchange clearly becomes uncompetitive and is therefore avoided. For example, even using unmodified **9a** gives high selectivity for **12g**.

3. Conclusion

In conclusion, we have developed a concise and efficient protocol for the preparation of methyl 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylates from various isatines with methyl acrylate catalyzed by mixture DMAP-nitrile-functionalized imidazolinum ionic liquid. As discussed above, mechanistic studies of DMAP-nitrile-functionalized imidazolinum ionic liquid-catalyzed the Morita-Baylis-Hillman reaction, have revealed that catalytic system promoted the addition of the activated enone to isatine and, at the same time, shows capable of stabilizing both the enolate oxygen arising from the adduct and the partial δ^{-} charge located on the C-3 carbonyl atom of isatine, and finally proton transferring in the rate determining step. The catalytic system discovered so far are applicable only to reactions that proceed in the presence of nitrile-functionalized imidazolinum ionic liquid.

This catalytic methodology is height attractive and provides a valuable choice for the organic synthesis. Is it possible to develop asymmetric complexes that promote a variety of reactions in highly enantioselective manner? Such reactions might include, for example, the asymmetric addition of the catalyst-activated enone to carbonyl followed proton transfer by use the chiral hydroxy-functionalized imidazolinum ionic liquid according scheme 1.

The research of the enantiospecific variant of the MBH reaction is being carried out in our laboratory.

Table 1

Morita-Baylis-Hillman reactions of N-substituted isatines with the methyl acrylate

Product	Co-Catalist	Time, min	Yield, %
12a	**9a**	90	85
	9b	75	84
	9c	75	70
	10a	60	84
	10b	30	89
	10c	30	77
12b	**9a**	90	48
	9b	150	55
	9c	150	61
	10a	75	86
	10b	75	82
	10c	75	83
12c	**9a**	270	82
	9b	255	87
	9c	240	82
	10a	120	84
	10b	90	98
	10c	60	86
12d	**9a**	60	81
	9b	120	87
	9c	120	80
	10a	50	80
	10b	40	84
	10c	40	75
12e	**9a**	210	79
	9b	210	81
	9c	210	78
	10a	120	80
	10b	120	81
	10c	120	82
12f	**9a**	260	87
	9b	290	86
	9c	260	84
	10a	90	95
	10b	90	88
	10c	90	93
12g	**9a**	90	96
	9b	90	85
	9c	90	78
	10a	90	86
	10b	90	82
	10c	90	77
12h	**9a**	120	86
	9b	240	93
	9c	240	89
	10a	240	63
	10b	240	75
	10c	120	79

4. Experimental methods

All used solvents were of reagent quality, and all commercial reagents were used without additional purification. Removal of all solvents was carried out under reduced pressure. Analytical TLC plates were Silufol® UV-254 (Silpearl on aluminium foil, Czecho-Slovakia). IR spectra were recorded on a Spectrum 100 FT-IR spectrophotometer (Perkin –Elmer) using the universal ATR sampling accessory. ^{1}H and ^{13}C NMR spectra have been recorded for $(CD_3)_2SO$ 2-% solution on a “Bruker -Avance III” (400.13 and 100.61 MHz) and “Bruker AC-80” (80 and 20 MHz).

2-(1*H*-1-Imidazolyl)ethilcarbonitrile 8 has been prepared according to the known procedure [25].

Synthesis of the 1-(2-cyanoethyl)-3-cyanomethyl-1*H*-imidazol-3-ium chloride 9a.

2-chloroacetonitrile (2.20 g, 0.035 mol) was added dropwise to a solution of **8** (4.2 g (0.035 mol) in 15 ml acetone. The reaction mixture was stirred for 6 hours. Solvent was removed in vacuum, followed by crystallization from EtOH to give 4.5 g of **9a**. Yield: 66%. M.p. 122-123^{0}C. IR (ν/cm^{-1}): 620 (Cl), 740, 1455, 1570 (CH=CH), 2250 (CN), 2800 (CH$_2$). ^{1}H NMR (80 MHz, δ, ppm, *J*/Hz): 3.33 t (2H, ^{5}CH$_2$, *J*=6.48), 4.58 t (2H, ^{4}CH$_2$, *J*=6.48), 5.75 s (2H, ^{7}CH$_2$), 7.99, 8.04, 9.58 s, s, s, (3H, imidazol). ^{13}C NMR (20 MHz, ppm): 132.71 (^{1}C), 120.12 (^{3}C), 118.01 (^{8}C), 117.81 (^{2}C), 116.19 (^{6}C), 43.16 (^{4}C), 42.92 (^{7}C), 20.11 (^{5}C). Found,%: C 48.12, H 4.44, N 29.01. $C_8H_9ClN_4$. Requires, % C 48.87, H 4.61, N 28.49.

Synthesis of the 1-(2-cyanoethyl)-3-cyanomethyl-1*H*-imidazol-3-ium hexafluorophosphate 9b.

KPF$_6$ (0.74 g, 0.0041 mol) was added to a solution of chloride **9a** (0.8 g, 0.0041 mol) in acetone (10 ml). The reaction mixture was stirred for 70 hours. Solids were filtered, and the solvent was removed to give 1.12 g of **9b**. Yield: 93%. M.p. 84-85^{0}C (EtOH). IR (ν/cm^{-1}): 740, 2090 (CH=CH), 822 (PF$_6$), 2250 (CN), 2800 (CH$_2$). ^{1}H NMR (80 MHz, δ, ppm, *J*/Hz): 3.28 t (2H, ^{5}CH$_2$, *J*=6.0), 4.56 t (2H, ^{4}CH$_2$, *J*=6.0), 5.62 s (2H, ^{7}CH$_2$), 7.92, 7.95, 9.37 s, s, s, (3H, imidazol). ^{13}C NMR (20 MHz, ppm): 132.14 (^{1}C), 121.16 (^{3}C), 119.42 (^{8}C), 117.14 (^{2}C), 116.90 (^{6}C), 45.12 (^{4}C), 43.91 (^{7}C), 21.16 (^{5}C). Found, %: C 31.14, H 3.12, N 18.65. $C_8H_9F_6N_4P$. Requires, %: C 31.39, H 2.96, N 18.30.

Synthesis of the 1-(2-cyanoethyl)-3-cyanomethyl-1*H*-imidazol-3-ium tetrafluoroborate 9c.

Chloride **9a** (0.8 g, 0.0041 mol) has reacted with KBF$_4$ (0.51 g, 0.0041) according to the procedure described for the preparation of **9b** to give **9c** (0.98 g) as a yellow oil. Yield: 97%. IR (ν/cm^{-1}): 740, 2090 (CH=CH), 1037 (BF$_4$), 2250(CN), 2800 (CH$_2$). ^{1}H NMR (80 MHz, δ, ppm, *J*/Hz): 3.20 t (2H, ^{5}CH$_2$, *J*=6.0), 4.52 t (2H, ^{4}CH$_2$, *J*=6.0), 5.53 s (2H, ^{7}CH$_2$), 7.75, 7.78, 9.24 s, s, s, (3H, imidazol). ^{13}C NMR (20 MHz, ppm): 133.15 (^{1}C), 121.70 (^{3}C), 118.16 (^{8}C), 116.72 (^{2}C), 116.03 (^{6}C), 44.11 (^{4}C), 43.13 (^{7}C), 20.99 (^{5}C). Found, %: C 38.12, H 3.54, N 23.02. $C_8H_9BF_4N_4$. Requires, %: C 38.75, H 3.66, N 22.59.

Synthesis of the 1,3-di(2-cyanoethyl)-1*H*-imidazol-3-ium chloride 10a.

Product **10a** (6.3 g) was prepared from **8** (4.1 g, 0.034 mol) and 3-chloropropanenitrile (2.7 ml, 0.034 mol) by the same procedure as for the preparation of **9a** for 10 hours. Yield: 88%. IR (ν/cm^{-1}): 770 (Cl), 1453, 1571 (CH=CH), 2249 (CN), 2945 (CH$_2$) 1639, 2469, 2489, 2500 (=N^{+}-). ^{1}H NMR (80 MHz, δ, ppm, *J*/Hz): 3.22 (t, 4H, ^{5}CH$_2$, ^{8}CH$_2$, J=6.4), 4.56 (t, 4H, ^{4}CH$_2$, ^{7}CH$_2$, J=6.4), 7.64, 7.85, 9.20 (s, s, s, 3H, imidazol). ^{13}C NMR (20 MHz, ppm): 140.16 (^{1}C), 124.02 (^{3}C), 121.35 (^{2}C), 115.93 (^{9}C), 115.63 (^{6}C), 48.03 (^{4}C), 40.21 (^{7}C), 17.29 (^{5}C), 10.93 (^{8}C). Found, %: C 51.12, H 5.03, N 26.90. $C_9H_{11}ClN_4$. Requires, %: C 51.31, H 5.26, N 26.60.

Synthesis of the 1,3-di(2-cyanoethyl)-1*H*-imidazol-3-ium hexafluorophosphate 10b.

Product **10b** was prepared from **10a** and KPF$_6$ by the same procedure as for the preparation of **9b**. Yield: 97%. IR (ν/cm^{-1}): 822 (PF$_6$), 1450, 1561, 3170 (CH=CH), 2259 (CN), 2988 (CH$_2$), 3336 (-NH=). ^{1}H NMR (80 MHz, δ, ppm, *J*/Hz): 3.14 t (4H, ^{5}CH$_2$, ^{8}CH$_2$, *J*=6.4), 4.50 t (4H, ^{4}CH$_2$, ^{7}CH$_2$, *J*=6.4), 7.61, 7.74, 9.07 s, s, s, (3H, imidazol). ^{13}C NMR (20 MHz, ppm): 136.14 (^{1}C), 122.79 (^{3}C), 120.92 (^{2}C), 115.99 (^{9}C), 115.42 (^{6}C), 48.12 (^{4}C), 45.42 (^{7}C), 17.52 (^{5}C), 10.93 (^{8}C). Found, %: C 33.64, H 3.79, N 17.53. $C_9H_{11}FN_4P$. Requires, %: C 33.76, H 3.46, N 17.50.

Synthesis of the 1,3-di(2-cyanoethyl)-1*H*-imidazol-3-ium tetrafluoroborate 10c.

Product **10c** was prepared from **10a** and KBF$_4$ by the same procedure as for the preparation of **9c**. Yield: 98%. IR (ν/cm^{-1}): 1037 (BF$_4$), 1453, 1576, 3169 (CH=CH), 2258 (CN), 756, 2988 (CH$_2$). ^{1}H NMR (80 MHz, δ, ppm, *J*/Hz): 3.14

t (4H, $^{5}CH_2$, $^{8}CH_2$, *J*=6.4), 4.50 t (4H, $^{4}CH_2$, $^{7}CH_2$, *J*=6.4), 7.62, 7.74, 9.08 s, s, s, (3H, imidazol). ^{13}C NMR (20 MHz, ppm): 139.98 (^{1}C), 123.16 (^{3}C), 122.00 (^{2}C), 116.04 (^{9}C), 115.90 (^{6}C), 47.92 (^{4}C), 41.19 (^{7}C), 17.14 (^{5}C), 11.12 (^{8}C). Found, %: C 41.38, H 4.63, N 20.68. $C_9H_{11}BF_4N_4$. Requires, %: C 41.26, H 4.23, N 21.38.

Isatines 11a-h have been prepared according to the known procedure [33].

Preparation of methyl 2-(3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylates. General procedure.

To a mixture of 0.37 g (0.0042 mol) of methyl acrylate, 0.17g (0.0014 mol) of DMAP and (0.0028 mol) of an appropriate N-substituted isatine was added ionic liquid (0.00017 mol). The reaction mixture was stirred at room temperature. On completion of the reaction (TLC moniroring by C_6H_6/acetone : 4/1) the mixture was dispered in 5% HCl, the residue was filtered off and washed with H_2O. A sample was recrystallized for the analysis from appropriate solvent.

The methyl 2-(1-ethyl-3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylate 12a.

M.p. 175-176^{0}C (EtOH). IR (ν/cm^{-1}): 730, 745 (CH-Ar), 795 (C_2H_5), 940, 2975 (C=CH_2), 1040, 3340 (OH), 1020, 1715 (CO_2CH_3), 1695 (N-C=O). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 1.16 t (3H, $^{14}CH_3$, *J*=6.8), 3.46 s (3H, $^{11}CH_3$), 3.63-3.73 m (2H, $^{13}CH_2$), 6.46 d (2H, $^{12}CH_2$, *J*=10.4), 6.56 s (1H, OH), 6.92-7.29 m (4H, Ar). ^{13}C NMR (100 MHz, ppm): 172.30 (^{7}C), 164.25 (^{10}C), 144.85 (^{2}C), 144.60 (^{9}C), 126.85 (^{6}C), 123.01 (^{12}C), 120 (^{1}C), 118.03 (^{3}C), 115.92 (^{5}C), 110.73 (^{4}C), 85.32 (^{8}C), 54.23 (^{11}C), 38.16 (^{13}C), 12.63 (^{14}C). Found, %: C 31.14, H 3.12, N 18.65. $C_{14}H_{15}NO_4$. Requires, %: C 64.36, H 5.79, N 5.36.

The methyl 2-(3-hydroxy-2-oxo-1-propyl-2,3-dihydro-1*H*-3-indolyl)acrylate 12b.

M.p. 176-177^{0}C (EtOH). IR (ν/cm^{-1}): 750, 760 (CH-Ar), 950 (C=CH_2), 805 (C_3H_7), 1050, 3340 (OH), 1170 (CO_2CH_3), 1695(N-C=O). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 0.93 t (3H, $^{15}CH_3$, *J*=7.2), 1.59-1.64 m (2H, $^{14}CH_2$), 3.46 s (3H, $^{11}CH_3$), 3.56-3.61 m (2H, $^{13}CH_2$), 6.46 d (2H, $^{12}CH_2$, *J*=10.8), 6.55 s (1H, OH), 6.93-7.28 m (4H, Ar). ^{13}C NMR (100 MHz, ppm): 171.53 (^{7}C), 164.25 (^{10}C), 148.15 (^{2}C), 143.20 (^{9}C), 128.40 (^{6}C), 123.80 (^{12}C), 121.95 (^{1}C), 119.12 (^{3}C), 116.45 (^{5}C), 115.02 (^{4}C), 87.36 (^{8}C), 51.32 (^{11}C), 46.42 (^{13}C), 22.05 (^{14}C), 12.05 (^{15}C). Found, %: C 65.38, H 6.29, N 5.12. $C_{15}H_{17}NO_4$. Requires, %: C 65.44, H 6.22, N 5.09.

The methyl 2-[1-(3-chloro-2-butenyl)-3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl]acrylate 12c.

M.p. 150-151^{0}C (C_6H_6). IR (ν/cm^{-1}): 740 (CH-Ar), 750(Cl), 960 (C=CH_2), 1160 (CO_2CH_3), 1700 (N-C=O), 3350 (OH). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 1.91 s (3H, $^{16}CH_3$), 3.25 s (3H, $^{11}CH_3$), 4.15 d (2H, $^{13}CH_2$, *J*=5.6), 5.41 t (1H, ^{14}CH, *J*=5.6), 6.25 d (2H, $^{12}CH_2$, *J*=10.8), 6.42 s (1H, OH), 6.65-7.07 m (4H, Ar). ^{13}C NMR (100 MHz, ppm): 165.65 (^{7}C), 160.52 (^{10}C), 145.02 (^{2}C), 142.48 (^{9}C), 134.50 (^{15}C), 126.72 (^{6}C), 122.97 (^{12}C), 121.32(^{14}C), 120.92 (^{1}C), 119.03 (^{3}C), 118.93 (^{5}C), 115.64 (^{4}C), 88.17 (^{8}C), 52.4 (^{11}C), 41.07 (^{13}C), 27.09 (^{16}C). Found, %: C 60.10, H 5.17, N 4.19. $C_{16}H_{16}ClNO_4$. Requires, %: C 59.73, H 5.01, N 4.35.

The methyl 2-(1-allyl-3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylate 12d.

M.p. 176-177^{0}C (C_6H_6). IR (ν/cm^{-1}): 760 (CH-Ar), 960, 3050 (C=CH_2), 1170, 1200 (CO_2CH_3), 1055, 3320 (OH), 1700 (N-C=O). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 3.46 (s, 3H, $^{11}CH_3$), 4.25-4.29 (m, 2H, $^{13}CH_2$), 5.17-5.39 (m, 2H, $^{15}CH_2$), 5.80-5.84 (m, 1H, ^{14}CH), 6.49(d, 2H, $^{12}CH_2$, J=0.8), 6.63 (s, 1H, OH), 6.89-7.02 (m, 4H, Ar). ^{13}C NMR (100 MHz, ppm): 172.60 (^{7}C), 165.54 (^{10}C), 145.90 (^{2}C), 144.95 (^{9}C), 130.01 (^{14}C), 128.02 (^{6}C), 126.17 (^{12}C), 125.31 (^{15}C), 120.91 (^{1}C), 120.14 (^{3}C), 119.03 (^{5}C), 116.92 (^{4}C), 88.12 (^{8}C), 54.72 (^{11}C), 52.16 (^{13}C). Found, %: C 66.14, H 5.81, N 5.02. $C_{15}H_{15}NO_4$. Requires, %: C 65.93, H 5.53, N 5.13.

The methyl 2-(1-allyl-3-hydroxy-5-methyl-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylate 12e.

M.p. 152-153^{0}C (EtOH). IR (ν/cm^{-1}): 750 (CH-Ar), 950, 3050 (C=CH_2), 1160, 1190, 1200, 1370 (CO_2CH_3), 1700(N-C=O), 1050, 3340 (OH). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 2.21 s (3H, CH_3), 3.48 s (3H, $^{11}CH_3$), 4.22-4.26 m (2H, $^{13}CH_2$), 5.17-5.38 m (2H, $^{15}CH_2$), 5.78-5.85 m (1H, ^{14}CH), 6.49 d (2H, $^{12}CH_2$, *J*=0.8), 6.57 s (1H, OH), 6.77-7.06 m (3H, Ar). ^{13}C NMR (100 MHz, ppm): 173.15 (^{7}C), 169.12 (^{10}C), 149.70 (^{2}C), 144.79 (^{9}C), 130.91 (^{14}C), 127.03 (^{3}C), 125.14(^{6}C), 124.01 (^{12}C), 123.11 (^{15}C), 120.73 (^{1}C), 116.18 (^{5}C), 112.3 (^{4}C), 86.32 (^{8}C), 52.10 (^{11}C), 49.15 (^{13}C), 22.71(^{16}C). Found, %: C 66.01, H 5.14, N 5.51. $C_{16}H_{17}NO_4$. Requires, % C 66.89, H 5.96, N 4.88.

The methyl 2-[3-hydroxy-2-oxo-1-(2-propynyl)-2,3-dihydro-1*H*-3-indolyl]acrylate 12f.

M.p. 169-170^{0}C (EtOH). IR (ν/cm^{-1}): 760 (CH-Ar), 970 (C=CH$_2$), 1170, 1390 (CO$_2$CH$_3$), 1700(N-C=O), 2140 (-C≡CH), 1040, 3290 (OH). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 3.28 s (1H, ^{15}CH), 3.46 s (3H, ^{11}CH$_3$), 4.49-4.51 m (2H, ^{13}CH$_2$), 6.47 d (2H, ^{12}CH$_2$, *J*=16), 6.70 s (1H, OH), 6.99-7.35 m (4H, Ar). ^{13}C NMR (100 MHz, ppm): 170.51 (^{7}C), 164.12 (^{10}C), 145.00 (^{2}C), 144.89 (^{9}C), 128.92 (^{6}C), 124.18 (^{12}C), 121.43 (^{1}C), 119.62 (^{3}C), 118.04 (^{5}C), 116.72 (^{4}C), 93.15 (^{8}C), 79.34 (^{14}C), 74.12 (^{15}C), 52.42 (^{11}C), 34.61 (^{13}C). Found, %: C 66.95, H 5.12, N 5.21. $C_{15}H_{13}NO_4$. Requires, %: C 66.42, H 4.83, N 5.16.

The methyl 2-(1-benzyl-3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylate 12g.

M.p. 199-200^{0}C (EtOH). IR (ν/cm^{-1}): 750, 1100 (CH-Ar), 960 (C=CH$_2$), 1175 (CO$_2$CH$_3$), 1650 (N-C=O), 1050, 3300 (OH). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 3.51 s (3H, ^{11}CH), 4.90 s (2H, ^{13}CH$_2$), 6.59 d (2H, ^{12}CH$_2$, *J*=8), 6.66 s (1H, OH), 6.91-7.40 m (9H, Ar). ^{13}C NMR (100 MHz, ppm): 170.72 (^{7}C), 162.83 (^{10}C), 146.08 (^{2}C), 145.00 (^{9}C), 136.17 (^{14}C), 129.98 (^{6}C), 129.63 (^{15}C, ^{18}C), 125.02 (^{17}C), 123.14 (^{12}C), 122.84 (^{16}C, ^{19}C), 122.01 (^{3}C), 120.01 (^{1}C), 119.16 (^{5}C), 116.72 (^{4}C), 80.94 (^{8}C), 54.42 (^{11}C), 50.19(^{13}C). Found, %: C 70.04, H 5.26, N 4.53. $C_{19}H_{17}NO_4$. Requires, %: C 70.58, H 5.30, N 4.33.

The methyl 2-(1-butyl-3-hydroxy-2-oxo-2,3-dihydro-1*H*-3-indolyl)acrylate 12h.

M.p. 124-125^{0}C (C_6H_6). IR (ν/cm^{-1}): 750 (CH-Ar), 950 (C=CH$_2$), 1050, 3360 (OH), 1170, 1200 (CO$_2$CH$_3$), 1370 (C_4H_9), 1700 (N-C=O). ^{1}H NMR (400 MHz, δ, ppm, *J*/Hz): 0.91 t (3H, ^{16}CH$_3$, *J*=7.2), 1.34-1.39 m (2H, ^{14}CH$_2$), 1.55-1.60 m (2H, ^{15}CH$_2$), 3.46 s (3H, ^{11}CH), 3.59-3.64 m (2H, ^{13}CH$_2$), 6.46 d (2H, ^{12}CH$_2$, *J*=11.6), 6.55 s (1H, OH), 6.93-7.27 m (9H, Ar). ^{13}C NMR (100 MHz, ppm): 175.92 (^{7}C), 168.13 (^{10}C), 148.44 (^{2}C), 146.30 (^{9}C), 130.18 (^{6}C), 128.15 (^{12}C), 123.74 (^{1}C), 120.74 (^{3}C), 117.75 (^{5}C), 15.61 (^{4}C), 88.94 (^{8}C), 55.31 (^{11}C), 50.30 (^{13}C), 35.60 (^{14}C), 24.03 (^{15}C), 14.06 (^{16}C). Found,%: C 65.95, H 6.67, N 4.92. $C_{16}H_{19}NO_4$. Requires, %: C 66.42, H 6.62, N 4.84.

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SYNTHESYS OF A FUNCTIONALIZED FURAN FRAGMENT THROUGH BROMINATION-CYCLIZATION OF A CONJUGATED DIENE

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Abstract: This paper describes the use of a terpenic model substrate to conjugate 1,4-additions of N-bromosuccinimide (NBS) to a diene system possessing a suitable oxygen functionality. The reaction leads to functionalized tetrahydrofuran derivatives, which can be developed further into different synthetic targets, such as polyethers, which are known to possess diverse biological activity.

Keywords: Terpenoids, furans, NBS, conjugate addition.

Introduction

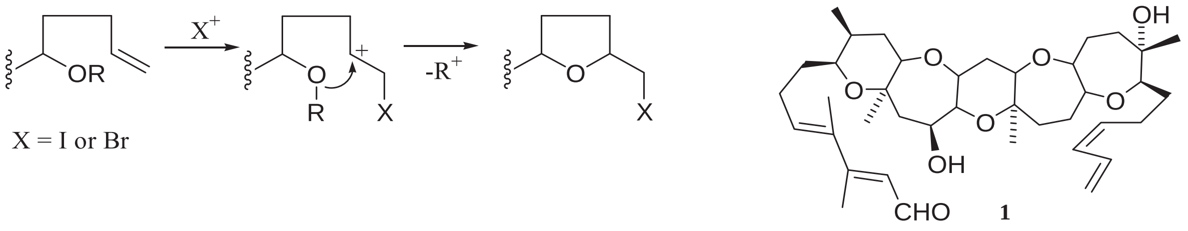
Polyethers are widespread in natural sources and are known for biological activity related to their metal complexation capability [1]. Many groups of natural products, such as *C*-nucleosides, acetogenins, brevetoxins, and ionophore antibiotics, have oxygen heterocycles incorporated into their structure. The presence of such functionalities helps to determine the bioactivity of the compound. The limited availability from renewable raw material has led to the elaboration of different synthetic tools to access cyclic ethers of different ring size [2]. Specific ring functionalization is often a requirement for the biological activity of target structures and their elaboration requires manipulation of complex synthetic intermediates. In this paper we describe a method for the synthesis of functionalized cyclic ether moieties using a common terpene as a model compound.

Results and discussion

The range of synthetic procedures used to access functionalized *O*-heterocycles is quite broad. The most general approach is based on a biomimetic strategies and includes two successive operations:

1) assembling a structural fragment comprised of an olefinic double bond and a hydroxyl group in neighboring positions;
2) a C-O cyclizaton reaction initiated by different electrophilic, nucleophilic or radical agents [2].

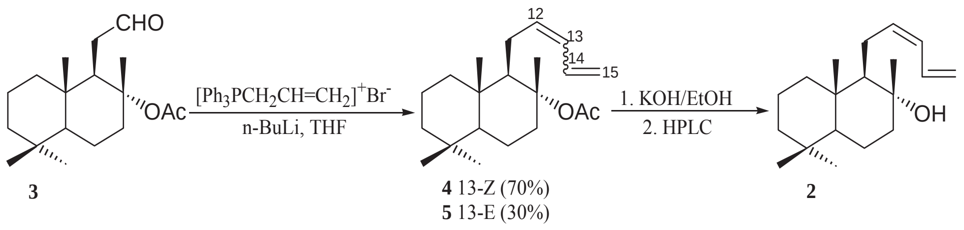
Halo-etherification reactions are of special interest in this context, since they allow both cyclization and incorporation of a halogen atom in the cyclic structure. The halogen atom can subsequently be utilized as a synthetic handle. Normally, addition of the halogen occurs in a 1,2-fashion, and the generated carbocation cyclizes with a neighboring oxygen functionality to provide the corresponding cyclic ether (Scheme 1). This strategy works well for the synthesis of furan ring systems [2].



1

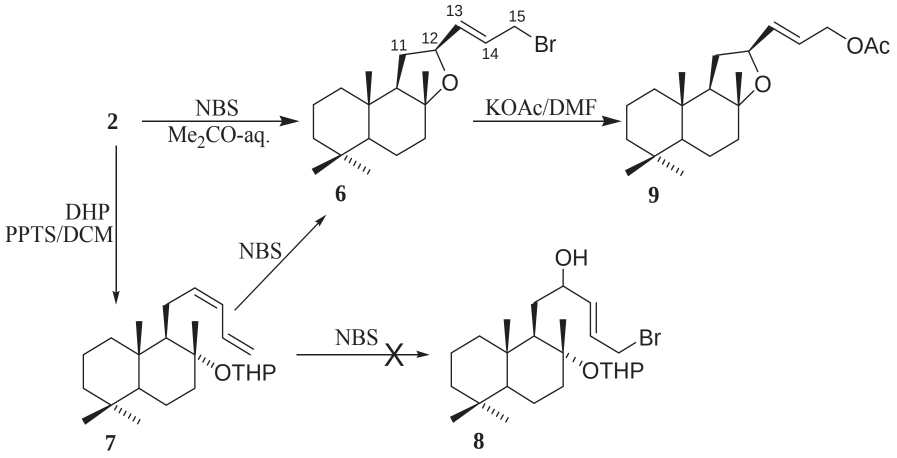
Scheme 1

Our recent research in the field of brevenal (a polyether compound isolated from laboratory cultures of the marine dinoflagellate *Karenia brevis* [2]) structure-activity relationships has required a synthetic method for the selective functionalization of the diene system in brevenal **1**. Due to the limited availability of the natural brevenal **1**, we decided to design a simpler model compound **2** to mimic the conjugated double bond system of **1**. The synthesis of olefin **2** is presented in Scheme 2. The bicyclic **2** possesses two of the structural features of brevenal: a conjugated double bond in an equatorial position and a tertiary hydroxyl group. It is known that isoprenoid polycycles are used successfully as models to demonstrate the biogenetic origin of marine polyether toxins [4].



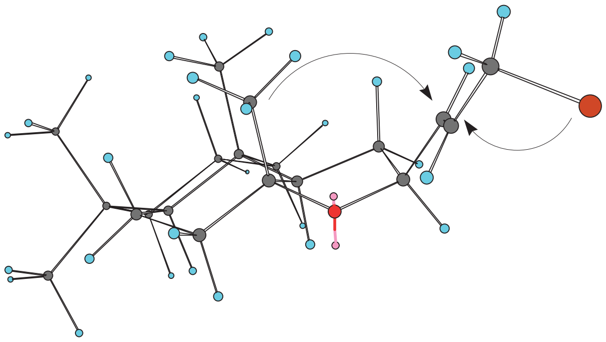
Scheme 2

The efficient functionalization of γ-pyronene using NBS has previously been described [5]. Since model compound **2** contains a similar conjugated fragment, it was expected that the reaction with NBS would lead to the addition of a bromonium ion to the more electron rich terminal double bond. The allylic stabilization of the formed carbonium ion was expected to provide a partial positive charge on the C12 carbon atom, which could then be cyclized efficiently through the hydroxyl group from the γ-position. This hypothesis was confirmed and the substrate **2** generated the allylic bromide **6** almost quantitatively (Scheme 3) under standard conditions (NBS, acetone-water, 0°C).



Scheme 3

The structure of **6** was elucidated on the basis of both spectroscopic data and subsequent chemical transformations. Attempts to oxidize **6** with MnO_2 proved unsuccessful, which verified the absence of the secondary hydroxyl group of a hypothetical bromohydrin of type **8**. It was also impossible to epoxidize **6** with *m*-CPBA under standard conditions. Such behavior normally is observed in the case of low electron density around the target double bond or as a consequence of steric hindrance. Examining the molecular models strongly supports a steric hindrance assumption. The optimized conformation of **6**, presented in the figure below, shows significant shielding of the double bond by the methyl group at C8 and the bromine atom. This model also provides the relative stereochemistry around the C12 chiral center, which was confirmed by a NOESY experiment.



Scheme 4

Surprisingly, the same bromide **6** was obtained on the reaction of THP-protected substrate **7** with DHP [6,7]. Contrary to our expectations, the THP-protection was not stable under the reaction conditions and the reaction did not proceed with the formation of the corresponding bromohydrin **8**.

Ultimately, the utility of the allylic bromide **6** for further functionalization was checked by its transformation to the corresponding acetate **9** on treatment with potassium acetate in DMF at room temperature [8].

In summary, an alternative method for the syntheses of tetrahydrofuran cyclic compounds has been demonstrated. The procedure, based on a tandem conjugate addition - cyclization reaction provides the desired heterocyclic compound, having a lateral chain for further functionalization, with excellent yield. The practical utility and biological activity of the newly synthesized compounds is currently under investigation.

Acknowledgements: V.K acknowledges CRDF-MRDA for a travel grant MTFP-04-05.

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[6]. Diene **7**. The olefin **2** (27 mg, 0.1 mmol) was dissolved in 1 mL DCM and PPTS (2 mg, 0.008 mmol) was added to this solution with stirring at r.t. After dissolution of the solid material, 45 μL of DHP (41 mg, 0.5 mmol) were added to the reaction mixture and the stirring continued overnight. Usual workup gave the crude THP-derivative that was submitted to FC. Elution with 5% EtOAc in petroleum ether gave 29 mg (83%) of analytically homogeneous **13** as a diastereomeric mixture. ^{1}H NMR (ppm, in C_6D_6): 0.76 (s); 0.78 (s); 0.79 (s); 0.81 (s); 0.83 (s) – all 9H; 1.1 (s); 1.29 (s) – all 3H; 2.00 (m, 1H); 2.25 (m, 1H); 2.47 (m, 1H); 2.69 (m, 1H); 3.3-4.1 (m, 3H); 4.85-4.95 (m, 1H); 5.07 (d, 1H, J=10Hz); 5.15-5.25 (m, 1H); 5.65-5.80 (m, 1H); 6.03 (t, 1H, J=10Hz); 6.88-7.0 (m, 1H). IR (cm^{-1}): 1022; 1128; 1389; 1456; 2941.

[7]. Bromide **6**. To the solution of of the protected olefin **7** (28 mg, 0.077 mmol) in 1.2 mL acetone and 0.2 mL water, NBS (16.5 mg, 0.093 mmol) was added in one portion at 0°C. After 45 min. of stirring TLC showed complete consumption of starting material. Usual workup gave 27 mg of crude **6**, homogeneous by TLC. ^{1}H NMR (ppm): 0.68 (s, 3H); 0.77 (s, 3H); 0.81 (s, 3H); 1.05 (s, 3H); 1.55 (s. 3H); 1.93/1.95 (dt, 1H); 3.56 (d, 2H); 4.29 (q, 1H); 5.59/5.62 (dd, 1H); 5.75-5.815 (m, 1H). ^{13}CNMR (ppm): 16.09; 19.14; 21.43; 21.56; 25.02; 30.23; 32.84; 33.52; 34.01; 36.77; 40.49; 41.18; 43.06; 57.50; 61.38; 77.74; 81.27; 126.09; 139.44. IR (cm^{-1}): 735; 980; 1122; 1203; 1379; 1456; 1716; 2927.

[8]. Acetate **9**. The bromide **6** (73 mg, 0.17 mmol) was dissolved in 5.4 mL DMF and treated with freshly dried potassium acetate (324 mg, 3.3 mmol). Stirring the reaction mixture overnight at r.t. and usual workup gave the crude product. Elution with 15% EtOAc in petroleum ether gave 54 mg (95%) of analytically homogeneous **9**. ^{1}H NMR (ppm): 0.83 (s, 3H); 0.85 (s, 3H); 0.88 (s, 3H); 1.14 (s, 3H); 2.06 (s. 3H); 1.93/1.95 (dt, 1H); 3.56 (d, 2H); 4.29 (q, 1H); 5.59/5.62 (dd, 1H); 5.75-5.815 (m, 1H). ^{13}C NMR (ppm): 15.73; 18.59; 21.00; 21.17; 21.25; 24.65; 29.99; 33.29; 33.73; 36.51; 40.22; 40.44; 42.62; 57.29; 61.08; 64.62; 78.09; 81.22; 124.35; 138.02; 170.99. IR (cm^{-1}): 968; 1026; 1122; 1228; 1379; 1458; 1741; 2937.

O. Chetraru et al./Chem. J. Mold. 2010, 5 (1), 121-123

A RETRO-BIOMIMETIC ONE-STEP SYNTHESIS OF NATURAL ATISANIC AND BEYERANIC DITERPENOIDS

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Abstract: An efficient retro-biomimetic procedure for the synthesis of two natural products having atisanic and beyeranic structure is reported. The readily available *ent*-kaurenoic acid is used as the substrate, which provides under superacidic treatment a mixture of natural *ent*-beyer-15-en-19-oic and *ent*-atis-16-en-19-oic acids. These compounds have been reported as components of medicinal plants and possess relevant biological activity. Their structure was confirmed on the basis of chemical transformations and spectral data.

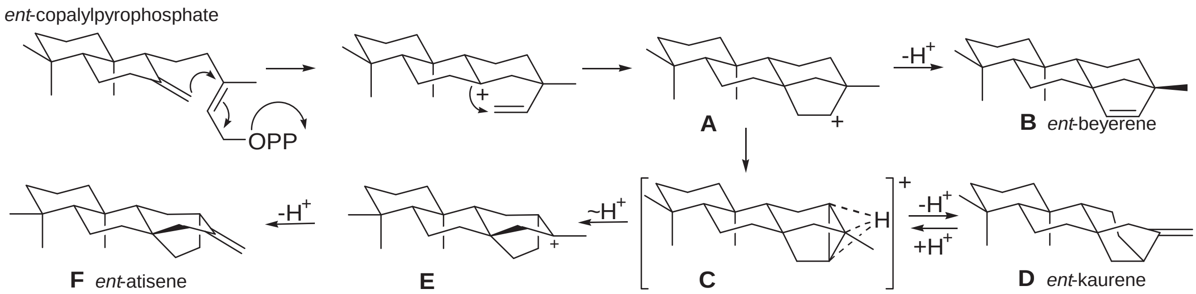
Keywords: Terpenoids, biomimetic synthesis, kaurane, atisane, beyerane.

1. Introduction

Diterpenoids represent a large family of natural products with a broad spectrum of biological activities. Continuous work on diterpenes reveal more and more representatives of this large group to possess interesting properties. Examples are the well known atisanic and beyeranic diterpenoids. They have been known since quite a long time, but their biological activity remained still unexplored. Only recent studies revealed quite surprising data. For example the *ent*-beyer-15-en-19-oic acid **1** isolated from the roots of the Mexican medicinal plant *Viguiera hypargyrea* showed antispasmodic and antimicrobial activity in low concentrations [1]. The related *ent*-atis-16-en-19-oic acids **2** was shown recently to be a oviposition stimulant for the banded sunflower moth, *Cochylis hospes* [2]. We present in the current communication our first results on the synthesis of natural acids **1** and **2**, basing on a one-step retro-biomimetic strategy.

2. Results and discussion

The beyeranic and atisanic diterpenoids posess a complex structure of condensed and bridged cyclic systems. Due to the complexity of these skeletons, total synthesis of these compounds proved to be quite difficult. In fact, there are only several publications relating on the total synthesis of beyeranes or atisanes. The synthetic strategies include multiple steps and the overall performance is relatively low [3, 4]. On the other hand, partial synthesis of atisanes and beyeranes have been reported, basing on biomimetic-like transformations of other available natural products like trachylobanic acid [5] or *iso*-steviol [6, 7]. These approaches proved to be more efficient, both from the point of view of length and overall yield. Basing on this conclusion, we have developed a semi-synthetic approach for the synthesis of above mentioned acids **1** and **2** starting from readily available [8] *ent*-kaurenoic acid **3**. This approach is very simple, and involves a single step transformation of the substrate to the target molecules.



Scheme 1

The transformation is a biomimetic, acid induced rearrangement of the *ent*-kauranic framework to atisane and beyerane compounds. More exactly, this is a retro-biomimetic procedure, since the beyeranic framework is regarded as biogenetical precursor for *ent*-kauranic compounds. This hypothesis [9] has been formulated on the basis of the known isoprenic rule and to the best of our knowledge was not turned down yet. Scheme 1 provides a general overview of this biogenetical scheme, and our primarily intention was to performe the retro-biomimetic transformation of kaurene D to beyerene B or atisene F (path D->C---B or F).

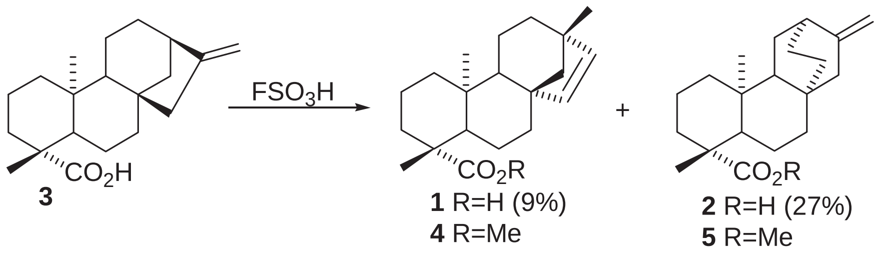
The rearrangements of *ent*-kauranic diterpenes has been reported under the action of different reagents [10]. Most of the examples relate on the reactions involving the formation of the non-classical carbocation of type C (Scheme 1). It is well known from the work of Olah, that superacids are better generators of these species and our own experience on the use of fluorosulfonic acid as an efficient promoter of terpenoids cyclization has provided a motivation to investigate the behavior of *ent*-kaurenic substrates under superacidic treatment. The mild reaction conditions (-78°C), as well as a moderate excess of the superacid can contribute to a sufficient lifetime of generated carbonium ions so that to assure the rearrangement of *ent*-kaurene skeleton in a more selective manner.

Submission of the substrate **3** to this reaction condition [12] has shown that isomerisation takes place smoothly, providing a basic product, having similar chromatographical behavior as starting material. Only a small fraction of more polar byproducts was detected. The reaction pathway proved to be not sensitive to reaction conditions variation (temperature, duration, quantity of superacid).

The basic reaction product, although chromatographically homogeneous, showed a complex NMR spectrum. Analysis of silver nitrate impregnated TLC plates revealed the presence of at least 3 components, which were tentatively separated by argentation column chromatography. One pure individual compounds was isolated and its structure was determined by extensive NMR studies. The determined structure corresponded to a atisane skeleton with the exocyclic double bond **2** [13].

The mixture of acids that was considered unresolved was further separated by semi-preparative HPLC, using a normal phase column. The major isolated compound was the starting *ent*-kaurenic acid **3** (19%). A minor amount (9%, on the basis of recovered **3**) of beyerane **1** [14] was also obtained. Both **1** and **2** were methylated with an ethereal solution of diazomethane, to provide individual methyl esters **4** [15] and **5** [16] respectively (Scheme 2). The analytical data of the acids **1** and **2**, as well as of the corresponding esters **5** and **6** matched perfectly the published data.

A minor fraction of the reaction product (cca. 30%) was eluted in the HPLC experiment unresolved. The posibility of isolation from this fraction of individual isomerisation compounds are currently under investigation.



Scheme 2

3. Conclusions

The direct, one step conversion of *ent*-kaurenoic acid **3** into atisanic and beyeranic acids **1** and **2** was performed under the action of fluorosulfonic acid.

4. Acknowledgements

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5. References and notes

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[12]. A solution of *ent*-kaurenoic acid **3** (403 mg, 1.324 mmol) in a mixture of *i*-PrNO$_2$ (2 ml) and DCM (9 ml), cooled at -70 °C, was treated with FSO$_3$H (662 mg, 6.623 mmol) in *i*-PrNO$_2$ (1.4 ml), under stirring. After 15 min., the reaction was stopped by adding a solution of Et$_3$N (4 ml) in light petroleum ether (4 ml). The usual work up gave

415 mg of a crude residue, which was submited to flash chromatography. Elution with a mixture of EtOAc in petroleum ether (2%) gave 298 mg (74%) of a TLC-homogenious reaction product.

[13]. *ent*-Atis-16-en-19-oic acid **2**. IR (neat): 2918, 1689, 1464, 1446, 1273, 1258 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$): δ = 4.73 (1H, bd, J=2Hz), 4.57 (1H, bd, J=2Hz), 2.22 (1H, bs), 2.15 (1H, bd, J=14Hz), 2.04 (1H, bd, J=17Hz), 1.29-2.00 (m, 19H), 1.25 (3H, s), 1.24 (3H, s), 0.91-1.18 (m, 8H), 0.90 (3H, s), 0.70-0.88 (m, 8H). ^{13}C NMR (100 MHz, CDCl$_3$): δ = 182.33 (s, C-19), 152.77 (s, C-15), 104.52 (t, C-17), 57.17 (d, C-5), 52.21 (d, C-9), 48.21 (t, C-16), 43.70 (s, C-4), 39.73 (t, C-1), 39.66 (t, C-7), 38.40 (s, C-10), 38.08 (t, C-3), 36.61 (d, C-12), 33.55 (s, C-8), 28.90 (q, C-18), 28.73 (t, C-14), 28.32 (t, C-13), 27.27 (t, C-11), 20.27 (t, C-6), 18.76 (t, C-2), 12.10 (q, C-20).

[14]. *ent*-Beyer-15-en-19-oic acid **1**. IR (neat): 2935, 1685, 1445, 1255, 1190 cm^{-1}. ^{1}H NMR (400 MHz, CDCl$_3$): δ = 5.76 (1H, d, J=5.7Hz), 5.47 (1H, d, J=5.7 Hz), 1.26 (3H, s), 1.01 (3H, s), 0.69 (3H, s). ^{13}C NMR (100 MHz, CDCl$_3$): δ = 184.3 (s, C-19), 136.5 (d, C-16), 134.8 (d, C-15), 61.1 (t, C-14), 57.2 (d, C-5), 52.4 (d, C-9), 49.2 (s, C-8), 43.9 (s, C-4), 43.7 (s, C-13), 39.6 (t, C-1), 38.0 (t, C-3), 37.7 (t, C-7), 37.7 (s, C-10), 33.2 (t, C-12), 29.1 (q, C-18), 24.9 (q, C-17), 21.6 (t, C-6), 20.5 (t, C-11), 19.3 (t, C-2), 13.8 (q, C-20).

[15]. Methyl-*ent*-beyer-15-en-19-oate **4**. ^{1}H NMR (400 MHz, CDCl$_3$): δ = 5.74 (1H, d, J=5.7Hz), 5.48 (1H, d, J=5.7 Hz), 3.60 (3H, s), 1.20 (3H, s), 1.02 (3H, s), 0.59 (3H, s). ^{13}C NMR (100 MHz, CDCl$_3$): δ = 178.08 (s, C-19), 134.77 (d, C-16), 136.52 (d, C-15), 61.09 (t, C-14), 57.15 (d, C-5), 51.09 (q, - CO$_2$Me), 52.32 (d, C-9), 49.16 (s, C-8), 43.66 (s, C-4), 43.66 (s, C-13), 39.59 (t, C-1), 38.23 (t, C-3), 37.67 (t, C-7), 37.76 (s, C-10), 33.15 (t, C-12), 28.97 (q, C-18), 24.87 (q, C-17), 21.67 (t, C-6), 20.46 (t, C-11), 19.33 (t, C-2), 13.64 (q, C-20).

[16]. Methyl-*ent*-atis-16-en-19-oate **5**. ^{1}H NMR (400 MHz, CDCl$_3$): δ = 4.74 (1H, bd, J=2Hz), 4.58 (1H, bd, J=2Hz), 3.66 (3H, s), 1.17 (3H, s), 0.81 (3H, s). ^{13}C NMR (100 MHz, CDCl$_3$): δ = 177.94 (s, C-19), 152.77 (s, C-15), 104.50 (t, C-17), 57.25 (d, C-5), 52.19 (d, C-9), 51.03 (q, -CO$_2$Me), 48.23 (t, C-16), 43.90 (s, C-4), 39.70 (t, C-1), 39.70 (t, C-7), 38.20 (s, C-10), 38.28 (t, C-3), 36.63 (d, C-12), 33.54 (s, C-8), 28.73 (q, C-18), 28.72 (t, C-14), 28.31 (t, C-13), 27.27 (t, C-11), 20.34 (t, C-6), 18.84 (t, C-2), 11.95 (q, C-20).

TUDOR LUPAŞCU – A BRILLIANT SCIENTIST AND SKILFULL MANAGER

Dear reader!

The Moldovan chemical community has recently honoured Professor Tudor LUPAŞCU on the occasion of his 60's anniversary. Known as brilliant scientist and skilful manager, Professor LUPASCU is now the director of the Institute of Chemistry and one of the founders of the "Chemistry Journal of Moldova", being the Managing Editor from the very beginning of its activity.

Notorious researcher in the field of physical chemistry, active promoter of environmental protection and follower of sustainable use of natural resources, doctor in chemical sciences, Tudor LUPAŞCU was born on March 2, 1950 in Flamanzeni – a small village in North-Eastern Moldova. His family provided him with a good sense of life, based on the profound folk philosophy and wisdom. Due to unfortunate circumstances, he was deprived from father's love from the very early age of 9, after his father sudden passing away. This unhappy situation made the young Tudor carry on his fragile shoulders the heavy family duties, along with his mother, brother and sister.

The interest to chemistry has developed from the early years of his secondary school studies. Being an active participant of chemistry Olympiads, he joined the Moldova University Chemistry Department in 1967, where he graduated in 1972. Following the military service in East Germany (1972-1974) as an active officer, he enrolled to doctoral studies at the famous Institute of Water and Colloidal Chemistry in Kiev (Ukraine).

With a solid training in theoretical chemistry, Professor Tudor LUPAŞCU directed his view towards problems related to the protection of the native country from anthropogenic effects, to avoidance and prevention of environmental pollution by toxic substances. He is known to the scientific world due to complex scientific investigations, devoted to the directed synthesis of carbonic adsorbents with scheduled properties by managing the activation technology and the chemical agents of treatment of the raw wood.

On the basis of this concept were developed and patented new kinds of carbonic adsorbents and catalysts for detoxification of the human body and protection of the environment. Surface chemistry was established for the new carbonic adsorbents and the mechanisms of interaction-immobilization-transformation of organic and inorganic pollutants on catalytic supports. Based on these concepts, technologies of potabilization of natural waters and purification of waste waters have been developed.

Nowadays, a trend of interaction between fundamental and applied research gets evidenced more and more, at the boundaries between different areas and disciplines. Professor Tudor LUPAŞCU, due to his outstanding intellectual and managerial skills, successfully combines fundamental scientific activity with practical elaborations and the work on implementation of scientific results into practice.

Over the years he studied the physico-chemical and mechanical properties of new construction materials, obtained on the basis of local raw material, and in particular of by-products of the extractive industry. New compositions for plastering surfaces inside and outside of buildings have been developed, patented and implemented. The economic effect of these implementations to date constitutes about 2 million lei.

In 2009, on the basis of patents of inventions elaborated by Professor Tudor LUPAŞCU, S.A. Monolit and S.L.R. Odgon built and put into operation the technological lines for production of construction materials. Industrial tests have shown that considering the weather conditions in the Republic of Moldova, the new materials are more efficient, and also cheaper in comparison with those imported.

Under the guidance of Dr. Sc. T. LUPAŞCU was developed the concept of oxidative cleavage of natural polymers and of formation of active biological compounds, were highlighted the functional groups and the principles of action of the biologically active substance Enoxil.

On the basis of the biologically active substance Enoxil were developed and patented new pharmaceutical products. Medicinal preparations produced at the S.A. "Farmaco" have been tested in four republican clinics in Chisinau. To our great moral satisfaction, results showed that medicinal preparations obtained on the basis of the biologically active substance Enoxil manifested highly efficient curative effects in the case of human bacterioses and mycoses, in the process of regeneration of thermal, chemical and physical wounds, in the treatment of post-operational wounds and post-radiant lesions in oncology patients, as well as in the treatment of traumatic lesions of soft tissues and inflammatory diseases of maxillo-facial region in children.

The rich scientific activity of Dr. Sc. T. LUPAŞCU is eloquently described by the high number of scientific papers that have exceeded 500 publications, including 4 monographs, 47 inventions. The results of the investigations undertaken by him have been validated and recognized by participation in approximately 70 scientific forums in the country and abroad, including in Bucharest, Moscow, Kiev, Odessa, Lvov, Riga, etc.

After the proclamation of the independence of the Republic of Moldova and the opening of borders, the investigator and manager T. LUPAŞCU obtained by contest 17 international projects, which have been carried out in collaboration with scientists from Romania, USA, France, Germany, Spain, Norway, Austria, Russia, Ukraine.

High erudition, creative spirit, outstanding capacity to analyze and generate new ideas, as well as his organizer qualities were fully manifested during his directorship at the Institute of Chemistry, from 2002 until now. During these years the Institute of Chemistry accomplished new results, theoretical as well as applied.

Also should be mentioned the outstanding educating skill of the honored, who guided several generations of chemists, activating as a Professor at the Faculty of Chemistry and Chemical Technology of the State University of Moldova, but also being the scientific advisor of 3 theses for Dr. Sc. and 2 theses for PhD in chemistry.

On this anniversary stopover, with the occasion of rounding off the beautiful age of 60 years of which nearly 40 years of research in the unknown labyrinths of chemistry, we address to our colleague Dr. Sc. Tudor LUPAŞCU most sincere wishes of prosperity, health and welfare, new achievements in research, training of researchers and implementation of his results to the benefit of the cultural and spiritual heritage of our people.

President of the Academy of Sciences of Moldova,
Academician Gheorghe DUCA