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INVITED REVIEW

Coordination Chemistry of Alkyl- and Aryl-Substituted N-Nitrosohydroxylamine Compounds

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Coordination chemistry of alkyl- and aryl-substituted N-nitrosohydroxylamine compounds has been reviewed. The ways of preparation of N-nitrosohydroxylamine derivatives and their metal complexes, their molecular, crystal and electronic structure, spectral criteria of coordination as well as ionic equilibria in solutions and area of application of N-nitrosohydroxylamine derivatives and their metal complexes are discussed.

Keywords: N-Nitrosohydroxylamine derivatives, Coordination Chemistry, Spatial and Electronic structures, Applications.

INTRODUCTION

Compounds containing N-nitrosohydroxylamine fragments are good chelating agents capable of giving stable metal complexes with metals of different types. They are widely used in analytical chemistry as reactants for the extraction of variety of metals and spectrophotometric analysis and as precursor for the production of metal oxide nanoparticles. Such properties were in particular characteristics for ammonium N-nitrosophenylhydroxylaminate better known as cupferron [1] (Fig. 1). It was very popular especially during the classical period of analytical chemistry but nowadays has lost its attraction with the evolution of physico-chemical methods of analysis [2].

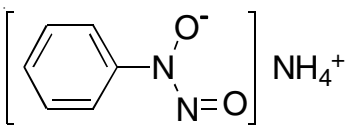


Fig. 1. Structure of cupferron

The biological activities of these compounds are also known, such as the ability to act as NO donors and exhibit antioxidant and other properties [3]. Compounds containing nitrosohydroxylamine fragments are used as medicaments of a broad spectrum of action (vasodilatory, sedative, analgesic, antitumoral, antiviral, *etc*.) [4]. The features of the spatial and electronic structures and properties of metal complexes with organic ligands containing N-nitrosohydroxylamine fragments may be useful in understanding the processes of interaction of nitrogen monoxide with metal-centers of biological macromolecules and thus contribute to the study of the mechanism of its effects on living systems.

The N-nitrosohydroxylamine functional groups occur in a variety of natural and synthetic compounds, for example alanosine (a substance that is being studied for the treatment of pancreatic cancer) and dopastine (inhibitor of dopamine-β-monohydroxilase) [5-7] (Fig. 2).

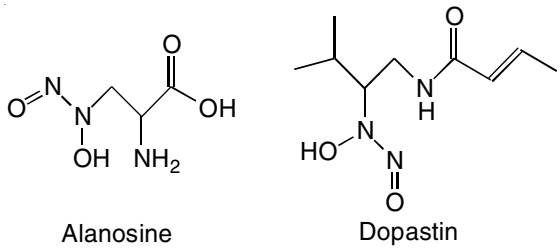


Fig. 2. Examples of natural compounds containing N-nitrosohydroxylamine functional group

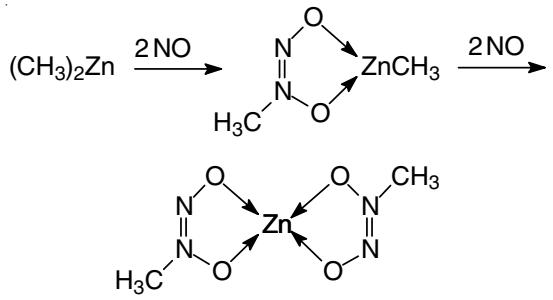
Apart from dopastin and alanosine, some other naturally occurring N-nitrosohydroxylamines have also been isolated [8].

Although there has been a great attention to N-nitrosohydroxylamine derivatives especially due to their NO release abilities, during the last 20 years only one review concerning organic chemistry of N-nitrosohydroxylamine derivatives has been available [9] and there have been no special revision on coordination chemistry of the above-mentioned substances except the one published by McCleverty in 1979 [10].

Here we present a review on the coordination chemistry of alkyl- and aryl-substituted N-nitrosohydroxylamine. It is focused on the features of their molecular, crystal and electronic structure, spectral criteria of coordination and includes the methods of their preparation and areas of application. Some information concerning non-coordinated organic molecules is also discussed.

Historical remarks

Historically the coordination chemistry of N-nitrosohydroxylamine derivatives started with the isolation of the product of interaction of nitrogen monoxide with dimethylzinc [11] and has been called "NO complex" until its real structure was determined after 100 years [12] (**Scheme-I**).



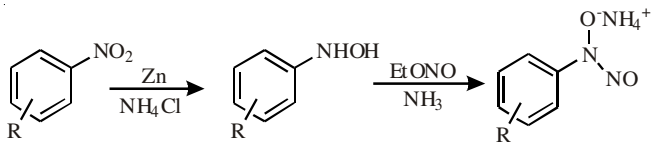
Scheme-I

Although formation of inorganic salts, containing this atomic grouping was first observed in 1802 [13] and the corresponding organic compounds were first reported in 1856 [11], their nomenclature looked confusing. The compounds of this class were known as isonitramines if prepared by reaction of NO with carbanions (Traube compounds) [14] or as nitrosohydroxylamines if prepared by nitrosation [15]. In 1969 Woodward and Wintner first recognized that these represented a distinct organic functional group, which they called the methoxazonyl group [16]. Now the term "nitrosohydroxylamine" is somewhat more satisfying as it correlates with the predominant tautomeric form despite a strong contribution from the dipolar form with an N=N double bond [17]. For the ionized forms of the organic species in ammonium salts and metal complexes, the term "diazenium diolates" is also convenient. It should be noted however that not one of the above names adequately represents the real nature of π-conjugated system of this structurally simple functional group.

An overview of the nomenclature protocols of the compounds of this class was presented by McCleverty [10].

Preparation of alkyl- and aryl-substituted N-nitrosohydroxylamines and their metal complexes

The precursors in the reactions of formation of alkyl- and aryl-substituted N-nitrosohydroxylamines are usually the corresponding N-hydroxylamines which are nitrosated by amyl nitrite/ammonia or methyl nitrite/ammonia [18] (**Scheme-II**).

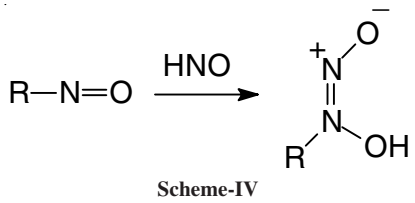


Scheme-II

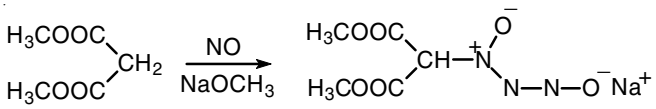
Some inorganic agents such as $NaNO_2$ [19], acidified nitrite [20,21], as well as nitrosyl chloride and nitrosyl sulfate [22] can replace the organic nitrosating agents.

The second approach deals with the insertion of the NO molecule in the M-C bond of the Grignard reagents [23-26] or organometallic compounds of some transition metals [11,27,28] (**Scheme-III**).

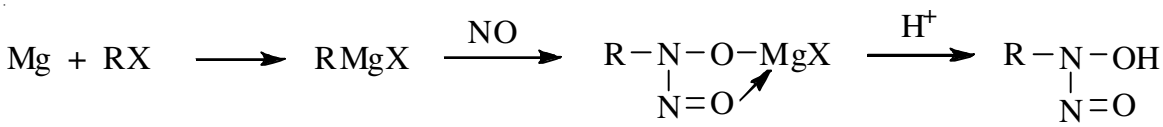
Among the other methods of isolation of alkyl- and aryl-substituted N-nitrosohydroxylamines we should mention the transformation of C-nitroso-compounds [29] (**Scheme-IV**) or the reaction of organic compounds containing acidic protons with nitrogen monoxide in strong alkaline media as developed by Traube [30] and extended by Yandovskii and co-authors [31-33] (**Schemes V** and **VI**).



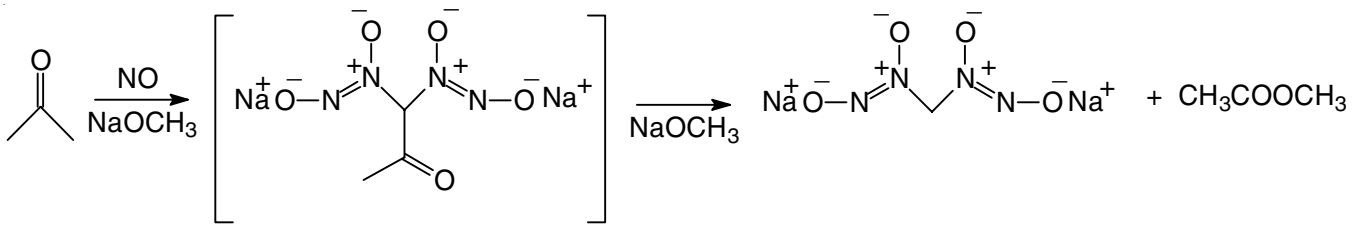
Scheme-IV



Scheme-VI



Scheme-III



Scheme-V

A feature of compounds containing N-nitrosohydroxylamine fragments is the ability to form stable chelate complexes with metals of various natures [10,34]. In strongly acidified solutions, they can precipitate a great number of ions, such as cerium(IV), niobium, gallium, iron, tantalum, tin(IV), titanium, tungsten, uranium(IV), vanadium and zirconium and in less acidic media some like aluminum, bismuth, cerium(III), copper, lead, mercury, silver and thorium.

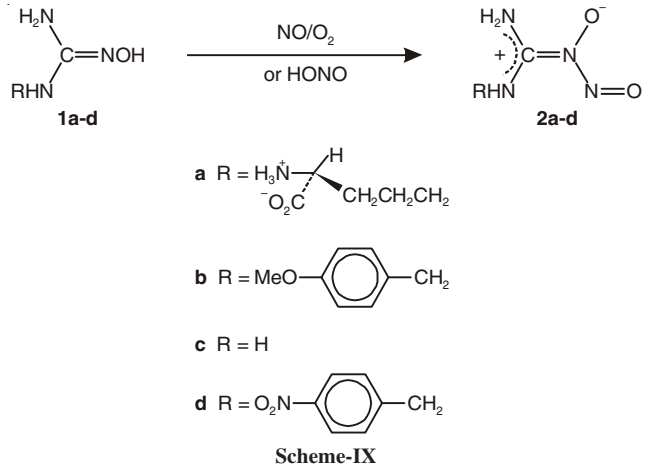
The interaction of nitric oxide with alkyl compounds of diamagnetic metals yields the metal containing N-nitroso-N-alkylhydroxylamine derivatives [35] (**Scheme-VII**).

Scheme-VII

The metals here include Zn, Cd, Mg [36]; Al, Ga [37]; Ti, Zr [38]; W, Rh, Cu(I) [39]; Nb, Ta [40,41] and Re [42].

Identification of the products presented in **Scheme-VI** was first carried out by Sand and Singer [43] who showed that the action of nitric oxide on phenylmagnesium bromide and the further hydrolysis of the obtained NO-complex gave a free acid of N-nitroso-N-phenylhydroxylamine (cupferron) because the isolated product showed the same properties as the product obtained by the action of nitrous acid on N-phenylhydroxylamine [44].

The other way of isolation of metal complexes of N-nitrosohydroxylamine derivatives is the direct exchange of an H atom of an N-nitrosohydroxylamine fragment (or ammonium or alkaline metal cation in diazeniumdiolates) by transitional metallic cations [35] (**Scheme-VIII**).



Scheme-IX

Molecular and crystal structures

The possible tautomeric forms of the N-nitrosohydroxylamine functional group concerning the position of a proton are shown in Fig. 3. The anionic form can most probably be presented as a hybrid of resonance forms 1 and 2.

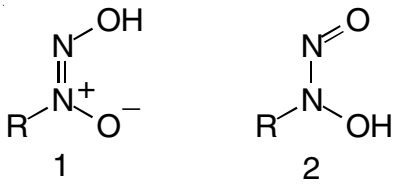


Fig. 3. Tautomeric forms of the N-nitrosohydroxylamine functional group (*syn-anti* isomerism is avoided)

The uncertainty in distinguishing between structures **1** and **2** with spectroscopic methods led to long debates which were not concluded until the X-ray crystal structures of cupferron free acid (Fig. 4) and its (4-methyl)cyclohexyl analogue were determined by Hickmann *et al.* [45].

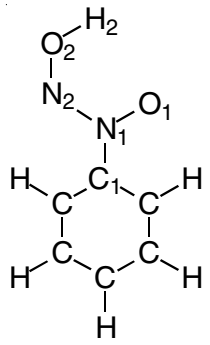
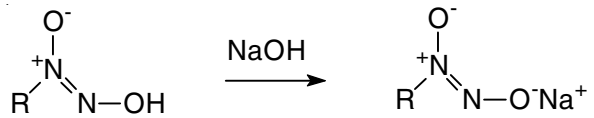


Fig. 4. Molecular structure of cupferron free acid

As was indicated, in both molecules all atoms of the ONNOH groups are coplanar. The O-atoms are in the *syn* configuration with respect to the diazene double bond, an arrangement designated the *Z* isomer. Both molecules have N-N double bonds with the N-N distance 1.280 and 1.267 Å for cupferron and (4-methyl)cyclohexyl-N-nitrosohydroxylamine free acids, respectively. The N(2)-O(2) bonds (1.357 and 1.365 Å) are considerably longer than the N(1)-O(1) bonds (1.297 and 1.287 Å, respectively).

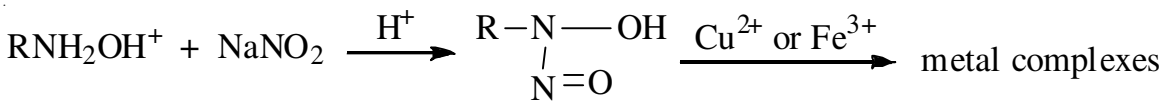
Because of the low stabilities of N-nitrosohydroxylamine free acids, only a few other structures have been determined by X-ray crystallography but all of them showed similar structures of the molecules [46,47].

Southan and co-authors [48] reported the synthesis and crystal structure determination of a series of zwitter-ionic compounds containing ionized nitrosohydroxylamine fragment (H_2N^+=C[NHR][ONNO]$^-$) (**Scheme-IX**).



Scheme-X

The molecular structure of **2b** is presented in Fig. 5. It indicates the *cis*-position of the two O atoms and the presence



Scheme-VIII

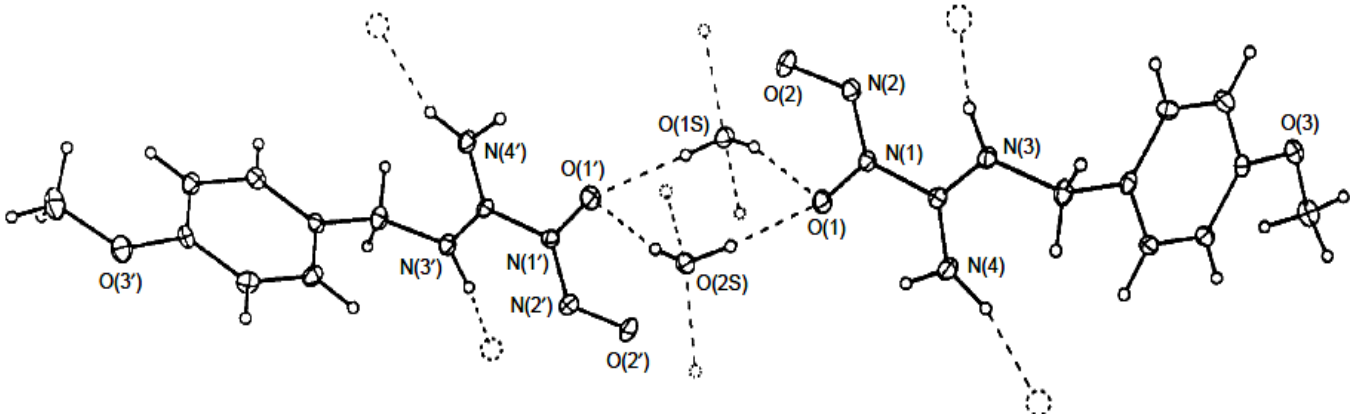


Fig. 5. Molecular structure of **2b**

of two different conformers along with two water molecules in an asymmetric unit that forms a hydrogen bonded helix. The proton of the nitrosohydroxylamine group is located at the N atom of the imino group. The N-O bond lengths of the deprotonated $NONO^-$ fragment are not fully equalized (1.325(5)/1.321(5) Å for the nitroso group and 1.248(5)/1.254(5) Å for the ionized hydroxylamine group in the crystallographically independent organic molecules, respectively). Both the above presented N-O bonds are significantly shorter than those reported for non-ionized free acids [45-47].

The same tendency of N-O bonds of N-nitrosohydroxylamine fragments to shorten at ionization (1.266 and 1.323 Å) was shown for the dipotassium [49] and disodium [16] analogues of Traube's salt (**Scheme-V**) as well as for several cyclohexadienone diazeniumdiolates [50].

The N-nitrosohydroxylamine group is an active electron donating specie and multiple X-Ray structure determinations indicate its great role in the formation of coordinate bonds with metals.

Most of the presented structures represent complex compounds with cupferron, which can be further divided into three groups. Metal complexes of the alkyl derivatives of N-nitrosohydroxylamine are less presented in the literature.

Metal complexes of aryl-derivatives

Three types of coordination of ionized N-nitrosohydroxylamine derivatives to the metallic cations can be proposed (Fig. 6) and only three of them have so far been identified by X-ray structural analyses: bidentate chelating (monometallic biconnective, O^1O^2-η^2) (Fig. 6a), bidentate bridging (μ-O^1O^2) (Fig. 6b) and bimetallic triconnective bridging (O^1O^2-η^2, O^2-η^1) (Fig. 6c).

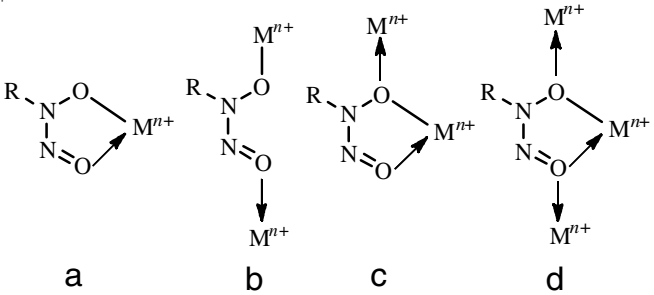


Fig. 6. Coordination modes of N-nitrosohydroxylamine derivatives

Bidentate chelating coordination: The bidentate chelating coordination of cupferron ($C_6H_5N_2O_2$) and its aromatic analogues is the most reported in the literature. In this type of coordination, the ligands exist in the forms of planar anions. The number of chelating ligands depends on the charge of metallic cation and on the presence of other coordinated anions. The descriptions of some of the typical structures are presented below.

The molecular structure of $[Fe(C_6H_5N_2O_2)_3]$ [51,52] is presented in Fig. 7. The ferric cation is six coordinated with three bidentate chelating cupferronate ligands. The octahedral surrounding of iron by the oxygen atoms is largely distorted.

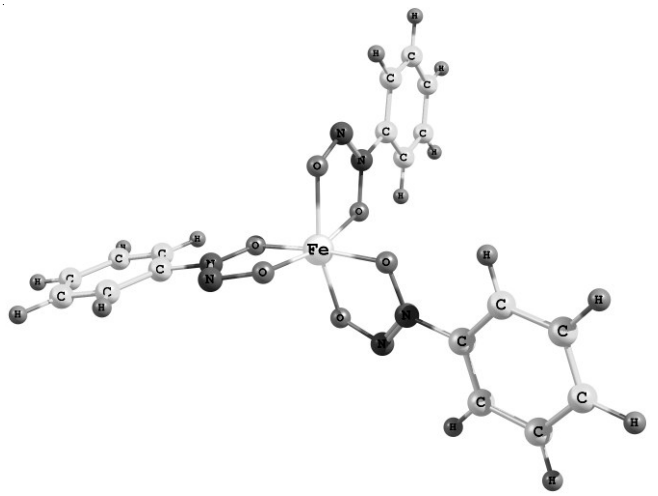


Fig. 7. Molecular structure of $[Fe(C_6H_5N_2O_2)_3]$

The distortion of the coordinate polyhedron can be explained by the high-spin character of the complex ($3d^5$ electronic configuration of Fe(III) cations). The repulsion of 3*d*-electrons provokes the distortion of the coordination polyhedron. This deduction was qualitatively sustained by magnetic susceptibility measurements of the compound.

The same distorted octahedral coordination of Fe(III) was reported for high-spin (N-phenyl-N-nitrosohydroxylaminato)-(*meso*-tetraarylporphyrinato)iron(III) [53]. The most interesting feature of the structure is that the cupferron ligand is bound to the six-coordinated Fe(III) center in a bidentate chelating fashion. The Fe atom is apically displaced 0.69 Å out of the

plane of the 24-atom porphyrin ring. The average Fe-O distance in the cupferron complex is 2.068(3) Å. The cupferron N-N bond length is 1.276(4) Å and the average N-O bond length of 1.302(4) Å is between that of a single bond (1.40 Å) and double bond (1.21 Å). These structural features suggest significant electron delocalization along the ON(Ph)NO moiety.

Similar distorted octahedral coordination was found in the *tris*(cupferronato)aluminum $[Al(C_6H_5N_2O_2)_3]$ [54].

In the case of divalent transition metals, the planar structure of the bidentate chelating ligand stabilizes a planar coordination of the central ion. If the square coordination is not common for a metallic cation, the axial coordination of the solvent molecules takes place to bring the octahedral coordination to the central ion.

The crystal and molecular structure of *bis*(cupferronato)-copper(II) was first reported by Skolnikova and Sugam [55] and refined by Elerman and co-authors [56] (Fig. 8).

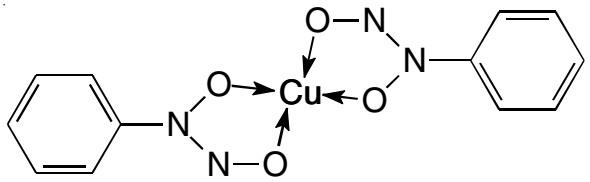


Fig. 8. Molecular structure of $[Cu(C_6H_5N_2O_2)_2]$

The ligands in the above structure have a *trans* arrangement. The average Cu-O bond length correlates well with that common for Cu(II) complexes with the O-donating ligands. Due to the higher charge density on O2, the Cu-O2 bond length (1.892(2) Å) is slightly shorter than that of Cu-O1 (1.902(2) Å). The N1-O1 and N2-O2 bond lengths (1.294(3) and 1.318(3) Å, respectively) are significantly equalized. The phenyl rings are twisted by 7.4(1)° out of the chelate plane.

On the other hand, the structure of *bis*(cupferronato)nickel bisolvate $[Ni(C_6H_5N_2O_2)_2(CH_3OH)_2]$ [57] can be described as a distorted octahedron (Fig. 9). The cupferronate anions are in the equatorial plane in the *trans* position to each other (the Ni-O distances 2.000(2) and 2.025(2) Å). The two methanol neutral molecules act as axial ligands with a longer Ni-O distance (2.126 Å). Thus, Ni is in the (4+2) coordination mode.

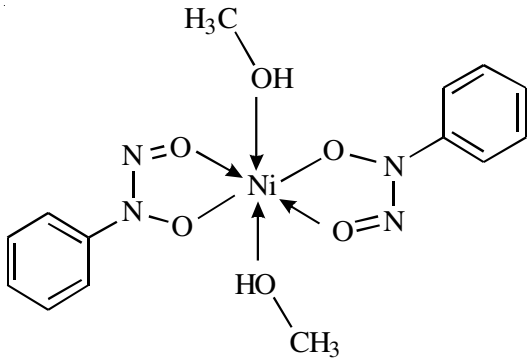


Fig. 9. Molecular structure of $[Ni(C_6H_5N_2O_2)_2(CH_3OH)_2]$

In the lattice, the structure is stabilized by intermolecular H bonds involving methanol molecules and nitroso fragments of cupferron: O(3)–H (3)···O(2) 2,731 (2) Å [57].

Bis(cupferronato) cobalt bissolvate $[Co(C_6H_5N_2O_2)_2(CH_3OH)_2]$ is isomorphous to the nickel complex described above. The Co(II) cation occupies the inversion center. The octahedral coordination is slightly distorted; the metal-to-ligand bonds are slightly longer than those in the nickel complex are. In the lattice, the infinite 1D chains connected by the H-bonds are formed [58].

While two N-O bonds in the Ni complex differ by 0.025 (2) Å, this difference is 0.077 (3) Å in the Co complex (1.320(3) and 1.309(4) Å). The difference between the longer axial and the mean equatorial M-O bonds are almost identical (0.11 Å for Ni and 0.10 Å for Co) [58].

In comparison to cupferron complex, *bis*(N-naphthyl-N-nitrosohydroxylaminato)cobalt dehydrate $[Co(C_{10}H_7N_2O_2)_2(H_2O)_2]$ (N-naphthyl-N-nitrosohydroxylamine is also well known as neocupferron), the organic anions are in the *cis* position (Fig. 10) [59]. In one of the chelating ligands, the plane of the nitrosohydroxylaminato group is twisted out of the naphthyl ring plane by 129.9(3)° and another is almost coplanar to it (twisting angle 1.1 (4)°). The Co-O distances are 2.095(2), 2.073(2) and 2.124(3) Å; the N-O distances (1.327(3) and 1.300(3) Å) correlate with those for the cupferronato complex of cobalt. The complexes are linked together by intermolecular hydrogen bonds between the O atoms of the water ligands and the nitrosohydroxylaminato groups [59].

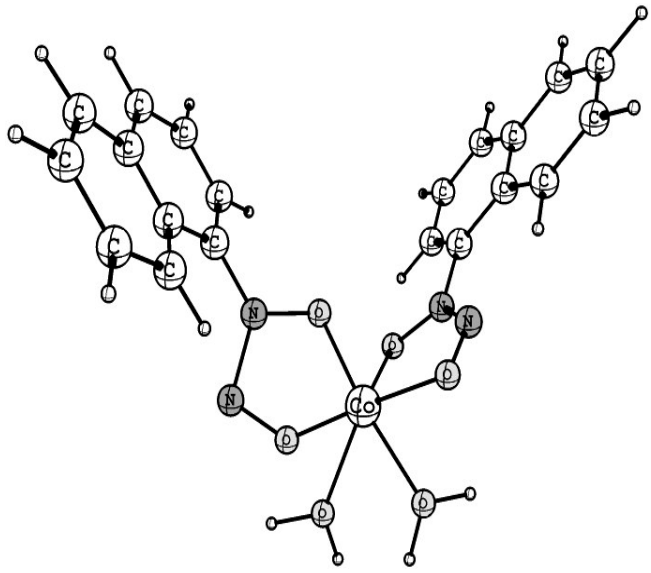


Fig. 10. Molecular structure of $[Co(C_{10}H_7N_2O_2)_2(H_2O)_2]$

The molecular structure of the cupferron complex with Sn(IV) $Sn[PhN(O)NO]_4$ [34] (Fig. 11) consists of discrete monomeric units. The distorted dodecahedral configuration of the central ion is determined by eight O atoms of four cupferronate anions leading to five-membered SnO_2N_2 chelate rings. The N(1)–N(2) bond length of 1.278(2) Å and the average N–O bond length of 1.306(19) Å suggest significant electron delocalization along the N(O)NO moiety which is common for the other structures described above. All Sn–O distances (2.1437(14) and 2.1850(12) Å) are in good agreement with those found for other similar tin complexes containing eight Sn–O bonds.

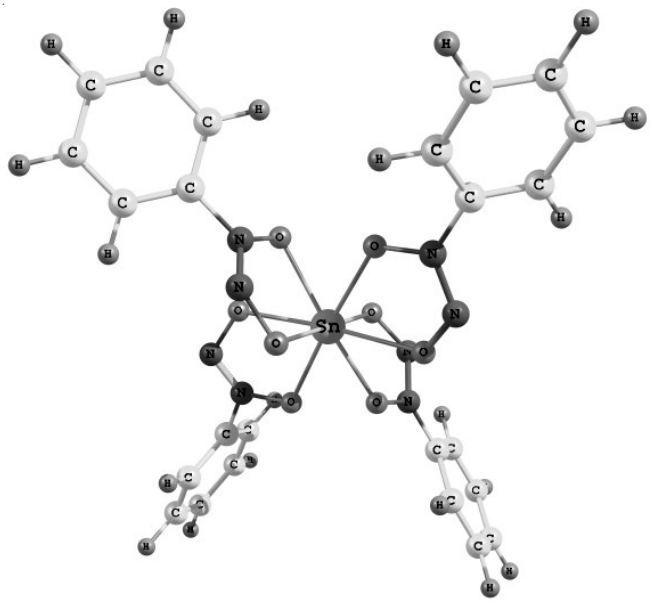


Fig. 11. Molecular structure of $Sn[PhN(O)NO]_4$

The stabilization of coordination polyhedra of the metallic cations may be also realized by interaction with the electron donating atoms of other neutral or anionic ligands. For example, a distorted planar square coordination of Rh(I) was found in $[Rh(C_{10}H_7N_2O_2)(C_{18}H_{15}P)(CO)](CH_3)_2CO$ [60] containing one chelating neocupferron anion, one carbonyl CO ligand coordinated through the carbon atom and one triphenylphosphine molecule (Fig. 12). The acetone molecule is of the lattice character.

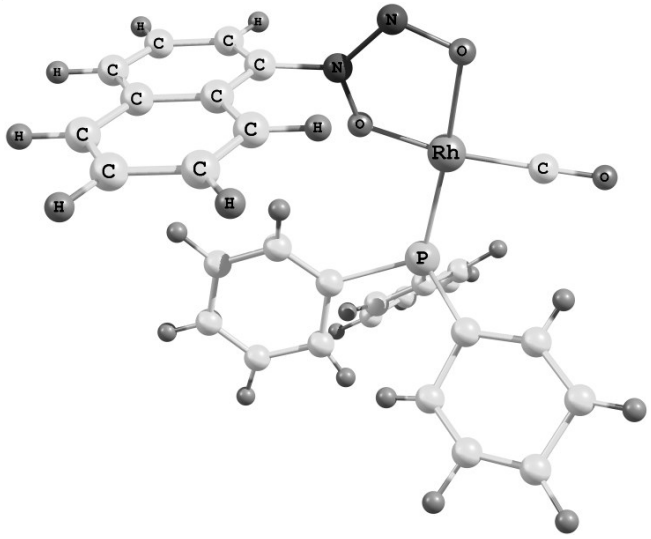


Fig. 12. Coordination sphere of Rh(I) in $[Rh(C_{10}H_7N_2O_2)(C_{18}H_{15}P)(CO)](CH_3)_2CO$

The distorted square planar $RhCO_2P$ coordination set is best illustrated by the small O-Rh-O bite angle of 77.74(10)°. The structure details of the above compound is the full absence of classical hydrogen bonds [60].

Same distorted square planar coordination of Rh(I) was reported by Basson and co-authors for the cupferron containing complexes of monovalent rhodium, *i.e.* carbonyl(N-hydroxy-N-nitrosobenzenaminato-O,O')(4-methyl-2,6,7-trioxa-1-phosphabicyclo[2.2.2]octane) rhodium(I) [61,62]. The bond distances here (Rh-O(nitroso) 2.026(5), Rh-O(hydroxo) 2.059(4), Rh-P 2.156(2) and Rh-C = 1.772(9) Å) are close to those in a previously described structure.

Structural details of four coordinated Rh(I) are comparable to those of penta-($[Rh(C_6H_5N_2O_2)(CO)(P(C_6H_5)_3\}_2]$) and hexa-coordinated $[Rh(C_6H_5N_2O_2)(CO)(CH_3)(I)(PPh_3)]$ [63] and $[Rh(Cl)_2(C_6H_5N_2O_2)(H_2O)(PPh_3)]\cdot 0.5Me_2CO$ [64] complexes. In a mixed-ligand complex of Pb(II) with two cupferronate ions and a phenanthroline molecule [65,66], the central atom is hexacoordinated and the coordination polymer of lead is Ψ-penta-angular pyramid (Fig. 13).

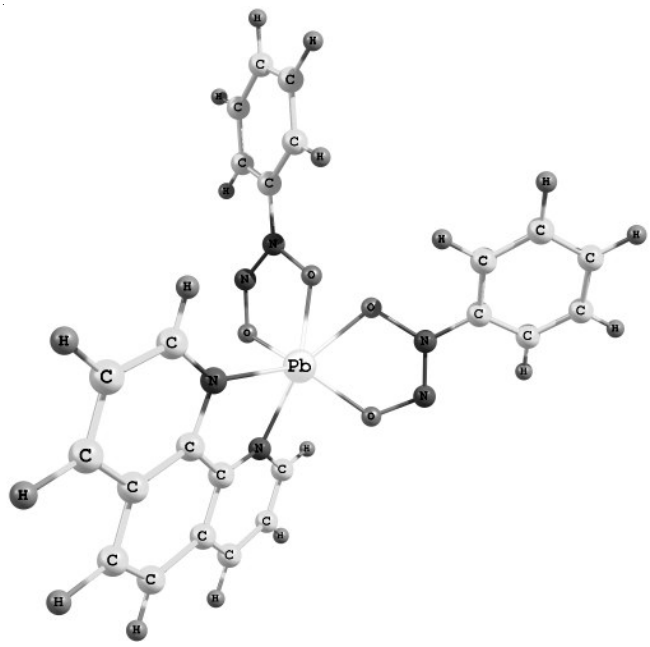


Fig. 13. Molecular structure of $[Pb(C_{12}H_8N_2)(C_6H_5N_2O_2)_2]$

The similarity to the above mentioned chelating pattern of cupferron was also found in several structurally characterized crystalline Cu(I) [67] and UO_2^{2+} complexes [68].

In some cases, the chelating coordination mode of cupferron can be found in binuclear complex species. For example, in tetracupferronato-*bis*(*m*-methoxy)-diiron(III) $[Fe_2(C_6H_5N_2O_2)_4(OCH_3)_2]$ [69] the two $[FeL_2]$ units are doubly linked by the two oxygen atoms of the (CH_3O) groups (Fig. 14).

Both iron atoms are six coordinated with a distorted octahedral geometry. The two iron atoms and the bridging oxygen atoms of the methoxy groups are in the same plane. The bridging Fe-O bond lengths were found to be 1.970(3) and 1.975(3) Å and Fe-O distances of the chelating cupferrone ligands lie in the range from 2.000(3) to 2.025(3) Å. The Fe-Fe distance in the molecule is 3.075(3) Å and the temperature-dependent magnetic susceptibility measurements reveal an antiferromagnetic exchange interaction between the iron(III) centers (J = -14 cm^{-1}).

Bidentate bridging coordination: The bidentate bridging coordination of cupferron is presented only by one tetrameric complex of the composition $[Me_3Sn(PhN(O)NO)]_4$, presented by Párkányi and co-authors [34] (Fig. 15).

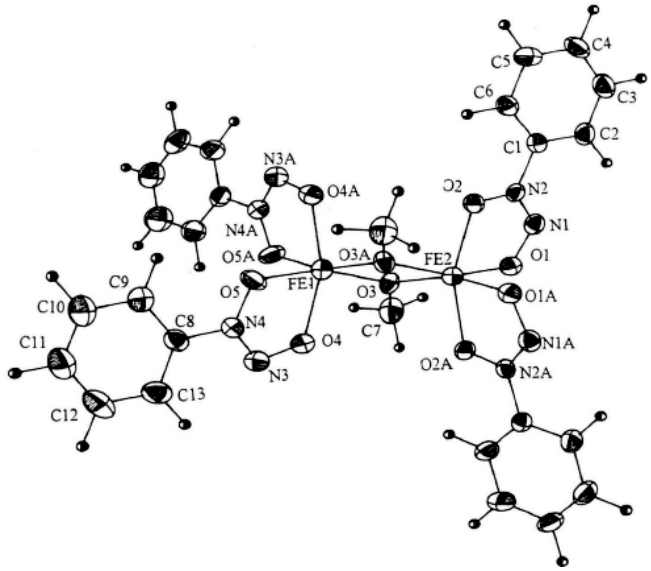


Fig. 14. Molecular structure of $[Fe_2(C_6H_5N_2O_2)_4(OCH_3)_2]$

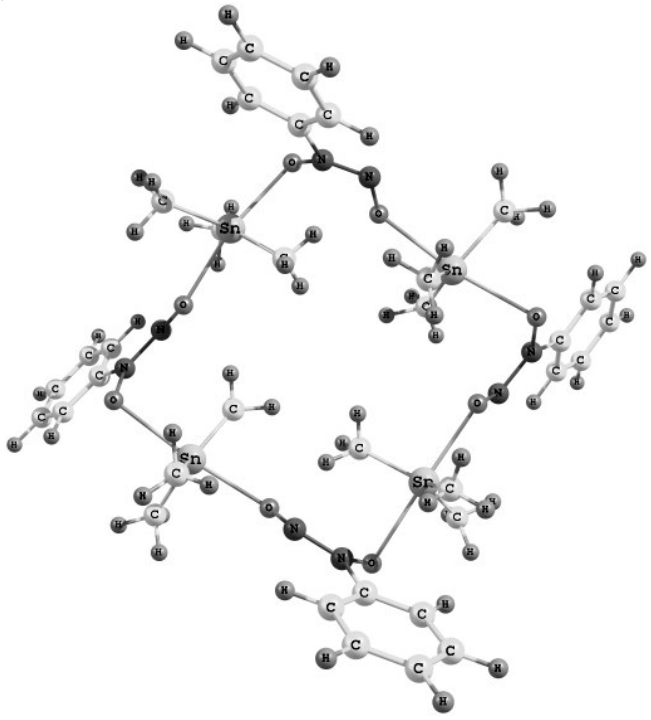


Fig. 15. Molecular structure of tetrameric $[Me_3Sn(PhN(O)NO)]_4$

It consists of a macrocyclic ring system self-assembled from four Me_3Sn units connected by bridging cupferronato ligands and may be described as a 20-membered inorganic metallomacrocycle $Sn_4O_8N_8$. Each metal centre is in a slightly distorted trigonal-bipyramidal configuration and is coordinated by two oxygen atoms of two bridging cupferronato ligands in the *trans* axial positions and three methyl groups in the equatorial plane. The C-Sn-C angels (127.48(12), 116.83(13) and 115.43(13)º) show a slight distortion of the equatorial plane of the polyhedron. The Sn-O bonds are essentially perpendicular to this plane, the C-Sn-O angles lie in the interval from 83.90(8) to 94.35(8)º. The Sn-O bonds [2.3321(16) and 2.2433(15) Å] are elongated in comparison to those of the chelating cupferronato ligand by 0.19 and 0.06 Å, respectively.

The four Sn-O bonds are lying in about the same plane (mean deviation 0.88º) and the others are folded by 20.78º and the bridging cupferronato aions are placed alternatively above and below the plane. They are bound to the metal centers in a bidentate bridging σ-O fashion. The N-O bond length of the nitroso group (1.321(2) Å) is slightly longer than the one of the ionized hydroxylamino fragment (1.293(2) Å). The N-N distance (1.285(2) Å) is closer to that of an N=N double bond (1.21 Å) than a single one (1.45 Å).

Bimetallic triconnective coordination: The third coordination mode of cupferron and its analogues can be determined as a bimetallic triconnective. In these structures, one of the O atoms of the nitrosohydroxylamino fragment is bridging two metallic atoms and chelating coordination also takes place. This type of coordination mode leads to the formation of di- or oligo-nuclear structures. There are only a few examples of such type of coordination.

The synthesis of lead(II) cupferronate and its spectroscopic characteristics [70] has been known for a long time and the compound was assumed to exist as a mononuclear compound until two polymorphs of a binuclear $[Pb_2(C_6H_5N_2O_2)_4]$ complex were crystallographically studied by Kovalchukova *et al.* [71] and Najafi and co-authors [71,72]. In the molecular structure, four cupferronate anions O,O'-chelate to two Pb(II) cations and two of the four nitroso O atoms are also involved in bridging (Fig. 16).

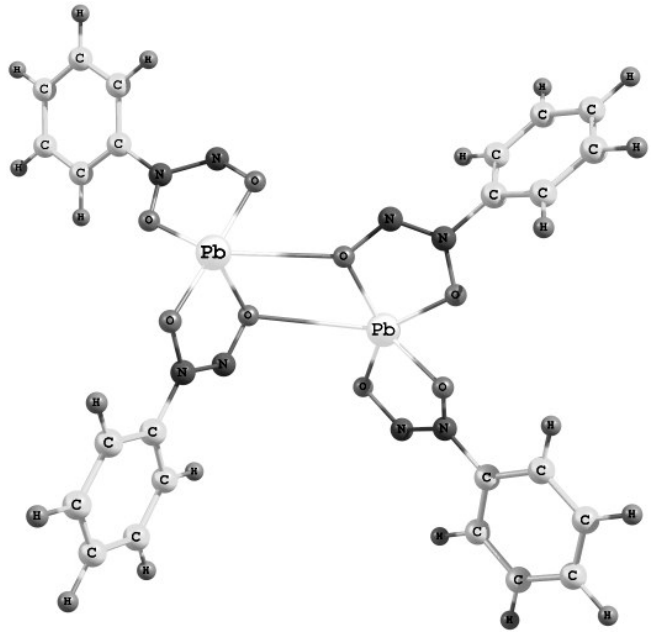


Fig. 16. Molecular structure of $[Pb_2(C_6H_5N_2O_2)_4]$

If only short contacts are taken into consideration, each of the Pb(II) cations is penta-coordinated and forms an octahedron with lead at the pyramid top. The bridge in one dimeric molecule is of a common Pb-O bond length (2.599(3) Å) compared to that in the other [2.943(3) Å].

If two longer Pb···O contacts are to be considered, one of the two Pb(II) atoms in the dimer is increased in the coordinate number to seven [additional Pb-O bond lengths 2.761(3) and 3.168(3) Å] and the other Pb(II) raises its coordination number to six [2.843(3) Å]. However, these long contacts were found to be shorter than the bridging interaction [2.943(3) Å].

For another polymorph, the longer Pb···O interactions are the same for both the lead atoms [2.955(1) and 3.099(1) Å]. As a result, the geometry of the coordination polyhedra can be described as distorted Ψ-square antiprisms.

In comparison to the cupferronato lead dimers, the polymeric structure $[Mn(C_6H_5N_2O_2)_2]_n$ is realized in a Mn(II) complex [73]. The four O atoms of two cupferronate ligands coordinate to the Mn^{2+} cation. Two oxygens of the nitroso groups of the neighboring molecules form additional bonds with the metallic atoms from axial and equatorial directions. As a result, the coordination number of manganese increases to six and the coordination polyhedron may be described as distorted octahedron. All six Mn-O coordinate bonds are of almost equal bond lengths [2.142(2)-2.198(2) Å]. The planes of the two ligands are nearly perpendicular to each other (dihedral angle 94.12(9)°). The O atom of the nitroso group is coordinated to two Mn(II) ions resulting in an $(-Mn-O-Mn-)_n$ network, which stabilizes the crystal structure.

Metal complexes of alkyl-derivatives

The metal complexes of N-alkyl derivatives of N-nitrosohydroxylamine are less studied crystallographically compared to their aryl analogues. All known structures are related to the first coordination mode, *i.e.* bidentate chelating or monometallic biconnective, O^1O^2-h^2 (Fig. 6a).

In a series of papers, crystal structures of Cu(II) complexes of a general composition $Cu(RNONO)_2$ are described (R = C_2H_5 [74], *i*-C_3H_7 [35], *n*-C_5H_{11} [75] and $C_6H_5CH_2$ [76]. Examples of the molecular structures are presented in Figs. 17 and 18.

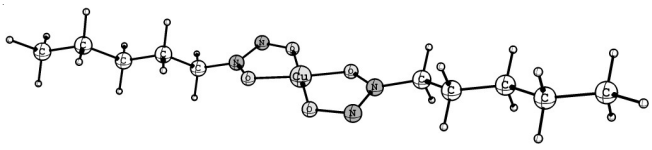


Fig. 17. Molecular structure of Cu(*n*-$C_5H_{11}NONO)_2$

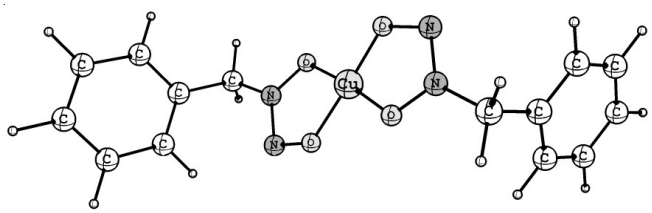


Fig. 18. Molecular structure of $Cu(C_6H_5CH_2NONO)_2$

According to all the presented results, the Cu(II) ions are in a distorted planar square coordination. Although the Cu-O bond lengths are almost equal and lie in the interval 1.8990(12) Å for the ethyl-derivative to 2.0283(12) Å for the *n*-penthyl analogue, the small bite of the ligand leads to angles significantly below 90° subtended at the metal atom (81.99(6)-82.59(9)°) and provokes the distortion of the coordination polyhedra.

The organic anionic ligands are in the *trans*-configuration. The N-O bond lengths become nearly equal after complexation. This fact differs from the Cu(II) complex of cupferron where the N-O bond lengths in the N-nitrosohydroxylamine fragment differ by 0.015 Å. The N=N bonds are of nearly double character. This suggests an important contribution of the $-O-N^+(R)=N-O^-$ canonical form. All the atoms of the N-nitrosohydroxylamine groups in the five membered CuONNO chelate rings are nearly coplanar.

The complexes are packed in stacks where N atoms of neighboring complexes approach the Cu(II) atom by 3.118(3)-3.306(2) Å [up to 3.653(2) Å in Cu(*n*-$C_5H_{11}NONO)_2$], thus forming so-called "long contacts" and completing the coordination of Cu(II) to an extremely elongated tetragonal bipyramid (4+2 or 4+1+1 coordination).

In the molecular structure of Fe(*n*-$C_3H_7NONO)_3$ [35], the six O atoms form a distorted octahedron around the Fe(III) cation (2.001(10) Å) and O-Fe-O chelate angle (76.2(2)°) correlate well with those for the Fe(III) cupferronato complexes (1.970(3)-2.025(3) Å and 74.9(1)-75.0(1)°, respectively [51,52] as described above.

In the centrosymmetric $[Ni((2\text{-}F\text{-}C_6H_4)CH_2NONO)_2(H_2O)_2]$ [77], the Ni(II) cation is in a slightly distorted octahedral environment as it was previously shown for the cupferron complex (Fig. 9). The central atom is surrounded by four O atoms from the N-O groups of the organic ligands [Ni-O 2.0179(13) and 2.0283(12) Å] and two water molecules [Ni-O 2.0967(14) Å]. The N-(2-fluorobenzyl)-N-nitrosohydroxylaminate monoanions act as bidentate chelating ligands. In the lattice, the Ni cations in the columns are shifted in such a way that the coordinated water molecules are involved in the formation of hydrogen bonds with the O atoms of the organic species of neighboring molecules. Thus, a two-dimensional network parallel to (100) is built up by hydrogen-bonded molecules (Fig. 19).

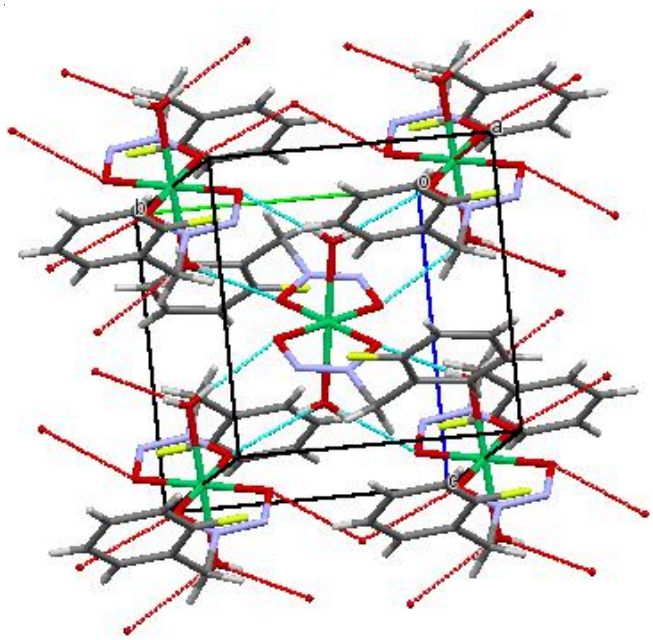


Fig. 19. Molecular packing in the crystal of $[Ni((2\text{-}F\text{-}C_6H_4)CH_2NONO)_2(H_2O)_2]$ along the crystallographic axis b

Some crystallographic parameters of coordinate compounds of alkyl- and aryl-substituted N-nitroso hydroxylaminates as well as some of their anionic forms and free acids are summarized in Table-1.

The analysis of the presented data permits us to conclude the following.

TABLE-1
SOME CRYSTALLOGRAPHIC PARAMETERS OF COORDINATE COMPOUNDS OF ALKYL- AND ARYL-SUBSTITUTED N-NITROSO HYDROXYLAMINES

Compound	M-O distances (Å)	O-N distances (Å)	N-N distance (Å)	O-M-O angles (°)	Ref.
Bidentate chelating (monometallic biconnective, O^1O^2-η^2) coordination					
$Fe(C_6H_5N_2O_2)_3$	1.97(7)	1.36(13)	–	78.1(3)	52
	2.08(8)	1.39(11)		79.0(3)	
	1.98(8)	1.37(10)		79.3(3)	
	2.05(8)				
	1.99(10)				
	2.04(6)				
$Fe(C_6H_5N_2O_2)(Porph)$*	2.044(3)	1.309(4)	1.276(4)	71.52(9)	53
	2.091(2)	1.296(4)			
$Al(C_6H_5N_2O_2)_3$	1.882(4)	1.314(5)	1.285(5)	80.1(2)	54
	1.885(4)	1.304(5)			
	1.875(4)	1.308(5)	1.282(6)	80,7(2)	
	1.888(4)	1.312(5)			
	1.871(4)	1.308(5)	1.291(6)	80.1(3)	
	1.894(4)	1.307(5)			
$Cu(C_6H_5N_2O_2)_2$	1.902(2)	1.294(3)	1.275(3)	81.77(9)	56
	1.892(2)	1.318(3)			
$Ni(C_6H_5N_2O_2)_2(CH_3OH)_2$	2.000(2)	1.308(2)	1.290(3)	78.43(6)	57
	2.025(2)	1.322(2)			
$Co(C_6H_5N_2O_2)_2(CH_3OH)_2$	2.008(2)	1.320(3)	1.280(4)	76.78(10)	58
	2.087(3)	1.309(4)			
$Co(C_{10}H_7N_2O_2)_2(H_2O)_2$	2.095(2)	1.327(3)	1.285(3)	74.80(7)	59
	2.073(2)	1.300(3)			
$Sn(C_6H_5N_2O_2)_4$	2.1850(12)	1.3091(17)	1.278(2)	70.14(5)	34
	2.1437(14)	1.303(2)			
$[Rh(C_{10}H_7N_2O_2)(C_{18}H_{15}P)(CO)](CH_3)_2CO$	2.026(3)	1.346(4)	1.281(4)	77.74(10)	60
	2.082(2)	1.323(4)			
$Rh(C_6H_5N_2O_2)(X)(CO)$**	2.059(5)	1.325(6)	1.264(7)	77.3(2)	61
	2.026(5)	1.325(7)			
$[Rh(C_6H_5N_2O_2)(CO)\{P(C_6H_5)_3\}_2]$	2.147(8)	1.33(1)	1.28(1)	69.6(3)	62
	2.339(9)	1.30(1)			
$[Pb_2(C_6H_5N_2O_2)_4]$	2.427(3)	1.310(5)	1.286(6)	64.06(11)	66
	2.384(3)	1.307(5)			
	2.382(3)	1.309(5)	1.293(6)	64.21(11)	
	2.433(3)	1.305(5)			
$Fe_2(C_6H_5N_2O_2)_4(\mu\text{-}OCH_3)_2$	1.970(3)			75.0(1)	69
	2.023(3)			74.9(1)	
	2.024(3)				
	2.025(3)				
	2.000(3)				
	1.975(3)				
$Cu(C_2H_5NONO)_2$	1.899(1)	1.315(2)	1.272(2)	82.5(1)	74
	1.901(1)	1.313(2)			
$Cu(i\text{-}C_3H_7NONO)_2$	1.906(4)	1.316(4)	1.273(3)	81.99(6)	35
$Cu(n\text{-}C_5H_{11}NONO)_2$	1.904(2)	1.325(3)	1.268(3)	82.3(1)	75
	1.910(2)	1.314(2)			
$Cu(C_6H_5CH_2NONO)_2$	1.914(2)	1.319(3)	1.275(3)	82.3(1)	76
	1.921(2)	1.306(3)			
$Fe(n\text{-}C_3H_7NONO)_3$	2.001(10)	1.313(11)	1.266(10)	76.2(2)	35
$Ni((2\text{-}F\text{-}C_6H_4)CH_2NONO)_2(H_2O)_2$	2.018(1)	1.323(2)	1.274(2)	78.3(1)	77
	2.028(1)	1.302(2)			
Bidentate bridging (μ-O^1O^2) coordination					
$[(CH_3)_3Sn(PhN(O)NO)]_4$	2.3321(16)	1.321(2)	1.285(2)	-	34
	2.2433(15)	1.293(2)			
Bimetallic triconnective bridging (O^1O^2-η^2, O^2-η^1) coordination					
$Pb_2(C_6H_5N_2O_2)_4$	2.382 (3)	1.305 (5)	1.293 (6)	64.06 (11)	71
	2.384 (3)	1.309 (5)	1.286 (6)	64.21 (11)	
	2.427 (3)	1.307 (5)	1.291 (6)	64.08 (11)	
	2.433 (3)	1.310 (5)	1.278 (6)	63.85 (11)	
	2.757 (3)	1.320 (5)			
	2.371 (3)	1.307 (5)			
	2.389 (3)	1.311 (5)			
	2.403 (3)	1.312 (5)			
	2.453 (3)				
	2.718 (3)				

$[Pb_2(C_6H_5N_2O_2)_4]$	2.464(3)	1.297 (4)	1.291 (5)	65.01 (9)	72
	2.475(3)	1.316 (4)	1.277 (4)	74.85 (9)	
	2.341 (3)	1.315 (4)	1.290 (5)	78.49 (9)	
	2.410 (3)	1.303 (4)	1.289 (5)	61.82 (9)	
	2.385 (3)	1.308 (4)			
	2.446 (3)	1.304 (4)			
	2.393 (3)	1.306 (4)			
	2.340 (3)	1.308 (4)			
	2.599 (3)				
	2.943 (3)				
$[Mn(C_6H_5N_2O_2)_2]_n$	2.159(2)	1.299(3)	1.279(4)	69.38(8)	73
	2.142(2)	1.307 (3)	1.274 (4)	70.84(8)	
	2.190(2)	1.316(3)			
	2.157 (2)	1.315 (3)			
	2.144 (2)				
	2.198 (2)				

*Porph-*meso*-tetraarylporphyrine; **X-4-methyl-2,6,7-trioxa-1-phosphabicyclo[2.2.2]octane; *** Phen-*o*-phenanthroline.

Although majority of the presented complexes are crystallized in the monoclinic space group, the complex compounds cannot be considered as isostructural. The major role in the shape of the lattice is played by steric factors due to the nature of the substituent at the N-nitrosohydroxylamine fragment.

The N-nitrosohydroxylamine free acids are characterized by a significant difference in the N-O bond lengths of nitroso- and hydroxylamine fragments, which remains at transition to zwitter ionic forms and "free" anions realized in sodium and potassium salts. In contrast, the formation of coordinate bonds with metal cations leads to an equalization of the N-O bond lengths due to the redistribution of the electron density within the chelate ring. The conjugation of the N-nitrosohydroxylaminato fragment with the aryl substituents in the cases of cupferron and neocupferron does not affect the structure of the chelate cycle.

The primary coordination mode of alkyl- and aryl-substituted N-nitroso hydroxylaminate anions is bidentate chelating (monometallic biconnective, O^1O^2-h^2) which can be realized for metal cations of different origin. For the aryl-substituted compounds, the bidentate bridging (μ-O^1O^2) and bimetallic triconnective bridging (O^1O^2-η^2, O^2-η^1) coordination modes are also known.

Spectral criteria of coordination

Vibrational spectroscopy: Infrared absorption spectra of cupferron and neocupferron are described [78]. The assignment of the spectra of cupferron and metal complex cupferrates was performed by comparison of the spectra of cupferron, deuterated cupferron and sodium cupferrate. Based on these investigations, three groups of absorption bands arising from the ring vibrations, the skeletal vibrations of ONNO group and C-N, NN and NO stretching vibrations were distinguished. Other studies [79-83] indicated that the N-nitrosohydroxylamine derivatives exhibit three distinct bands two of which are due to N-O stretching (1510-1470 and 1315-1270 cm^{-1}) and the third one of a weaker intensity is assigned to N-N stretching at 1060-1000 cm^{-1}. The absorption band at around 900 cm^{-1} is assigned to a bending mode of O-N-N-O group.

At complexation with metals, the stretching modes of N-O groups show considerable shifts to lower frequencies while the bending O-N-N-O mode shows a high frequency shift. The shifts values are related to the degree of covalency of metal-to-ligand interaction. For example, there is a marked change in covalency of the M-O bond on replacement of sodium by lanthanum and the observed doublet of N-O stretchings in sodium cupferrate (1263/1222 cm^{-1}) is significantly shifted in the case of lanthanum cupferrate to 1205/1175 cm^{-1}. However, the replacement of lanthanum by heavier rare earths does not produce any appreciable change in covalency and there are no significant differences in IR spectra of lanthanide cupferrates.

Studies of FT-Raman spectra of cupferron, its Ph-substituted analogues and metal complexes were reported [84-86]. The assignments of the ν(N–N), ν(N–O) and δ(O-N-N-O) vibrational modes, specific for the neutral ligands at 1336, 1265-1223 and 906 cm^{-1}, respectively, are in good agreement with the corresponding IR data. The vibrational behaviour of the cupferronato anion derivatives bound to the metal center confirms the electron delocalization over the ONNO unit, as well as the bidentate coordination pattern.

UV-visible spectroscopy: The N-nitrosohydroxylamine functional group is a monobasic acid (**Scheme-X**), which is able to dissociate and to form salts in alkaline solutions.

The ionization abilities depend on the nature of the substituents. For cupferron and its analogues the pKa values were determined between 3.5 and 4.4 in aqueous solutions [87,88]. As for the aliphatic derivatives of N-nitrosohydroxylamine, they are in the pKa range from 5.1 to 6.4 [89,90].

The acidic forms of N-nitrosohydroxylamine (so called "free acids") have an intense wide asymmetric UV absorption band at 229-232 nm (extinction coefficient, log e 6.0-7.0 mM^{-1} cm^{-1}). The number of absorption maxima, their position and intensities strongly depend on the solvent's nature [91]. The incorporation of aromatic fragments into the composition of the molecules leads to the widening of the absorption bands and their long wave shift that complicates their interpretation [92]. The observed absorption is assigned with the π-π* electron transition. The absence of n-π* bands has been tentatively attributed to intramolecular and/or intermolecular hydrogen bonding [45,93,94].

On deprotonation with sodium hydroxide, the absorption bands of the organic molecules undergo a bathochromic shift of the absorption band to 244-258 nm accompanied by a slight increase in the molar extinction coefficient (7.5-8.7 mM^{-1} cm^{-1}) [74,76,89,90,95-100].

In the example of *tris*(hydroxymethyl)methylnitrosohydroxylamine and the corresponding model nitramine compounds, Carmack and Leavitt [98] showed that the significant bathochromic shift of the absorption bands in the alkaline media is caused by ionization and not tautomeric transformation or destruction of N-nitrosohydroxylamine fragments of molecules.

The addition of metal salts to solutions of ionized aryl- and alkyl-derivatives of N-nitrosohydroxylamine in the form of ammonium, sodium or potassium salts, provokes an hypsochromic shift and a decrease in intensity of the ligand absorption band. This indicates a change in the electronic structures of the organic anions due to their complexation and formation of coordinate bonds of a covalent character [74-76] (Figs. 20 and 21). The value of the shift in the absorption band is in good accordance with the DFT/B3LYP calculation of the atomic charges in the metal complexes of some alkyl(benzyl)-derivatives of N-nitrosohydroxylamine [101] (Table-2). Thus, the shift is minimal for the cations that, according to calculations form ionic bonds with the N-nitrosohydroxylamine derivatives (the calculated atomic charge does not differ a lot from the traditional value). If the character of the metal-to-ligand interaction significantly differs from ionic, the hypsochromic shift in the absorption band is greater and reaches 10-12 nm remaining less than that in a fully covalent bond in the case of a corresponding "free acid" (18 nm).

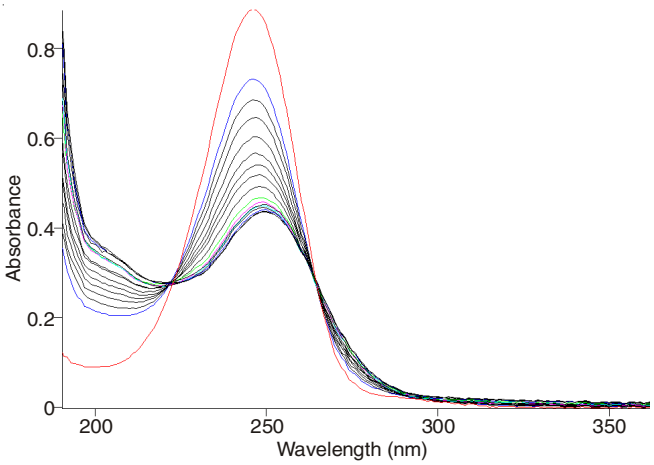


Fig. 20. Changes in the UV-visible absorption spectrum of a 10^{-4} M aqueous solution of $K(C_2H_5NONO)$ (upper band) after stepwise addition of a 10^{-2} M aqueous solution of $NiCl_2$

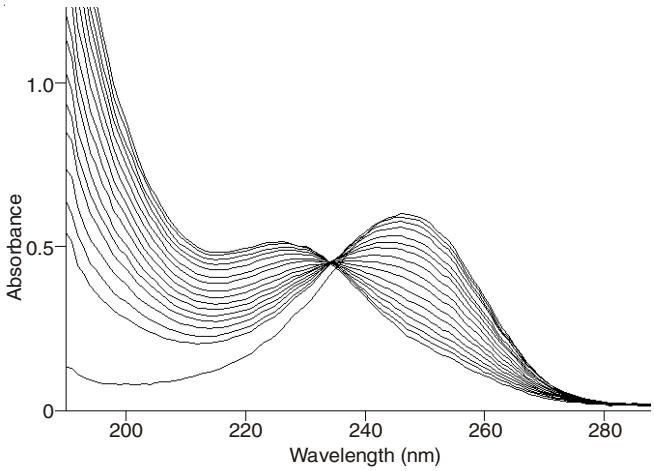


Fig. 21. Changes in the UV-visible absorption spectrum of a 10^{-4} M aqueous solution of $K(i\text{-}C_4H_9NONO)$ (right band) after stepwise addition of a 10^{-2} M aqueous solution of $CrCl_3$

NMR spectroscopy: Nuclear magnetic resonance (NMR) spectroscopy of alkyl- and aryl-derivatives of N-nitrosohydroxylamine is rather poorly reflected in the literature [25,102-107]. As is indicated, the aliphatic protons at the carbon to which the ONNO group is attached are shifted downfield by 2-3 ppm and that carbon generally appears at 58-62 ppm in ^{13}C NMR spectra. Most useful is a study of the ^{15}N NMR spectra of several N-nitrosohydroxylamine derivatives. The ^{15}N chemical shifts of the N-O nitrogens of the nitroso-fragment were reported to be 320-360 ppm relative to ammonia.

Unfortunately, there is no information concerning change in the NMR spectra of N-nitrosohydroxylamine derivatives at complexation with metal cations.

Theoretical modeling

Studying of the features of the spatial and electronic structure and properties of complex compounds of metals with organic ligands containing N-nitrosohydroxylamine fragments can be useful to the understanding of the processes of interaction of nitrogen monoxide with the metal-containing centers of biological macromolecules and thus make a certain contribution to the study of the mechanism of its impact on living systems [108,109].

The stabilities of two possible tautomers **1** and **2** (Fig. 3) for a series of "free acids" (RONNO)H were studied theoretically by Taylor and co-authors [110]. The authors showed

TABLE-2
EXPERIMENTAL SHIFT IN THE LIGAND ABSORPTION BAND AT COMPLEXATION AND SOME CALCULATED ATOMIC CHARGES IN THE METAL COMPLEXES OF $(C_2H_5NONO)^-$ ANION

Compound	Experimental shift in the absorption band at complexation (nm)	Some calculated atomic charges					
		C	N_1	N_2	O_1	O_2	M
$K(C_2H_5NONO)$	-	-0.145	+0.126	+0.219	-0.819	-0.743	+0.958
$Mg(C_2H_5NONO)_2$	2.0	-0.146	+0.136	+0.185	-0.753	-0.698	+1.686
$Ca(C_2H_5NONO)_2$	0.0	-0.146	+0.153	+0.245	-0.836	-0.785	+1.847
$Ni(C_2H_5NONO)_2$	3.0	-0.145	+0.145	+0.255	-0.755	-0.713	+1.500
$Zn(C_2H_5NONO)_2$	7.0	-0.148	+0.154	+0.250	-0.801	-0.766	+1.701
$Cu(C_2H_5NONO)_2$	11.0	-0.204	+0.140	+0.169	-0.652	-0.578	+1.265
$Al(C_2H_5NONO)_3$	11.5	-0.145	+0.155	+0.283	-0.741	-0.695	+2.304
$Ga(C_2H_5NONO)_3$	12.0	-0.146	+0.161	+0.271	-0.722	-0.677	+1.942

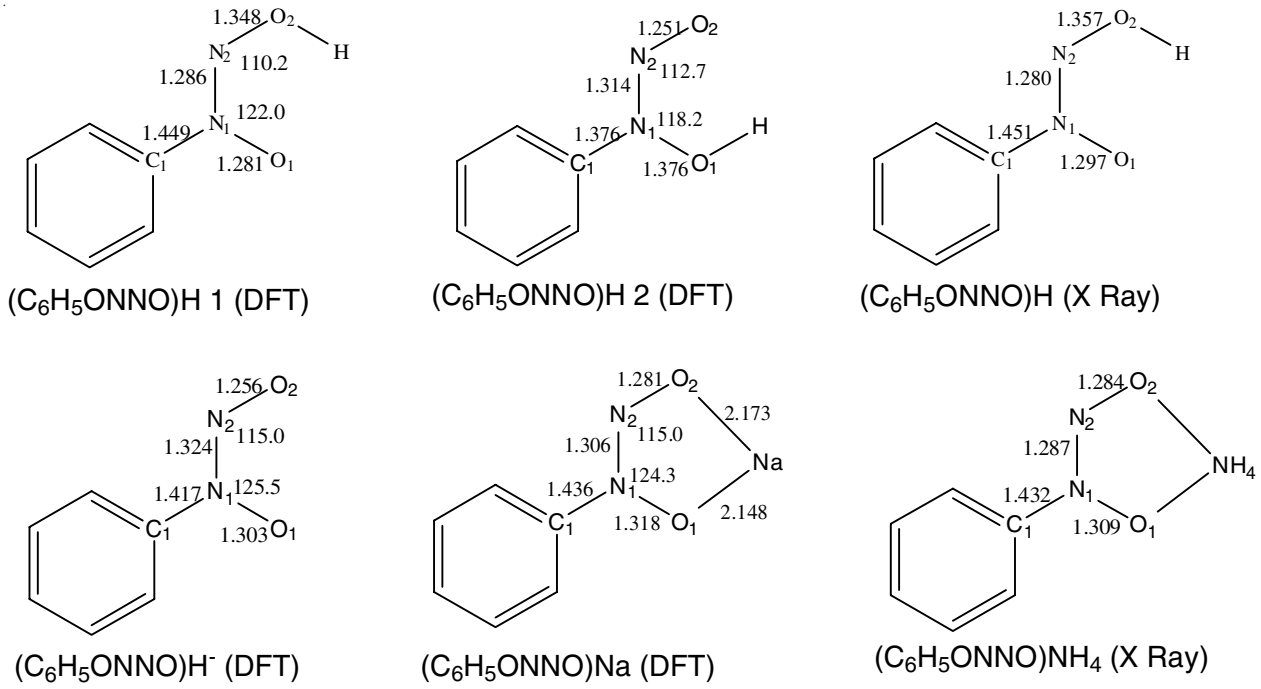


Fig. 22. DFT/B3LYP/6-31+G optimized structures of tautomers A and B of $(C_6H_5ONNO)H$, its anion and sodium salt with comparison with the structural data

that the tautomer 1 is more preferable for the compounds with the small sized R such as (HONNO)H or $(H_2NONNO)H$ and for (CNONNO)H the equilibrium between the two form exists.

The comparison of theoretical (DFT/B3LYP/6-31+G*) and experimental (X-ray single crystal analysis) was performed [111] (Fig. 22).

The relative stabilities of the tautomers 1 and 2 were studied [47] for $((C_2H_5)_2NONNO)H$ and the tautomer 1 was found 1.8 kcal/mol more stable. The similar results were reported [102] for a series of alkyl(benzyl) derivatives of N-nitrosohydroxylamine (RONNO)H; R = CH_3; C_2H_5; *i*-C_4H_9; *tert*-C_4H_9; *n*-C_5H_{11}; $C_6H_5CH_2$; (2-F)$C_6H_4CH_2$. However, the energy difference between the two tautomers is not too large, so the possibility of the tautomeric transformations in solutions should not be ignored. The atomic charges and electronic structures of the N-nitrosohydroxylamino fragments are slightly sensitive to the nature of R. The deprotonation of the molecules leads to equalizing of N-O bond lengths and slight elongation of N-N bonds.

In the frames of DFT/B3LYP/def2-SV(P) approach, the modeling of a $(C_2H_5ONNO)^-$ anion, $K(C_2H_5ONNO)$ salt as well as $Cu(C_2H_5ONNO)_2$ and $Zn(C_2H_5ONNO)_2$ complexes was performed [101] (Fig. 23). The interaction of the $(C_2H_5ONNO)^-$ anion with the potassium cation shortens the N-N bond (by 0.008 Å with respect to the neutral $(C_2H_5ONNO)H$ and 0.028 Å with respect to its anion). At the same time, the N-O bonds are extended by 0.01 and 0.02 Å because of the interaction of the O atoms with the metal cation.

The interaction of a Cu^{2+} cation with two $(C_2H_5ONNO)^-$ anions (formation of $Cu(C_2H_5ONNO)_2$) provokes elongation of N-O bonds by 0.02 and 0.03 Å and further shortening of an N-N bond by 0.05 Å. The metal cation is in a distorted planar square coordination with the OCuO angle at 80.3°. The charge on the Cu atom was found to be +1.265 instead of +2. This fact

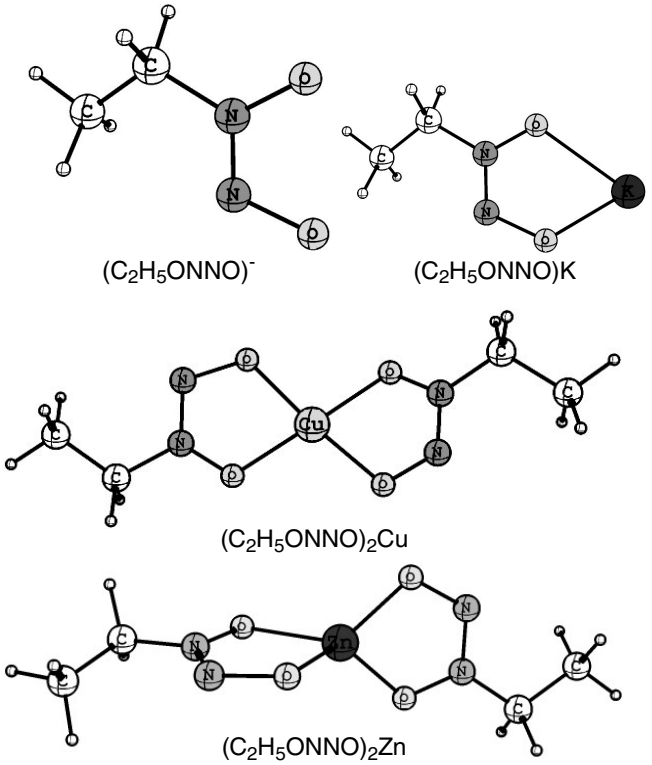


Fig. 23. The optimized structures (DFT/B3LYP/def2-SV(P)) of the species containing C_2H_5ONNO fragments

indicates the strong covalent character of the Cu-O bond. In this regard, the distribution of the electron density in $Cu(C_2H_5ONNO)_2$ differs significantly from those in $K(C_2H_5ONNO)$.

The major bond lengths in the organic anions and valence angles of $Zn(C_2H_5ONNO)_2$ do not change a lot from those in $Cu(C_2H_5ONNO)_2$ but the two complexes strongly differ by their coordination polyhedron (distorted tetrahedron in the case

of $Zn(C_2H_5ONNO)_2$) and the distribution of the electron density in the molecules. While Cu forms strong covalent bonds with the O atoms, the charge on the Zn atom was found to be +1.70 $\bar{e}$ (only 0.15 $\bar{e}$ are transmitted from each organic anion to the metal cation). This better indicates the ionic character of Zn-O bonds. In total, the way of redistribution of the electron density in $Zn(C_2H_5ONNO)_2$ is closer to $K(C_2H_5ONNO)$ than to $Cu(C_2H_5ONNO)_2$.

The results of the comparative study of theoretical and experimental results are presented in Table-3. As is evident, the DFT calculated data for the isolated metal complexes of N-nitrosohydroxylamines are in good agreement with those obtained by the X-ray crystallography. This proves the reliability of the conclusions derived from the DFT calculations.

Natural analogues and biological activity

Systematic studies on the natural occurrence of N-nitroso compounds are lacking [8] but a few studies have shown that these compounds may occur in certain microorganisms [112,113] and mushrooms [114]. They have also been found in meat [115], beer [116] and cosmetics [117].

The N-hydroxy-N-nitrosamine fragments (Fig. 24) occur naturally in the antibiotics alanosine [118,119] and dopastin [120].

Alanosine [l-2-amino-3-(N-nitrosohydroxylamino)-propionic acid], an antibiotic isolated from *Streptomyces alanosinicus* possesses antiviral and antitumor activity. Dopastin is an experimental antihypertensive agent. Their pharmacological properties are assigned to their structural analogy with carboxylic acids [121,122] and ability to chelate metal ions [123].

Among other naturally occurring N-nitrosohydroxylamine derivatives, we should also mention fragin, which was first isolated as a plant growth inhibitor [124] and has later been found in some bacterial cultures [125]. Nitrosofungin was detected in a soil screen for antibiotics [126] and nitrosoxacins A, B, C were isolated from the soil microbe fermentation [127]. The stromelysin inhibitor nitrosostromelin was isolated from a related *Streptomyces* culture [128].

Nowadays, a variety of synthetic analogues of the above mentioned substances were isolated and their biological activities such as vasodilating, sedative, analgetic, antineoplastic, antiviral and other were reported [129-132]. Recently it was shown that the biological activity of such substances correlate with their ability to release NO both *in vitro* and *in vivo* [8,133,134]. For example, during the one-electron oxidation step, cupferron is oxidized to an unstable oxy radical, which spontaneously decomposes to nitrosobenzene and NO [135]. Cupferron and its derivatives have a NONO moiety attached directly to carbon. The advantage of this type of NO donor is that after NO release, the byproducts can be selected to be noncarcinogenic [136]. *ortho*-Substituted derivatives of

TABLE-3
COMPARATIVE STUDY OF BOND LENGTHS OF SOME METAL COMPLEXES OF A SERIES OF N-DERIVATIVES OF N-NITROSOHYDROXYLAMINE

Complex	Bond lengths (Å)						Ref.
	$C-N_1$	N_1-N_2	$N_1.O_1$	$N_2.O_2$	$M-O_1$	$M-O_2$	
$Cu(C_2H_5ONNO)_2$	1.464	1.275	1.317	1.282	1.941	1.962	[101]
$Cu(C_2H_5ONNO)_2$	1.470(2)	1.272(2)	1.314(2)	1.316(2)	1.899(1)	1.902(1)	[74]
$Cu(n\text{-}C_5H_{11}ONNO)_2$	1.469(3)	1.268(3)	1.325(3)	1.314(2)	1.904(2)	2.028(1)	[75]
$Cu(C_6H_5CH_2ONNO)_2$	1.470(2)	1.275 (3)	1.319 (3)	1.306 (3)	1.914 (2)	1.921(2)	[76]
$Cu(i\text{-}C_4H_9ONNO)_2$	1.473(3)	1.273(3)	1.316(4)	1.316(4)	1.906(4)	1.906(4)	[35]
$Cu(C_6H_5ONNO)_2$	1.439(4)	1.275(3)	1.318(3)	1.294(3)	1.892(2)	1.902(2)	[56]
$Ni(C_2H_5ONNO)_2$	1.467	1.269	1.324	1.291	1.856	1.862	101]
$Ni((2\text{-}F)C_6H_4CH_2ONNO)_2{\cdot}2H_2O$	1.470(2)	1.274(2)	1.323(2)	1.302(2)	2.018(1)	2.028(1)	[77]
$Ni(C_6H_5ONNO)_2{\cdot}2CH_3OH$	1.445(3)	1.290(3)	1.322(2)	1.322 (2)	2.025(2)	2.000(2)	[57]
$Al(C_2H_5ONNO)_3$	1.460	1.277	1.312	1.285	1.908	1.925	[101]
$Al(C_6H_5ONNO)_3$	1.444(6)	1.285(5)	1.304(5)	1.314(5)	1.885(4)	1.882(4)	[54]
	1.445(7)	1.282(6)	1.312(6)	1.308(5)	1.888(4)	1.875(4)	
	1.432(7)	1.291(6)	1.307(5)	1.308(5)	1.894(4)	1.881(4)	
	$M-O_1/M-O_2$		$N_1.O_1/N_2.O_2$		N_1-N_2	$C-N_1$	Ref.
$Cu(C_2H_5ONNO)_2$	1.941/1.962		1.317/1.282		1.275	1.464	[101]
$Cu(C_2H_5ONNO)_2$	1.899(1)/1.902(1)		1.314(2)/1.316(2)		1.272(2)	1.470(2)	[74]
$Cu(n\text{-}C_5H_{11}ONNO)_2$	1.904(2)/2.028(1)		1.325(3)/1.314(2)		1.268(3)	1.469(3)	[75]
$Cu(C_6H_5CH_2ONNO)_2$	1.914 (2)/1.921(2)		1.319 (3)/1.306 (3)		1.275 (3)	1.470(2)	[76]
$Cu(i\text{-}C_4H_9ONNO)_2$	1.906(4)/1.906(4)		1.316(4)/1.316(4)		1.273(3)	1.473(3)	[35]
$Cu(C_6H_5ONNO)_2$	1.892(2)/1.902(2)		1.318(3)/1.294(3)		1.275(3)	1.439(4)	[56]
$Ni(C_2H_5ONNO)_2$	1.856/1.862		1.324/1.291		1.269	1.467	101]
$Ni((2\text{-}F)C_6H_4CH_2ONNO)_2{\cdot}2H_2O$	2.018(1)/2.028(1)		1.323(2)/1.302(2)		1.274(2)	1.470(2)	[77]
$Ni(C_6H_5ONNO)_2{\cdot}2CH_3OH$	2.025(2)/2.000(2)		1.322(2)/1.322 (2)		1.290(3)	1.445(3)	[57]
$Al(C_2H_5ONNO)_3$	1.908/1.925		1.312/1.285		1.277	1.460	[101]
$Al(C_6H_5ONNO)_3$	1.885(4)		1.304(5)		1.285(5)	1.444(6)	[54]
	1.888(4)		1.312(6)		1.282(6)	1.445(7)	
	1.894(4)/1.882(4)		1.307(5)/1.314(5)		1.291(6)	1.432(7)	
	1.875(4)		1.308(5)				
	1.881(4)		1.308(5)				

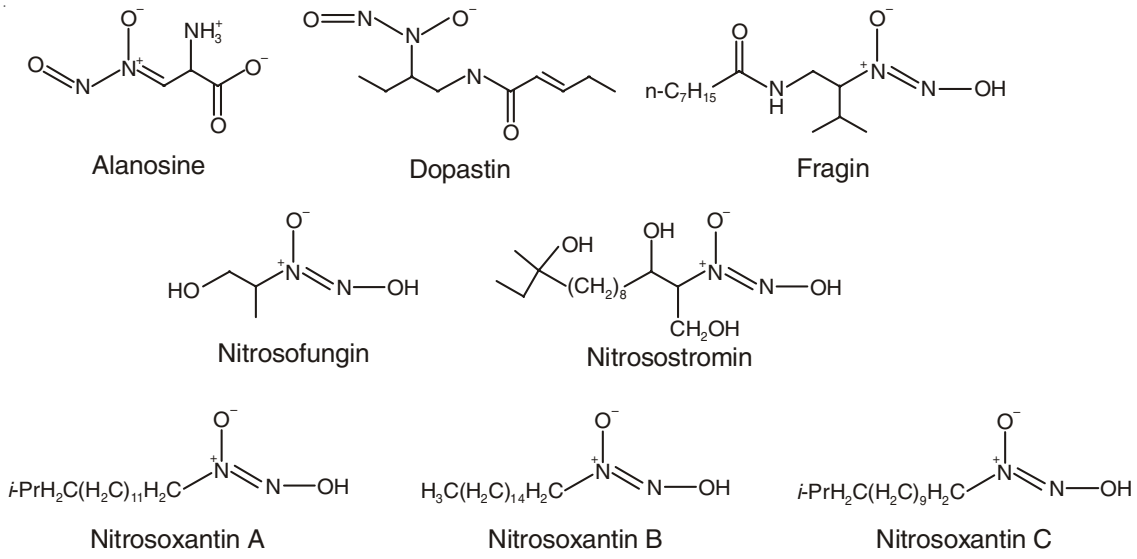


Fig. 24. Naturally occurring substances containing N-nitrosohydroxylamine fragment

cupferron show faster decomposition rates. *para*-Substituted cupferrons release NO *via* spontaneous dissociation during one-electron oxidation (**Scheme-XI**). Electron-withdrawing groups can increase the oxidation potential and make NO release easier.

The substituents in the benzene ring of cupferron can also be biologically active moieties, such as progesterone, estrogen, epinephrine or other catecholamines, which can be designed to target the NO-releasing agent to a specific organ or tissue [137].

In clinical practice, compounds containing N-nitrosohydroxylamine fragments are used for the reversal of cerebral vasospasm, treatment of impotency, nonthrombogenic blood-contact surfaces for minimizing the thrombogenic foreign-body response in transplantations. Many N-nitrosohydroxylamines are being examined as candidate prodrugs for the chemotherapeutic treatment of drug-resistant tumors, reducing the risk of restenosis after coronary angioplasty, killing intracellular parasites and inhibiting metastasis [8].

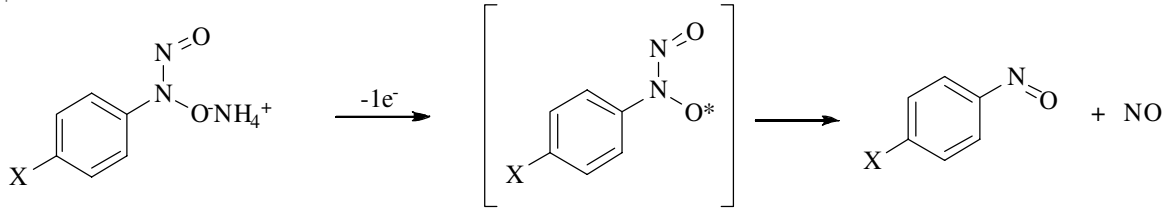
Application of N-nitroso hydroxylamine derivatives and their metal complexes

Analytical uses: The compounds containing N-nitrosohydroxylamine fragments are good chelating agents, which form stable chelates with metals of different origins. The best-known member of the synthetic N-nitroso-N-oxyarylamine family is cupferron [138], which is commonly used as a metal chelator [139] and as a polymerization inhibitor [140,141].

The analytical chemistry of cupferron, its cyclohexyl analogue and neocupferron (naphthyl-N-nitrosohydroxylamine) has been elaborated for more than 100 years [142] but still attracts the attention of analysts [143]. The use of cupferron as a quantitative reagent was originally recommended by Baudisch and King [144] who showed its application to the gravimetric determination of iron in brown iron ore and of iron and copper in nickel ore. It is reported to be used in the determination of zirconium in its ores and metallurgical products, as well as for minor purposes such as the separation of iron and titanium from manganese and aluminum in limestone analysis [142]. Precipitations of metal cations have been performed in cold solutions containing free mineral or organic acids. Biltz and Hödtke [145] found that complete precipitation of copper takes place in weak solutions of hydrochloric acid and in solutions of acetic acid containing sodium acetate, but not in the presence of excessive amounts of mineral acids. The change in the conditions of precipitation allows us to separate metal ions of different origins.

Cupferron and neocupferron show definite promise as precipitating reagents for the rare earth ions. The exact conditions for precipitation and the properties of the resulting complexes were described by Popov and Wendlandt [146].

Extraction of metal cupferrates and neocupferrates is also a traditional field of application of the organic compounds of this class. The solubility of ferric cupferrate in ether was indicated by Bamberger and Ekecranta [147]. Meunier was



Scheme-XI

one of the earliest to use extraction of metal cupferrates as a means of separating metallic ions [148], who found that all iron(III), titanium and copper could be removed from a (1 + 9) hydrochloric acid solution by extraction with chloroform using excess cupferron.

The extraction of cupferrates to chloroform has been found to be a very effective procedure for removing iron, titanium, molybdenum, vanadium, *etc*. [149]. The procedure is effective in the collection of microgram to milligram quantities of iron, titanium, vanadium, *etc*.

The other way of the application of N-nitrosohydroxylamine derivatives in quantative analysis is UV-visible spectrophopometric determination. Land and Sanchez-Caldaz [150] reported the spectroscopic investigations of an Nb(V) complex with cupferron. The formation constant for the last step of complexation at pH 2.5 was computed to be 6.8×10^4.

The recent determination of positions of absorption bands in the UV-visible spectra at spectrophotometric titrations of alkyl- and benzy-derivatives of N-nitrosohydroxylamine with a variety of metal cations and their formation constants calculations (Table-4) make these organic species attractive for the elaboration of analytical methods for spectrophotometric quantitative analysis [74,76,101].

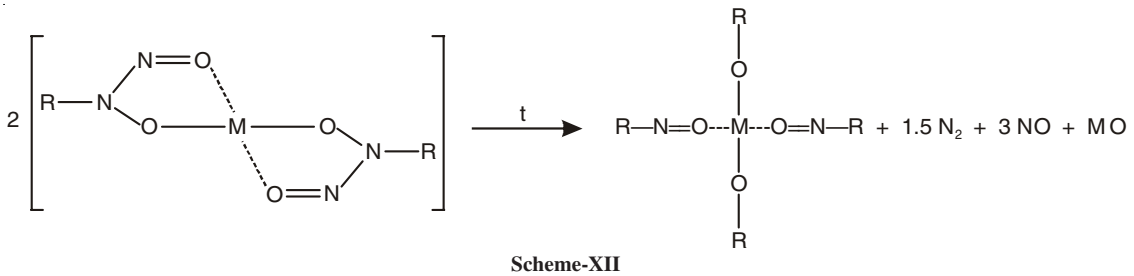
Separation and detection of lanthanides by capillary zone electrophoresis in the presence of cupferron as an UV absorbing complexing agent was studied [143]. An on-column separation of 14 lanthanides was achieved in only 7 min using 0.1 mmol/L cupferron at pH 4.9. Under optimum conditions, the complete separation of thorium and uranium from mixed lanthanides was achieved. Stability constants of La and Sm with cupferron were calculated to be for log K_1 5.30; log K_2 4.30; log K_3 3.30 for La and K_1 5.75; log K_2 4.75; log K_3 3.75 for Sm. Cupferron, being a UV active small-molecule ligand, gave partial complexation with the lanthanides with medium stability and provided the electrophoretic mobility differences that was sufficient for a satisfactory direct detection of all the 14 lanthanides.

TABLE-4
POSITION OF λ_{max} OF THE LONG WAVE ABSORPTION BANDS OF COMPLEX COMPOUNDS $M(RONNO)_n$ (nm) AND THEIR FORMATION CONSTANTS

R	M^{n+}	n	log β/n	λ_{max}	Ref.
CH_3	K^+	1	–	246	[74]
	Cr^{3+}	3	5.01	225	[74]
	Mn^{2+}	2	5.69	245	[74]
	Fe^{3+}	3	5.23	242	[74]
	Co^{2+}	2	5.10	239	[74]
	Ni^{2+}	2	4.85	250	[74]
	Cu^{2+}	2	5.06	235	[74]
	Zn^{2+}	2	5.50	246	[74]
C_2H_5	K^+	1	–	247	[74]
	Al^{3+}	3	4.78	238	[74]
	Cr^{3+}	3	5.23	235	[74]
	Mn^{2+}	2	6.24	245	[74]
	Co^{2+}	2	4.94	241	[74]
	Ni^{2+}	2	5.11	249	[74]
	Cu^{2+}	2	5.01	235	[74]
	Zn^{2+}	2	5.51	246	[74]
	Cd^{2+}	2	6.31	244	[74]
	Ba^{2+}	2	6.03	246	[74]
	Pb^{2+}	2	5.50	242	[74]
n-C_5H_{11}	K^+	1	–	247	[101]
	Cr^{3+}	3	5.14	224	[101]
	Co^{2+}	2	5.22	239	[101]
	Ni^{2+}	2	4.92	251	[101]
	Cu^{2+}	2	5.12	236	[101]
	Zn^{2+}	2	5.58	245	[101]
$C_6H_5CH_2$	K^+	1	–	251	[76]
	Al^{3+}	3	4.88	233	[76]
	Cr^{3+}	3	4.85	243	[76]
	Mn^{2+}	2	5.24	249	[76]
	Co^{2+}	2	5.30	245	[76]
	Ni^{2+}	2	4.93	253	[76]
	Cu^{2+}	2	5.18	238	[76]
	Zn^{2+}	2	5.65	250	[76]
	Cd^{2+}	2	5.79	250	[76]
	Ba^{2+}	2	6.70	251	[76]
	Pb^{2+}	2	5.27	248	[76]
(2-F)$C_6H_4CH_2$	K^+	1	–	252	[101]
	Cr^{3+}	3	5.45	236	[101]

Precursors for metal oxide micro and nanoparticles: The synthesis of inorganic nano dimensioned materials of a given morphology is now representative of an area of intense scientific development. It is connected to the considerable potential of their application in such areas as biomedicine, optics, electronics, *etc*.

One of the approaches to the preparation of metal and metal oxide nanoparticles is the thermal or photoinduced decomposition of transition metal complexes with organic ligands (so called precursors) in high molecular weight inert compounds. In particular, for the preparation of copper(II) oxide, zinc oxide, cobalt oxide and nickel oxide nanoparticles, appropriate cupferrates have been proposed, which decompose in polyethylene glycol (PEG) at 250-350 °C to form nanoparticles [151-154]. The prerequisites for development of this method were studies of thermal stabilities of *d*- and *f*-metal cupferrates [154-158], which indicated that the decomposition of the above complexes starts in the interval 200-300 °C and is accompanied by a significant gas evolution. The process of the thermal decomposition can be described as shown in the **Scheme-XII**.



Scheme-XII

Heating some Cu(II) N-alkyl(benzyl)-N-nitrosohydroxylaminates in solvents stabilizing the nanoparticles (polyethylene glycol and 2-dodecyl-1H-imidazole) leads to the formation of dark brown colloids and precipitation of dark powders. In the case of polyethylene glycol, the process begins with the formation of isolated "nanorods" with dimensions from 0.2 to 10 μm in diameter and from 5 to 50 μm in length. Increasing the holding time of the precursor at 250 °C leads to changes in the morphology of the "rods," which take the form of "grains" ranging in size from 0.2 × 1.0 to 0.5 × 2.5 μm and then gradually self-organize into more complex ensembles. The use of 2-dodecyl-1*H*-imidazole instead of polyethylene glycol stabilizes the flake like shape of the nanoparticles, which range in size from 0.5 to 2 μm. According to X-ray diffraction powder analysis, the nano-particles correspond to cubic Cu_2O. The increase in heating time leads to decomposition of Cu_2O and its transformation into nano dimentional metallic copper.

Conclusion

The chemistry of alkyl- and aryl-substituted N-nitrosohydroxylamine compounds is of significant interest not only because of their traditional analytical uses and natural occurrence as antibiotic fragments. They also possess various biological activities, which are related to the ability of NO release. N-nitrosohydroxylamine derivatives are of potential use in clinical practice and as precursors for the synthesis of nano dimensional metal oxides. The useful properties of the above substances are strongly assigned with their complexing abilities. The multiple crystallographic data indicate three possible coordination modes of N-nitroso hydroxylamine derivatives, *i.e.* bidentate chelating (monometallic biconnective, O^1O^2-η^2), bidentate bridging (μ-O^1O^2) and bimetallic triconnective bridging (O^1O^2-η^2, O^2-η^1). The structural characteristics of the chelating center do not significantly depend either on the substituent in the N-nitrosohydroxylaminate anion or on the origin of the metal cation. However, the shifts in the absorption bands in IR and UV-visible spectra at complexation together with theoretical modeling of the electronic structures of metal N-nitrosohydroxylaminates indicate that the covalency of metal-to-ligand chemical bonds may change in wide ranges.

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REFERENCES

1. R.C. Mehrotra, in ed.: G. Wilkinson, Comprehensive Coordination Chemistry, vol. 2, Chap. 15.9, Pergamon: Oxford, U.K. (1987).
2. F. Feigl, Chemistry of Specific, Selective and Sensitive Reagents, Academic Press, New York (1949).
3. L.K. Keefer, D. Christodoulou, T.M. Dunams, J.A. Hrabie, C.M. Maragos, J.E. Saavedra and D.A. Wink, in eds.: R.N. Loeppky and C.J. Michejda, Nitrosamines and Related N-Nitroso Compounds: Chemistry and Biochemistry, ACS Symposium Series 553, American Chemical Society: Washington, DC, Chap. 11 (1994).
4. D. Christodoulou, C.M. Maragos, C. George, D. Morley, T.M. Dunams, D.A. Wink and L.K. Keefer, in eds.: K.D. Karlin and L.Z. Tyekl, Bioinorganic Chemistry of Copper, Chapman and Hall: New York, p. 427 (1993).
5. K. Kano and J.-P. Anselme, *Tetrahedron*, **48**, 10075 (1992).
6. K. Kano and J.-P. Anselme, *Tetrahedron*, **49**, 9453 (1993).
7. K. Kano and J.-P. Anselme, *J. Org. Chem.*, **58**, 1564 (1993).
8. P.G. Wang, T.B. Cai and N. Taniguchi, Nitric Oxide Donors, WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim (2005).
9. J.A. Hrabie and L.K. Keefer, *Chem. Rev.*, **102**, 1135 (2002).
10. J.A. McCleverty, *Chem. Rev.*, **79**, 53 (1979).
11. E. Frankland, *Justus Liebigs Ann. Chem.*, **99**, 333 (1856).
12. I.S. Butler and M.L. Newbury, *J. Coord. Chem.*, **5**, 195 (1976).
13. H. Davy, *Bibl. Br. Sci. Arts*, **20**, 350 (1802).
14. W. Traube, *Chem. Ber.*, **28**, 1785 (1895).
15. R. Behrend and E. König, *Justus Liebigs Ann. Chem.*, **263**, 175 (1891).
16. V.D. Cherepinskii-Malov, A.S. Mukhametzyanov, V.G. Andrianov and G.A. Marchenko, *Zh. Strukt. Khim*, **24**, 164 (1983); V.D. Cherepinskii-Malov, A.S. Mukhametzyanov, V.G. Andrianov and G.A. Marchenko, *J. Struct. Chem.*, **24**, 157 (1983).
17. R.B. Woodward and C. Wintner, *Tetrahedron Lett.*, **10**, 2689 (1969).
18. C. Hugh and C.R. St. Louis, Conard US Patent 3314349 (1965).
19. A. Wohl, *Ber. Dtsch. Chem. Ges.*, **27**, 1432 (1894).
20. G.C. Lancini, E. Lazzari and A. Diena, *Farmaco Sci.*, **24**, 169 (1969).
21. C. Hugh and C.R. St. Louis, Conard US Patent 3413349 (1968).
22. K. Massonne and M. Fischer, US Patent 5393874 (1995).
23. E. Müller and H. Metzger, *Chem. Ber.*, **89**, 396 (1956).
24. G.A. Marchenko, O.G. Yakovleva, V.Z. Latypova, L.N. Punegova, D.A. Semanov, V.V. Cherevin, Y.M. Kargin and I.V. Tselinskii, *J. Org. Chem. USSR*, **24**, 1429 (1988).
25. I.N. Zyuzin and D.B. Lempert, *Bull. Acad. Sci. USSR, Div. Chem. Sci.*, **34**, 753 (1985).
26. I.N. Zyusin, G.N. Nechiporenko, N.I. Golovina, R.F. Trofimova and N.V. Loginova, *Russ. Chem. Bull.*, **46**, 1421 (1997).
27. C.J. Jones, J.A. McCleverty and A.S. Rothin, *J. Chem. Soc., Dalton Trans.*, 405 (1985).
28. A.R. Middleton and G.J. Wilkinson, *J. Chem. Soc., Dalton Trans.*, 1898 (1981).
29. D.W. Shoeman and H.T. Nagasawa, *Nitric Oxide*, **2**, 66 (1998).
30. W. Traube, *Justus Liebigs Ann. Chem.*, **300**, 81 (1898).
31. V.N. Yandovskii, G.M. Frolova and I.V. Tselinskii, *J. Org. Chem. USSR*, **18**, 441 (1982).
32. V.N. Yandovskii, V.S. Kuznetsov, I.V. Tselinskii and G.M. Frolova, *J. Org. Chem. USSR*, **18**, 445 (1982).
33. V.N. Yandovskii, T.I. Doshchechkina, I.V. Tselinskii and V.S. Kuzentsov, *J. Org. Chem. USSR*, **19**, 427 (1983).
34. L. Párkányi, A. Kálmán, A. Deák, M. Venter and I. Haiduc, *Inorg. Chem. Commun.*, **2**, 265 (1999).
35. M.H. Abraham, J.I. Bullock, J.H.N. Garland, A.J. Golder, G.J. Harden, L.F. Larkworthy, D.C. Povey, M.J. Riedl and G.W. Smith, *Polyhedron*, **6**, 1375 (1987).
36. M.H. Abraham, J.H.N. Garland, J.A. Hill and L.F. Larkworthy, *Chem. Ind.,* 1615 (1962).
37. S. Amirkhalili, P.B. Hitchcock, J.D. Smith and J.G. Stamper, *J. Chem. Soc., Dalton Trans.*, 2493 (1980).
38. P.C. Wailes, H. Weigold and A.P. Bell, *J. Organomet. Chem.*, **34**, 155 (1972).
39. S.S. Basson, J.G. Leipoldt and J.T. Nel, *Inorg. Chim. Acta*, **84**, 167 (1984).
40. A.R. Middleton and G. Wilkinson, *J. Chem. Soc., Dalton Trans.*, 1888 (1980).
41. J.D. Wilkins and M.G.B. Drew, *J. Organomet. Chem.*, **69**, 111 (1974).
42. P. Edwards, K. Mertis, G. Wilkinson, M.B. Hursthouse and K.M.A. Malik, *J. Chem. Soc., Dalton Trans.*, 334 (1980).
43. J. Sand and F. Singer, *Justus Liebigs Ann. Chem.*, **329**, 190 (1903).
44. E. Bamberger, *Chem. Ber.*, **27**, 1548 (1894).
45. E. Hickmann, E. Hädicke and W. Reuther, *Tetrahedron Lett.*, **20**, 2457 (1979).
46. J.A. Hrabie, E.V. Arnold, M.L. Citro, C. George and L.K. Keefer, *J. Org. Chem.*, **65**, 5745 (2000).
47. L.K. Keefer, J.L. Flippen-Anderson, C. George, A.P. Shanklin, T.M. Dunams, D. Christodoulou, J.E. Saavedra, E.S. Sagan and D.S. Bohle, *Nitric Oxide*, **5**, 377 (2001).
48. G.J. Southan, A. Srinivasan, L.K. Keefer, C. George and H.M. Fales, *Chem. Commun.*, 1191 (1998).
49. J.H. Bryden, *Acta Crystallogr.*, **12**, 581 (1959).
50. D.S. Bohle and J.A. Imonigie, *J. Org. Chem.*, **65**, 5685 (2000).
51. D. van der Helm, L.L. Merritt Jr., R. Degeilh and C.H. MacGillavry, *Acta Crystallogr.*, **18**, 355 (1965).

52. H.J. Lindner and S. Gottlicher, *Acta Crystallogr. B*, **25**, 832 (1969).
53. G.-B. Yi, M.A. Khan and G.B. Richter-Addo, *Inorg. Chem.*, **34**, 5703 (1995).
54. N. Okabe, K. Tamaki and T. Suga, *Acta Crystallogr. C*, **51**, 1295 (1995).
55. L.H. Skolnikova and E.A. Sugam, *J. Struct. Chem.*, **4**, 350 (1963).
56. Ya. Elerman, O. Atakol, I. Svoboda and M. Geselle, *Acta Crystallogr. C*, **51**, 1520 (1995).
57. N. Okabe and K. Tamaki, *Acta Crystallogr. C*, **51**, 2004 (1995).
58. A. Deák, L. Párkányi, A. Kálmán, M. Venter and I. Haiduc, *Acta Crystallogr. C*, **54**, IUC9800036 (1998).
59. K. Tamaki and N. Okabe, *Acta Crystallogr. C*, **54**, 195 (1998).
60. J.A. Venter, W. Purcell, H.G. Visse and T.J. Muller, *Acta Crystallogr.,* **E65**, m1578 (2009).
61. S.S. Basson, J.G. Leipoldt, W. Purcell and J.A. Venter, *Acta Crystallogr. C*, **48**, 171 (1992).
62. S.S. Basson, J.G. Leipoldt, A. Roodt and J.A. Venter, *Inorg. Chim. Acta*, **118**, L45 (1986).
63. S.S. Basson, J.G. Leipoldt and J.A. Venter, *Acta Crystallogr. C*, **46**, 1324 (1990).
64. M. Ahmed, A.J. Edwards, C.J. Jones, J.A. McCleverty, A.S. Rothin and J.P. Tate, *J. Chem. Soc., Dalton Trans.*, 257 (1988).
65. A. Szorcsik, L. Nagy, I. Kökény, A. Deák, M. Scopelliti, T. Fiore and L. Pellerito, *J. Organometal. Chem*., **692**, 3409 (2007).
66. E. Najafi, M.M. Amini and S.W. Ng, *Acta Crystallogr. E*, **67**, m378 (2011).
67. J. Charalambous, L.I.B. Haines, N.J. Harris, K. Hendrick and F.B. Taylor, *J. Chem. Res. (M)*, **220**, 2101 (1984).
68. W.S. Horton, *J. Am. Chem. Soc*., **78**, 897 (1956).
69. Y. Ellerman, N. Kabak, I. Svoboda, H. Fuess, K. Griessar and W. Haase, *Z. Naturforsch*, **50b**, 1587 (1995).
70. R.S. Bottei and R.G. Schneggenburger, *J. Inorg. Nucl. Chem.*, **32**, 1525 (1970).
71. O.V. Kovalchukova, N. Namichemazi, A.I. Stash, S.B. Strashnova and I.N. Zyuzin, *Russ. J. Inorg. Chem*., **61**, 718 (2016).
72. E. Najafi, M.M. Amini and S.W. Ng, *Acta Crystallogr. E*, **68**, m791 (2012).
73. K. Tamaki and N. Okabe, *Acta Crystallogr. C*, **52**, 1612 (1996).
74. O.V. Kovalchukova, A.S. Bostanabad, A.I. Stash, S.B. Strashnova and I.N. Zyuzin, *Russ. J. Inorg. Chem.*, **59**, 192 (2014).
75. A. Sheikh Bostanabad, O. Kovalchukova, S. Strashnova, A. Stash and I. Zyuzin, *Acta Crystallogr. E*, **70**, m137 (2014).
76. O. Kovalchukova, A.S. Bostanabad, V. Sergienko, I. Polyakova, I. Zyuzin and S. Strashnova, *Open J. Inorg. Chem.*, **3**, 1 (2013).
77. O. Kovalchukova, A.S. Bostanabad, A. Stash, S. Strashnova and I. Zyuzin, *Acta Crystallogr. E*, **70**, m98 (2014).
78. N.V. Thakur, V.B. Kartha, C.R. Kanekar and V.R. Marathe, *J. Inorg. Nucl. Chem.*, **34**, 2831 (1972).
79. M. Piskorz and T. Urbañski, *Bull. Acad Pol. Sci., Ser. Sci. Chim.*, **11**, 597 (1963).
80. V.N. Yandovskii, E.Y. Dobrodumova and I.V. Tselinskii, *Zh. Org. Khim.*, **16**, 933 (1980); *J. Org. Chem. USSR*, **16**, 813 (1980).
81. V.N. Yandovskii, E.Y. Dobrodumova, I.V. Tselinskii, A.D. Misharev and U. Traore, *J. Org. Chem. USSR*, **16**, 250 (1980).
82. S. Amirkhai.ili, A.J. Conway and J.D. Smith, *J. Organomet. Chem.*, **149**, 407 (1978).
83. R. Kellner and A.J. Prokopowski, *Anal. Chim. Acta*, **86**, 175 (1976).
84. M. Bolboaca, S. Cinta, M. Venter, A. Deak, I. Haiduc, O. Cozar, T. Iliescu, P. Röschc and W. Kiefer, *Spectrosc. Lett.*, **33**, 857 (2000).
85. I. Pavel, S. Cýnta, M. Venter, A. Deak, I. Haiduc, P. Rösch, O. Cozar, T. Iliescu and W. Kiefer, *Vib. Spectrosc.*, **23**, 71 (2000).
86. A. Deak, I. Haiduc, L. Parkanyi, M. Venter and A. Kalman, *Eur. J. Inorg. Chem.*, **1999**, 1593 (1999).
87. P.J. Elving and E.C. Olson, *J. Am. Chem. Soc.*, **78**, 4206 (1956).
88. E.G. Kovach, *Chem. Ber.*, **91**, 844 (1958).
89. A. Murayama and S. Tamura, *Agric. Biol. Chem.*, **34**, 122 (1970).
90. L.A. Dolak, T.M. Castle, B.R. Hannon, A.D. Argoudelis and F.J. Reusser, *Antibiotics*, **36**, 1425 (1983).
91. N.V. Kol'cheva and O.M. Petrukhin, *Koord. Khim*, **12**, 449 (1986).
92. A. Bartecki, J. Szoke, G. Varsanyi and M. Visesy, Absorption Spectra in the Ultraviolet and Visible Region, Academic Press Inc., New York, vol. 3 (1966).
93. R.N. Jones and G.D. Thorn, *Can. J. Res.*, **27b**, 828 (1949).
94. R.N. Haszeldine and J. Jander, *J. Chem. Soc.*, 691 (1954).
95. A. Murayama, K. Hata and S. Tamura, *Agric. Biol. Chem.*, **33**, 1599 (1969).
96. T. Natori, Y. Kataoka, S. Kato, H. Kawai and N. Fusetani, *Tetrahedron Lett.*, **38**, 8349 (1997).
97. G. Kortüm and B. Finckh, *Z. Phys. Chem. B*, **48**, 32 (1940).
98. M. Carmack and J.J. Leavitt, *J. Am. Chem. Soc.*, **71**, 1221 (1949).
99. C.N.R. Rao and K.R. Bhaskar, in ed.: H. Feuer, The Chemistry of the Nitro- and Nitroso Groups, Interscience Publishers (1969).
100. J. Rydberg, *Acta Chem. Scand*. **14**, 157 (1960).
101. O. Kovalchukova, A.S. Bostanabad, M. Ryabov, N. Namichemazi, I. Zyuzin and T. Berikashvili, *J. Appl. Chem. Sci. Int.*, **1**, 1 (2014).
102. P.C. Mohr, A. Mohr, T.P. Vila and H.-G. Korth, *Langmuir*, **26**, 12785 (2010).
103. Yu. Kou and A. Wan, *Bioorg. Med. Chem. Lett.*, **18**, 2337 (2008).
104. H. Schultheiss and E. Fluck, *Z. Naturforsch.*, **32b**, 257 (1977).
105. Y.A. Red'kin, G.A. Marchenko, L.N. Punegova, G.S. Stepanov and I.V. Tselinskii, *J. Org. Chem. USSR*, **24**, 441 (1988).
106. M.A. Kuznetsov, Y.P. Artsybasheva, B.V. Ioffe, P. Rademacher and M. Woydt, *J. Mol. Struct.*, **263**, 329 (1991).
107. O.A. Luk'yanov, G.A. Smirnov and V.V. Sevost'yanova, *Russ. Chem. Bull.*, **44**, 1474 (1995).
108. M. Ziche, S. Donnini, L. Morbidelli, E. Monzani, R. Roncone, R. Gabbini and L. Casella, *ChemMedChem*, **3**, 1039 (2008).
109. J.M. Fukuto, C.H. Switzer, K.M. Miranda and D.A. Wink, *Annu. Rev. Pharmacol. Toxicol.*, **45**, 335 (2005).
110. D.K. Taylor, I. Bytheway, D.J.R. Barton, C.A. Bayse and M.B. Hall, *J. Org. Chem.*, **60**, 435 (1995).
111. A.D. McGill, W. Zhang, J. Wittbrodt, J. Wang, H.B. Schlegel and P.G. Wang, *J. Bioorg. Med. Chem.*, **8**, 405 (2000).
112. Y.K.S. Murthy, J.E. Thiemann, C. Coronelli and P. Sensi, *Nature*, **211**, 1198 (1966).
113. P. Goldman, in ed.: D.J. Hentges, Human Intestinal Microflora in Health and Disease, Academic Press, New York, p. 241 (1983).
114. H. Herrmann, *Naturwiss*, **47**, 162 (1960).
115. B.J. Canas, D.C. Havery, F.L. Joe Jr. and T. Fazio, *J. Assoc. Off. Anal. Chem.*, **69**, 1020 (1986).
116. S.M. Billedeau, B.M. Miller and H.C. Thompson, *J. Food Sci.*, **53**, 1696 (1988).
117. S.M. Billedeau, T.M. Heinze, J.G. Wilkes and H.C. Thompson Jr., *J. Chromatogr. A*, **688**, 55 (1994).
118. A.K. Tyagi and D.A. Cooney, *Adv. Pharmacol. Chemother.*, **20**, 69 (1984).
119. C. Coronelli, C.R. Pasqualucci, G. Tamoni and G.G. Gallo, *Edizione Scientifica*, **21**, 269 (1966).
120. H. Iinuma, N. Yagisawa, S. Shibahara, Y. Suhara, S. Kondo, K. Maeda, T. Takeuchi, M. Ohno and H. Umezawa, *Agric. Biol. Chem*., **38**, 2099 (1974).
121. H.N. Jayaram and D.A. Cooney, *Cancer Treat. Rep.*, **63**, 2 (1979).
122. H.N. Jayaram, A.K. Tyagi, A. Anandaraj, J.A. Montgomery, J.A. Kelley, J. Kelley, R.H. Adamson and D.A. Cooney, *Biochem. Pharmacol.*, **28**, 3551 (1979).
123. G. Powis and J.S. Kovach, *Biochem. Pharmacol.*, **30**, 771 (1981).
124. N. Xu, J.H. Christian, N.S. Dalal, E.G. Abucayon, C. Lingafelt, D.R. Powell and G.B. Richter-Addo, *Dalton Trans*., **44**, 20121 (2015).
125. H. Tanaka, S. Sawairi and T. Okuda, *J. Antibiot.*, **47**, 194 (1994).
126. H. Iinuma, S. Kondo, T. Takeuchi and H. Umezawa, *Agric. Biol. Chem*., **38**, 2093 (1974).
127. M. Nishio, M. Hasegawa, K. Suzuki, Y. Sawada, D.J. Hook and T. Oki, *J. Antibiot.*, **46**, 193 (1993).
128. T. Umino, H. Yoshizaki and H. Wakatabe, Br. Patent 2297324 (1996); *Chem. Abstr.*, **125**, 245813 (1996).
129. D. Fumarola, *Pharmacology*, **3**, 215 (1970).
130. M. Shiino, Y. Watanabe and K. Umezawa, *Bioorg. Med. Chem.*, **9**, 1233 (2001).
131. M. Shiino, Y. Watanabe and K. Umezawa, *Bioorg. Chem.*, **31**, 129 (2003).
132. R.E. Garfield, A.T. Balaban, W.A. Seitz, D.J. Klein and M. Lesko, International Patent WO 96/36326 (1996).
133. Y. Hou, W. Xie, N. Ramachandran, B. Mutus, A.J. Janczuk and P.G. Wang, *Tetrahedron Lett.*, **41**, 451 (2000).
134. Y. Hou, W. Xie, A.J. Janczuk and P.G. Wang, *J. Org. Chem.*, **65**, 4333 (2000).
135. R. Castagnou and J. Pabia, *Bull. Soc. Pharm. Bord.*, **91**, 48 (1953).

136. D.K. Taylor, I. Bytheway, D.H.R. Barton, C.A. Bayse and M.B. Hall, *J. Org. Chem.*, **60**, 435 (1995).
137. R.E. Garfield, A.T. Balaban, W.A. Seitz, D.J. Klein and M. Lesko, US Patent 5698738 (1997).
138. I. Kende, L. Sumegi and F. Tudos, *Polymer Bull*. **3**, 325 (1980).
139. M. Paneli, H. Ouguenoune, F. David and A. Bolyos, *Anal. Chim. Acta*, **304**, 177 (1995).
140. M.O. Scates and E.F. Dougherty, Eur. Patent 0301879A2 (1989).
141. J. Ulbricht and S. Hoering, *Plaste Kaut*, **15**, 396 (1968).
142. G.E.F. Lundell and H.B. Knowles, *J. Ind. Eng. Chem.*, **12**, 344 (1920).
143. N. Öztekin and F.B. Erim, *J. Chromatogr. A*, **895**, 263 (2000).
144. O. Baudisch and V.L. King, *J. Ind. Eng. Chem.*, **3**, 629 (1911).
145. H. Biltz and O. Hödtke, *Z. Anorg. Chem.*, **66**, 426 (1910).
146. A.I. Popov and W.W. Wendlandt, *Anal. Chem.*, **26**, 883 (1954).
147. E. Bamberger and T. Ekecrante, *Compt. Rend.*, **29**, 2412 (1896).
148. P. Meunier, *Compt. Rend.*, **199**, 1250 (1934).
149. N.H. Furman, W.B. Mason and J.S. Pekola, *Anal. Chem.*, **21**, 1325 (1949).
150. J.E. Land and J.R. Sanchez-Caldas, *J. Less Common Met.*, **12**, 41 (1967).
151. M. Ghosh and C.N.R. Rao, *Chem. Phys. Lett.*, **393**, 493 (2004).
152. S. Thimmaiah, M. Rajamathi, N. Singh, P. Bera, F. Meldrum, N. Chandrasekhar and R. Seshadri, *J. Mater. Chem.*, **11**, 3215 (2001).
153. U.K. Gautam, M. Ghosh and C.N.R. Rao, *Chem. Phys. Lett.*, **381**, 1 (2003).
154. O.V. Kovalchukova, A.S. Bostanabad, N.N. Lobanov, T.A. Rudakova, P.V. Strashnov, Yu.A. Skarzhevskii and I.N. Zyuzin, *Inorg. Mater.*, **50**, 1093 (2014).
155. W.W. Wendlandt, S. Iftikhar Ali and C.H. Stembridge, *Anal. Chim. Acta*, **31**, 501 (1964).
156. J.A. Hrabie, J.R. Klose, D.A. Wink and L.K. Keefer, *J. Org. Chem.,* **58**, 1472 (1993).
157. T. Koenig, M. Deinzer and J.A. Hoobler, *J. Am. Chem. Soc.*, **93**, 938 (1971).
158. W.W. Wendlandt, *J. Anal. Chem.*, **27**, 1277 (1955).