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Recent contributions to the aqueous coordination chemistry of beryllium

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Abstract

The aqueous coordination chemistry and the structural chemistry of beryllium are reviewed focusing on simple fluoride, aquo, hydroxo, oxo, and peroxo complexes. Complex formation with the heavier halide and chalkogenide anions plays no role in aqueous solution. Formation and structure of beryllium carboxylates, oxo carboxylates, dicarboxylates, hydroxy-carboxylates, carbonates, phenolates, enolates, and polyolates under various pH regimes are also considered in the context of the bioinorganic chemistry of beryl-

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lium. The coordination chemistry of beryllium with amino acids is almost completely unexplored.

Keywords: Aqueous coordination chemistry; Beryllium; Bioinorganic chemistry of beryllium

1. Introduction

Compared to the chemistry of its neighboring elements in the periodic table-lithium, boron, sodium, magnesium, and aluminium, the chemistry of beryllium is undeveloped. While in the first half of the 20th century, 1900–1950, the slow growth in beryllium chemistry was probably due to the very limited uses of this element and its compounds [1,2], the situation was entirely different in the period 1950–2000: Beryllium-containing materials gained high importance in many key technologies including nuclear fission and nuclear fusion, radiation sources, high temperature ceramics for microelectronics, and high-performance alloys for naval, aircraft and space technology [3–6]. This development was paralleled, however, by a growing concern about the toxicity of beryllium and its compounds, which discouraged basic research on beryllium and even industrial activities [7–11]. The classification of beryllium as 'the most toxic non-radioactive element', placing beryllium right next to plutonium, made scientific studies extremely difficult and for some time brought investigations almost to a complete standstill in most academic chemistry departments. Already in the 1980's the theoretical studies outnumbered by far the experimental studies [12]. Organoberyllium chemistry was one of the few remaining research areas in the 1960's and 1970's, mainly owing to the extensive studies by Coates and his school, but this branch also became undernourished soon thereafter [12].

Progress in epidemiological and immunological research lead to a more temperate attitude towards beryllium toxicity in the 1990's. With appropriate precautions taken in a responsible way, beryllium chemistry research can be carried out safely just as any other experimental work in science. It appears that surveillance studies on the sensitivity (immunogenic status) of prospective workers in laboratories and plants where beryllium is handled in major quantities over extended periods may help to reduce the cases of chronic beryllium disease (CBD), the most ominous form of beryllium poisoning [13]. Most industrial chemistry of beryllium, and of course all beryllium toxicity, is based on equilibria in aqueous solutions [1,2,14]. This chemistry is exceedingly complex even in the absence of ligands other than water, hydroxide or oxide anions [15]. Not unlike aluminium, beryllium cations are amphoteric and form numerous aquo, hydroxo and oxo species of a variety of nuclearities. A literature survey shows that the pertaining equilibria are still poorly understood, and this is even more true in the presence of other components [1–6,14].

The present review summarizes some recent progress in the chemistry of aquo-, hydroxo-, oxo- and fluoroberyllates and of the corresponding beryllium carbonates and carboxylates. Hydroxy- and amino-carboxylates are particularly important classes of complexes because of their direct relevance to the physiological action of beryllium. They have often been related to acute or chronic beryllium poisoning, but no definite conclusions could be reached [7–11]. Recent theories consider the role of inorganic phosphates as the target functions for beryllium cations, but again no unambiguous evidence for such a mechanism of action is available.

2. Aquo-, hydroxo- and fluoroberyllates

Aqueous solutions of most beryllium(II) salts BeX_2 in the acidic regime (pH 1–4) contain the ions of complete electrolytic dissociation, namely the tetraaquoberyllium(II) dication and solvated anions. Owing to the high affinity of water for Be^{2+}, only very few of the anions compete successfully with H_2O for a place in the first coordination sphere of the metal dication. Notable exceptions are fluoride anions and chelating counterions (below). The $[Be(H_2O)_4]^{2+}$ dication is also present in many aquo complexes obtained upon crystallization [16–19].

With increasing pH condensation reactions ensue and finally precipitates of beryllium hydroxide (pH 5.8–9.0) appear, which redissolve as the pH is increased further. Complicated equilibria of several condensed hydroxyberyllate species have been proposed for these systems on the basis of very detailed electrochemical and other measurements of colligative properties, but there is no complete agreement about the individual components and their relative abundance [20–34].

With the advent of high-performance NMR equipment there was hope that ^{9}Be-NMR spectroscopy would shed some new light on the nature of hydroxyberyllate solutions. However, the overall range of ^{9}Be chemical shifts is generally very narrow, and the shift differences between individual species barely exceed the line-width and/or the standard errors of the experiments. NMR spectroscopy therefore did not prove to be of real value even at very high magnetic field strengths [35,36].

Early attempts to crystallize hydroxyberyllates were of limited success. Elemental analyses and powder diffraction data gave the crude stoicheiometry and preliminary structural data, but the structures of the hydroxyberyllate units could not be elucidated [37,38].

Recent work afforded detailed structural information on three polynuclear hydroxyberyllates [39–41], only one of which had been predicted from the earlier electrochemical studies. Mederos et al. were able to crystallize the picrate salt of the cyclic hexaquo-trihydroxo-triberyllate trication $\{[BeOH(H_2O)_2]_3\}^{3+}$ (Fig. 1) [39]. The existence of this trianion had been proposed based on potentiometric data with a maximum abundance in the pH range 4–6 [1,2,5,14].

For solutions at very high pH the literature proposed virtually unanimously the dominant role of the tetrahydroxyberyllate dianion $[Be(OH)_4]^{2+}$, and a few salts of the corresponding composition $M'[Be(OH)_4]$ or $M_2[Be(OH)_4]$ had been isolated, but not structurally characterized (Eq. (1)). Scholder et al. was able to crystallize the calcium and strontium salts which were assigned the above formula with $M' = Ca$, Sr (as the sesquihydrates) [38].

$$Be(OH)^2 + M'(OH)_2 \rightarrow M'[Be(OH)_4] \qquad (1)$$

In attempts to repeat this work (at pH 13.5–14.0) and to determine the structure of the product, crystals of the net composition $Ca[Be(OH)_4]\cdot 1.5H_2O$ were indeed obtained [40]. However, the structure turned out to be not as expected. The lattice contains two calcium cations, three water molecules, a hydroxide–hydrate anion, and a diberylliumheptahydroxide trianion: $Ca_2[Be_2(OH)_7](HOHOH)(H_2O)_2$. The dinuclear trianion has the structure of two vertex-sharing tetrahedra, while the hydroxide–hydrate anion has a Z-shaped configuration (Fig. 2(a,b)).

It thus appears that even at very high OH^- concentration (pH greater than 11.5) the equilibrium shown in Eq. (2) is not shifted fully to the tetra(hydroxo)beryllate dianion. Instead, a hydroxide anion is trapped by a water molecule to give the $[HOHOH]^-$ anion. This anion was observed in other salts and its Z-structure is known [42,43].

$$2[Be(OH)_4]^{2-} \underset{+OH^-}{\overset{-OH^-}{\rightleftharpoons}} [Be_2(OH)_7]^{3-} \qquad (2)$$

$[Be_2(OH)_7]^{3-}$ has not been observed previously and its role as a component of strongly alkaline beryllate solutions had not been considered. Its formation may be induced in the crystallization process by the large dications (Ca^{2+}, Sr^{2+}).

In order to further delineate the influence of the cations on the nature of the hydroxoberyllate species, related experiments with NaOH were carried out [41]. Crystal growth was finally successful from aqueous sodium beryllate solutions at pH values as high as 13.2 upon layering with acetone at 20°C (Eq. (3)). The net composition of the product is $Na_2[Be_4(OH)_{10}](H_2O)_5$, and the lattice is composed of hydrated sodium cations in two different environments, interstitial water molecules, and tetraberylliumdecahydroxide dianions (Fig. 3(a–c)).

$$2NaOH + 4Be(OH)_2 \rightarrow Na_2[Be(OH)_{10}] \qquad (3)$$

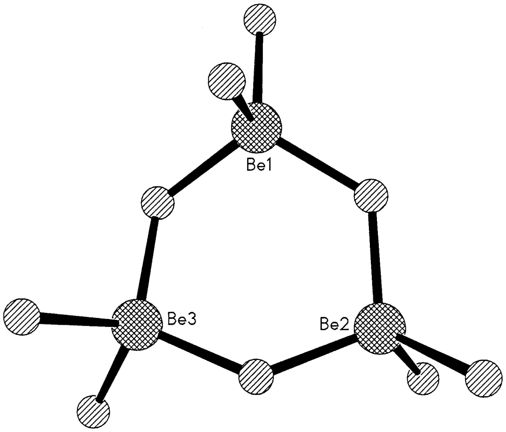

Fig. 1. Structure of the cyclic trication $[Be_3(OH)_3(H_2O)_3]^{3+}$ in the picrate salt.

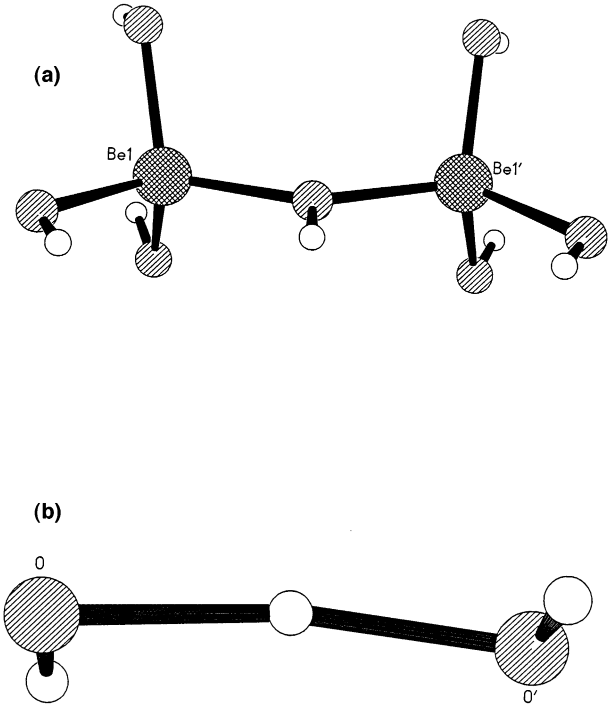

Fig. 2. (a) Structure of the trianion $[Be_2(OH)_7]^{3-}$ in the calcium salt $Ca_2[Be_2(OH)_7](HOHOH)(H_2O)_2$. (b) Structure of the HOHOH anion in this salt.

The tetranuclear dianion has an adamantane structure with six hydroxide anions bridging the edges of a tetrahedron of beryllium atoms. Each of these beryllium atoms bears one terminal hydroxide anion to complete its tetrahedral coordination sphere of four oxygen atoms. This structure is novel in beryllium chemistry. Again, its formation may be induced by the counterions in the crystallization process. Quantum chemical calculations (MP2, DFT) have consistently shown, however, that the free cluster (in the gas phase) is a stable species which has a ground state structure very similar to that found in the crystal [41]. Nevertheless, its presence in strongly alkaline solution remains an open question.

The close relation between hydroxide and fluoride anions suggested complementary studies of aqueous beryllium fluoride solutions in the absence of extra fluoride sources and at high concentrations of excess fluoride [44]. These investigations did not rely only on crystallization of well-defined products, but could be complemented by NMR measurements. Although the ^{9}Be spectra suffer from the narrow range of chemical shifts and the line broadening by quadrupolar nuclei, the ^{19}F spectra have all advantages of well-resolved first-order spectra. Several NMR studies of aqueous beryllium fluoride solutions were published, but with only a limited range of (relative) concentrations (Be^{2+}/F^-) and pH [45–49].

Aqueous solutions of BeF_2 at 20°C show a pH of 4.5. The ^{9}Be-NMR spectrum is a complicated pattern which results from an intimate overlap of the multiplet resonances of at least three species: $[BeF(OH_2)_3]^+$, $[BeF_2(OH_2)_2]$, and $[BeF_3(OH_2)]^-$ (Fig. 4). The lines of the overall multiplet belong to a 1:1 doublet, a 1:2:1 triplet and a 1:3:3:1 quartet of these three complexes, which have similar coupling constants and chemical shifts progressing in a systematic way (Table 1).

This composition is also immediately obvious from the ^{19}F-NMR spectrum (Fig. 5), which has three different 1:1:1:1 quartets (^{9}Be: $s = 3/2$). The relative intensity is roughly 10:30:60 suggesting that about one third of the hydrated BeF_2 molecules (Eq. (4)) undergo ligand redistribution and electrolytic dissociation as expressed by Eq. (5). This finding is in agreement with the results of early potentiometric and conductivity measurements [23,27,28,33,34].

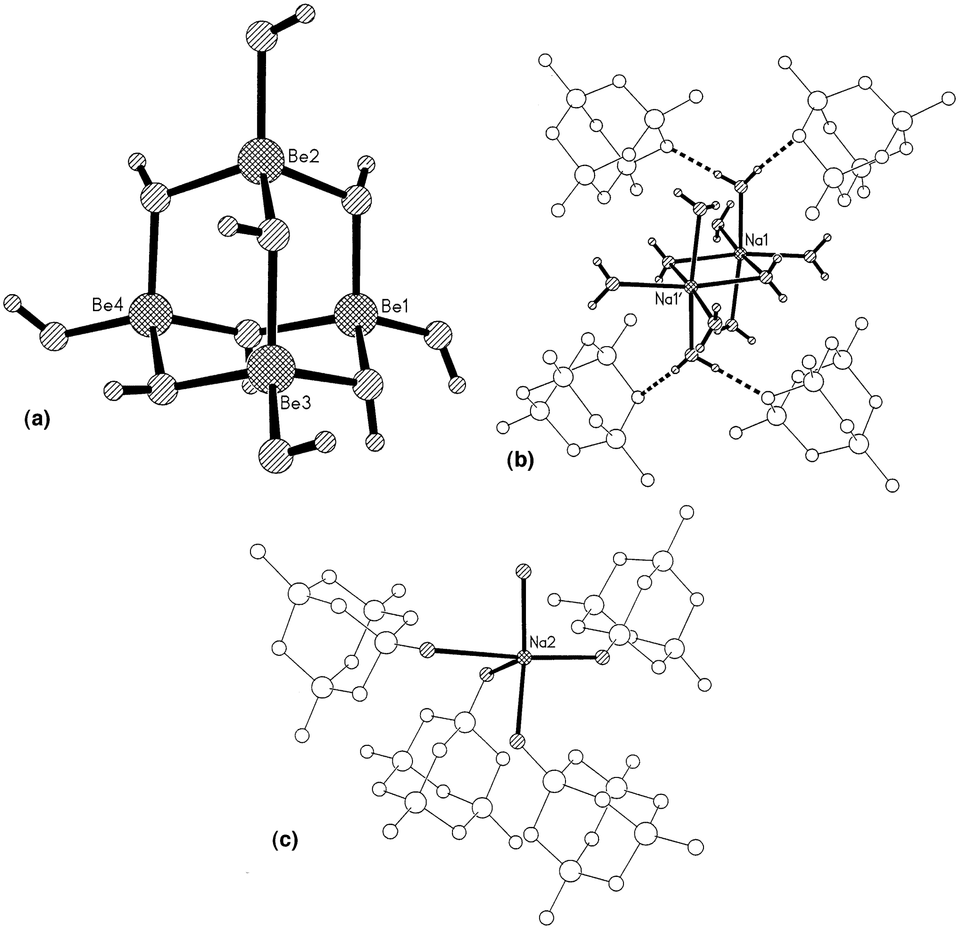

Fig. 3. (a) Structure of the dianion $[Be_4(OH)_{10}]^{2-}$ in the sodium salt $Na_2[Be_4(OH)_{10}](H_2O)_5$. ((b) and (c)) Environment of the sodium atoms Na1 and Na2, respectively, in this salt.

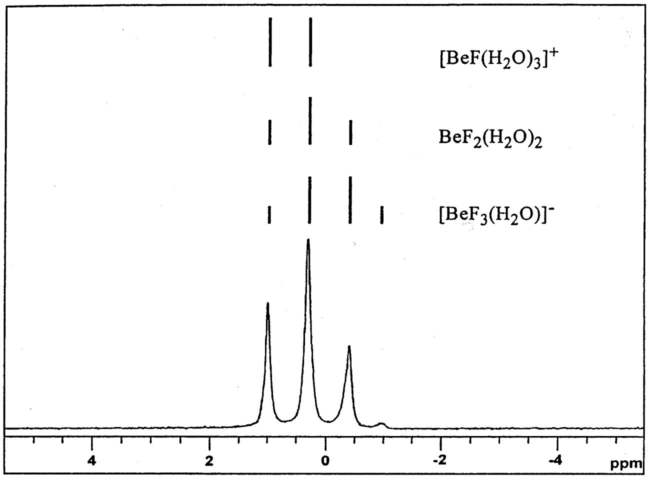

Fig. 4. ^{9}Be-NMR spectrum of an aqueous solution of beryllium difluoride in water at room temperature. The components of the multiplet are shown in the upper part.

Table 1

	^{19}F-NMR		^{9}Be-NMR	
	δ (ppm)	$^{1}J_{\text{F–Be}}$ (Hz)	δ (ppm)	δ_{theo} (ppm)
$[BeF_4]^{2-}$	−87.71−−87.41	33.6	−0.34−−0.28	−1.68
$[BeF_3(H_2O)]^-$	−90.22−−88.81	36.3	−0.13–0.02	
$[BeF_2(H_2O)_2]$	−92.65−−91.11	39.3	0.17–0.33	−0.05
$[BeF(H_2O)_3]^+$	−95.55−−93.98	41.2	0.53−0.68	0.38

$$BeF_2 + 2H_2O \rightarrow [BeF_2(OH_2)_2] \tag{4}$$

$$2BeF_2(OH_2)_2 \rightleftharpoons [BeF(OH_2)_3]^+ + [BeF_3(OH_2)]^- \tag{5}$$

At reduced relative concentration of F^- (F^-/Be^{2+} smaller than 2) the intensity of the signal of $[BeF(OH_2)_3]^-$ increases on the expense of that of $[BeF_3(OH_2)]^-$ (Fig. 5). At very low F^- concentrations $Be(OH)_2$ starts to precipitate.

At high relative F^- concentrations (F^-/Be^{2+} greater than 2) the signal of $[BeF(OH_2)_3]^+$ decreases and a fourth quartet appears which is readily assigned to the tetrafluoroberyllate dianion $[BeF_4]^{2-}$. It corresponds to a 1:4:6:4:1 quintet in the ^{9}Be-NMR spectrum of the same solutions. It is interesting to note that even at a F/Be ratio greater than 4 there is significant dissociation into complexes with less than four fluoride anions at the beryllium centers (Fig. 5). Water molecules are thus competing successfully with fluoride anions for a place in the coordination sphere of the Be^{2+} dication.

At pH 10.5 the aqueous solutions of BeF_2 give a precipitate of $Be(OH)_2$ while the supernatant shows only the ^9Be and ^{19}F resonances of the $[BeF_4]^{2-}$ dianion. Alkali hydroxides appear to induce the redistribution of F^- and OH^- anions shifting the equilibrium completely towards tetrafluoroberyllate dianions owing to the precipitation of beryllium hydroxide.

There has been no evidence of the existence of condensed, di- or polynuclear fluoroberyllates in any of the experiments . Diberylliumheptafluoride trianions $[Be_2F_7]^{3+}$ were detected in the crystal structure of salts like $Li_2Rb[Be_2F_7]$ [50], but not all of these experiments could be repeated in the present author's laboratory. The analogous $[B_2F_7]^-$ has also been confirmed [51]. The fluoride analogues of the hydroxyberyllates $[Be_2(OH)_7]^{3-}$ and $[Be_4(OH)_{10}]^{2-}$ thus have not yet been detected in the beryllium fluoride system.

It should be pointed out that the well-resolved ^9Be- and ^{19}F-NMR spectra clearly demonstrate that fluoride exchange between different beryllium centers is very slow on the NMR time scale. In aqueous solution with a pH close to neutral the mean time of residence of F^- at Be^{2+} is almost in the range of seconds and allows (a) separate registration of different F resonances at ambient temperature and (b) the observation of resolved ^9Be–^{19}F coupling. This phenomenon also makes it unlikely that condensed species like $[Be_2F_7]^{3-}$ play any significant role in equilibrium mixtures of various aqueous fluoroberyllates.

3. The quest for beryllium peroxides [52]

The peroxides of lithium and boron are classics in the inventory of compounds of these two elements, and several of these peroxides are important industrial chemicals: Lithium peroxide is a potent disinfectant for water systems, and an

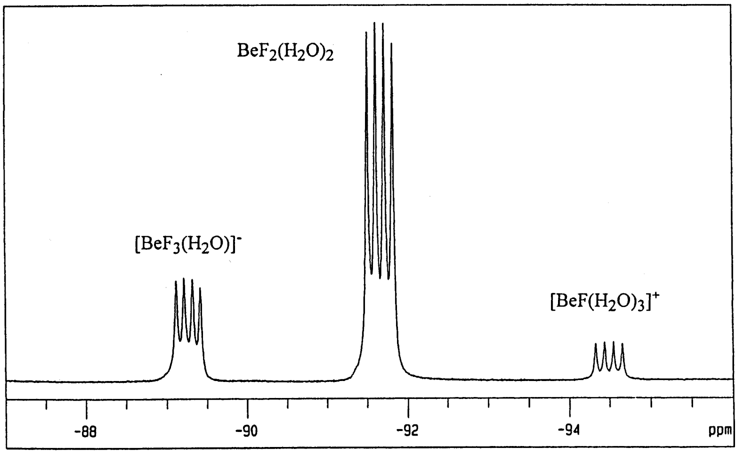

Fig. 5. ^{19}F-NMR spectrum of an aqueous solution of beryllium difluoride at room temperature.

oxygen source in submarine and aerospace technology. Several peroxoborates are used on a grand scale as the oxidative components of detergents.

With this background it is very surprising that there is no experimental proof documented in the literature for the existence of any beryllium peroxide compound [1–6,14]. All recent pertinent preparative attempts in the TUM laboratories, using various beryllium salts and various peroxides as reagents under mild conditions, were also unsuccessful. ^{1}H- and ^{9}Be-NMR investigations of aqueous solutions containing beryllium salts and hydrogen peroxide in a broad pH range gave no evidence for the presence of significant amounts of peroxoberyllates as components of the manifold of equilibria prevailing in such solutions.

Quantum chemical calculations have therefore been carried out to delineate the energetics and structures of various beryllium peroxide model compounds. Standard Hartree-Fock ab initio and density functional methods were employed at various levels of sophistication. The series of prototypes consisted of $[BeOH]^+$, $Be(OH)_2$, $[Be(OH)_4]^{2-}$, Be(OH)(OOH), $Be(OOH)_2$, $[Be(O_2)_2]^{2-}$, $[Be(O_2)(OH_2)_2]$, and $[Be_2(O_2)_2(OH_2)_4]$ (all in the gas phase). The results for the known tetraaquo complex are in excellent agreement with experimental data. Surprisingly, the triatomic cation $[BeOH]^+$ has been found to have a linear structure. In the mononuclear peroxides, the peroxide groups are chelating units at in most cases tetrahedrally coordinated metal atoms. The binuclear complex has a puckered six-membered ring structure. A significant lengthening of the O–O bonds upon coordination to the Be^{2+} center was calculated, but it is unlikely that the polarization of the peroxide group by the high charge–density at Be^{2+} is so significant to cause the intrinsic instability of beryllium peroxides [52]. It rather appears that hydrogen peroxide and its anions are unable to compete with water and its anions for a coordination site at a beryllium center, because peroxides are much weaker donors.

It should be noted that the area of aluminium peroxides is a similar white patch on the map of metal and metalloid peroxides, reminiscent of the well established 'cross-relation' of Be and Al in the periodic table of the elements.

4. Beryllium carboxylates and beryllium oxo carboxylates

It was mentioned already in the classical literature that it is difficult to isolate simple beryllium salts of monocarboxylic acids RCOOH [1,2]. Attempts to generate salts of the composition $(RCOO)_2Be$ more often than not resulted in the formation of tetranuclear oxo carboxylates $[(RCOO)_6Be_4O]$. In fact, compounds of this composition are the standard products of any reactions between beryllium salts and carboxylates in aqueous solution at ambient temperature [53–56] (Eq. (6)). It requires considerable effort to avoid the condensation reaction, which affords the tetranuclear species [57].

$$4[Be(OH_2)_4]^{2+} + 8RCOO^- \rightarrow [(RCOO)_6Be_4O] + 2RCOOH + 15H_2O \qquad (6)$$

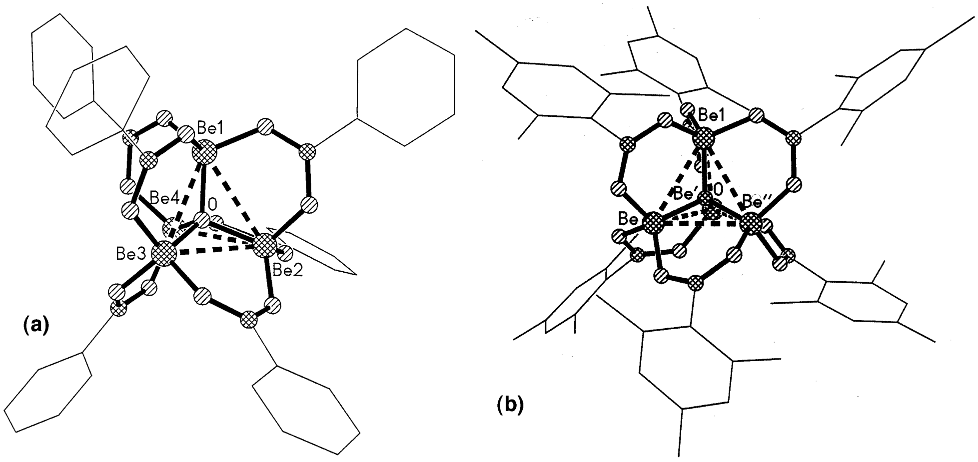

Fig. 6. Molecular structures of tetraberyllium-oxo-hexacarboxylates. (a) Benzoate; (b) Mesitylcarboxylate.

Early X-ray diffraction experiments [58,59] have shown that the tetraberyllium oxo hexaacetate has a cage structure with an oxygen atom in the center of a tetrahedron of four beryllium atoms. The six edges of this tetrahedron are bridged by the acetate groups. The unique oxygen atom is thus the bridgehead atom for no less than six six-membered rings, while each beryllium atom is shared by three of these six-membered rings. Except for the acetate, no other carboxylates have been structurally characterized, but the oxo nitrate and carbonate are known to have related structures [60,61].

In more recent experiments arylcarboxylic acids have been employed for the construction of the $[(RCOO)_6Be_4O]$ cages, because the rigid aryl groups R were expected to lead to interesting supramolecular arrays [62]. Single crystals could be grown of the benzoate and mesitylcarboxylate, and both compounds were found to follow the same structural principle (Fig. 6(a,b)). The lattices give room for interstitial solvent molecules, which separate the cages rather efficiently. Unlike the experiments with acetate, benzoate or mesitylcarboxylate, all preparative work aimed at the synthesis of the formiate gave no product of the expected composition. While the other three homologues are soluble in organic solvents and volatile in a vacuum, the formiate appears to have entirely different properties, for which we have presently no explanation.

The geometric details of the cages are very similar and suggest that the central Be_4O element together with the 12 carboxylate oxygen atoms as nearest neighbors is a very rigid and robust unit.

Surprisingly, the fragmentation of the molecular ions generated from the tetraberyllium oxo hexacarboxylates in a mass spectrometer follows a uniform pattern and leads to cations of the type $[(RCOO)_3Be_3O]^+$ in highest abundance ($R = Me$, Ph, Mes) [62,63]. This observation suggests a pronounced energy minimum of the trinuclear cores which must result from a loss of $[(RCOO)_2Be]$ and $[RCOO]$ units from the parent compounds. A highly symmetrical structure of point group D_{3h} was proposed for the new cations and could be confirmed by quantum chemical calculations (Fig. 7). Structures were computed for cations with $R = H$, Me and compared with a few related systems (Fig. 8). The system is found completely planar.

It should be noted that e.g. phenalenyl anions (Fig. 8) are strictly iso-electronic as suggested by the same electron count for CC, BN and BeO units [64]. However, the quantum chemical calculations show that there is no significant ring current in the beryllium oxo carboxylate cation owing to the atom sequence of the periphery and its centroid and to the high polarity of the Be–O units. Attempts to isolate salts of these cations met with no success. It is very likely that the strong acceptor character of the three-coordinate beryllium atoms of the trinuclear cation leads to a reaction with virtually any anion or solvent molecule.

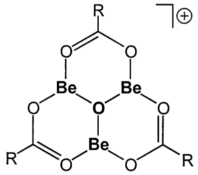

Fig. 7. Proposed structure of the cations $[Be_3O(OCOR)_3]^+$ observed in the mass spectra of tetraberyllium-oxo-hexacarboxylates (R = Me, Ph, Mes).

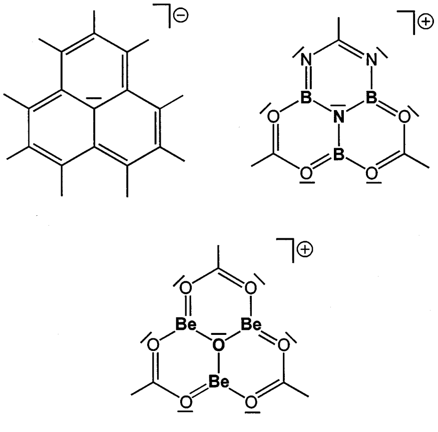

Fig. 8. Analogies in the electronic structures of the cation shown in Fig. 7 of a related boron-nitrido-carboxylate cation, and the phenalenyl anion.

5. Beryllium complexes of dicarboxylic acids

Contrary to the chemistry of beryllium monocarboxylates, where oxo compounds with bridging carboxylate groups $[(RCOO)_6Be_4O]$ play a central role, the coordination chemistry of beryllium with dicarboxylate anions is largely dominated by the chelate effect of these ligands. Equimolar quantities of Be^{2+} and $[E(COO)_2]^{2-}$ units [E = saturated, unsaturated or arene bridging] in aqueous solution at low pH give diaquo complexes $[E(COO)_2]Be(OH_2)_2$ with one chelate ring, while for the 1:2 ratio of reagents and at pH larger than 7 dianionic 1:2 complexes of the general type $\{[E(COO)_2]_2Be\}^{2-}$ are formed. Crystal structures were recently determined for the potassium beryllium-bis-maleate (E = –CH=CH–) [65] and for a beryllium-bis-phthalate ($E = 1,2\text{-}C_6H_4$) [64] with keto-ammonium cations $[MeCOCH_2\text{-}CMe_2NH_3]^+$ (Fig. 9(a, b)). In both dianions the beryllium atoms are spiro centers for two seven-membered rings. Structural data are also available for the oxalate [67] and malonate [66], and analytical and spectroscopic data have been reported for the succinate [65].

NMR studies at variable pH have shown that in the intermediate pH range (3–7), condensation products are formed including mainly the trinuclear trianions $\{Be_3(OH)_3[E(COO)_2]_3\}^{3-}$, for which a crystal structure has also been presented with $E = CH_2$ (malonate) and potassium counterions [68,69] (Fig. 10). In this structure, the malonate donor may be replaced by pyridine-2-carboxylate or pyrazolylborate anions [70–72]. The six-membered ring array $[Be_3(OH)_3]$ is derived from the corresponding tricationic hexaaquo complex (above).

The experiments with dicarboxylic acids have demonstrated that these chelating units can substitute two water molecules of the beryllium tetraaquo complex in the acidic to neutral regime. Monocarboxylic acids, which can only bridge two beryllium centers in a strain-free arrangement, will not displace water from the inner coordination sphere of beryllium under these conditions. Squaric acid was found to be monodentate in crystals of the trihydrate $[Be(C_4O_4)(H_2O)_3]$ [19].

Rigid dicarboxylate dianions with a structure ruling out any chelation are also poor ligands for Be^{2+}. Beryllium acetylenedicarboxylate tetrahydrate contains the $[Be(OH_2)_4]^{2+}$ dication and completely separated $[O_2CCCCO_2]^{2-}$ dianions [18].

Nitrilo-tripropionic acid $N(CH_2CH_2COOH)_3$ forms an anionic mononuclear complex with tetrahedral NO_3 coordination of the beryllium atom. In the sodium salt, the water molecules of the trihydrate are interstitial molecules with no beryllium contact [73].

6. Beryllium complexes of hydroxycarboxylic acids

Beryllium hydroxycarboxylates play an important role in the therapy of beryllium poisoning, because sulfosalicylic acid (SSA) has been used successfully as a chemotherapeutic agent [1,2,11]. Sulfosalicylic acid was chosen as a water-soluble form of salicylic acid and is believed to trap beryllium dications in body fluids by chelation. However, the complexes were not isolated and their stoicheiometry was

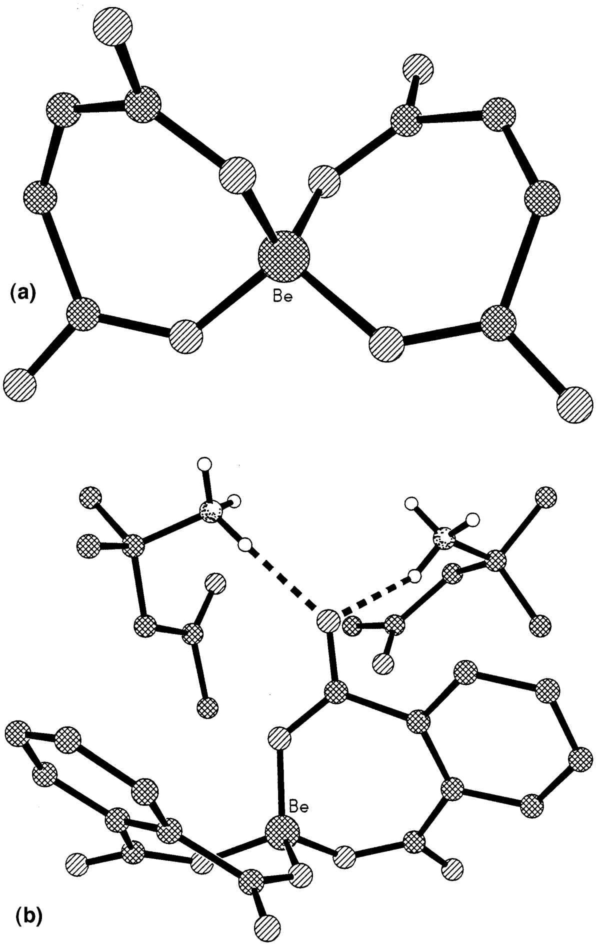

Fig. 9. Double-chelated dicarboxylato-beryllium dianions: (a) Molecular structure of the di(maleinato)-beryllate dianion in the potassium salt. (b) Molecular structure of the di(phthalato)beryllate dianion in a ketoammonium salt.

unknown. Many other hydroxycarboxylic acids were also tested in this context, including glycolic acid. The latter was reported to form a complex salt of the stoicheiometry $Na_2[Be_3(C_2H_2O_3)_4](H_2O)_{4.5}$ of unknown structure [74]. In an attempt to answer these open questions preparative and structural studies were recently initiated which provided the basic information required [75].

The experimental results of Rosenheim and Lehmann regarding the beryllium glycolate [74] could largely be confirmed in that a crystalline material was obtained which had the composition $Na_4[Be_6(OCH_2CO_2)_8](H_2O)_{9.5}$ (Fig. 11(a,b)). It is important to note that this product is formed in aqueous solution at pH 5.7, near physiological conditions. The tetraanion is a hexanuclear cluster with the beryllium atoms arranged in a peculiar array of non-crystallographic D_{2d} symmetry (Fig.

11(a)). All carboxylic and alcoholic groups are deprotonated, and two oxygen atoms of each glycolic acid become part of the coordination sphere of the metal atoms. The dianions of glycolic acid are chelating the beryllium atoms, which are in a tetrahedral environment of oxygen atoms (Fig. 11(b)). Four Be atoms are mono-chelated (Be2, Be3, Be5, Be6), while two unique Be atoms are bis-chelated (Be1, Be6). Perhaps surprisingly, the alkoxide oxygen atoms are found as three-coordinate bridging atoms between three beryllium atoms. The water molecules take up interstitial positions and are hydrogen-bonded to their neighboring molecules.

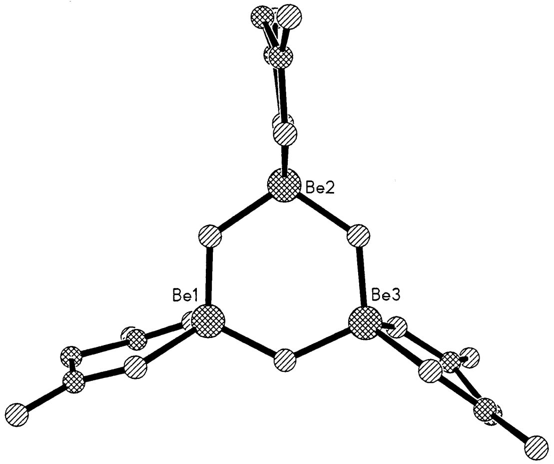

Fig. 10. The cyclic triberyllium-trihydroxo-trimalonato trication in the potassium salt.

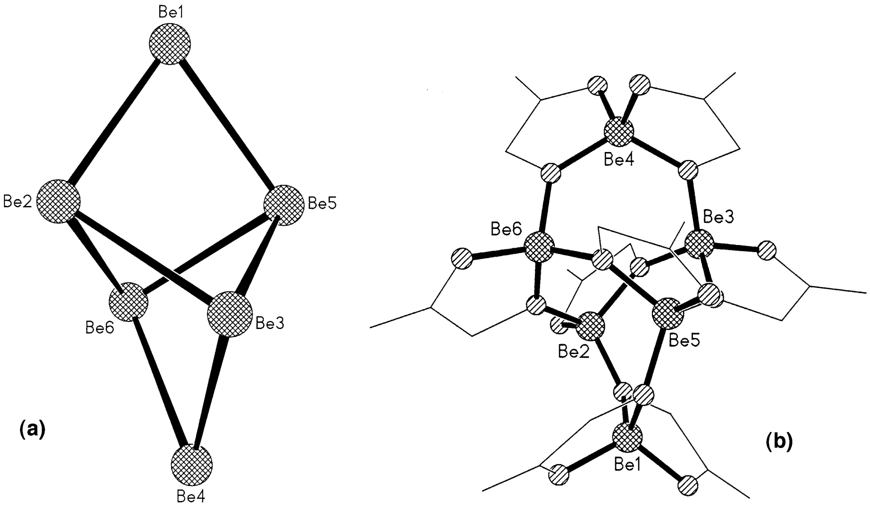

Fig. 11. The hexanuclear beryllium glycolate. (a) Structure of the beryllium core unit. (b) Chelating/bridging motif of the glycolate ligands.

The formation, stoicheiometry and structure of the new sodium beryllium glycolate hydrate in water at room temperature and at neutral pH, demonstrate that beryllium dications are capable to deprotonate aliphatic alcohols under these near-physiological conditions. The compound can be dissolved in water and the ^{9}Be spectra of the resulting solutions (pH 6) are in agreement with an intact cluster structure. This high affinity of beryllium for alcoholic groups is only paralleled by that of aluminium, which has a similar charge/radius ratio. An example in this case is aluminium citrate, which also features a deprotonated C–OH group [76].

Chelation of beryllium dications by salicylic and cresotic acid (3-methyl-salicylic acid) in aqueous solution at near-neutral pH could be confirmed by spectroscopic studies and by isolation of crystalline products. Beryllium salicylate was recovered as a dihydrate and its crystal structure determined (Fig. 12(a)) [77]. The carboxylic and phenolic groups are deprotonated and a six-membered ring is formed. Two water molecules complement the environment of the Be atom. The cresotate has the same composition, but it could not be crystallized [77].

At pH 9 or higher, and with two equivalents of salicylate/cresotate, the bis-chelated anions are generated in which the Be atom is at a spiro-center of two six-membered rings. Fig. 12(b) shows the dianion of the salt $(NH_4)_2[Be(C_6H_4OCO_2)_2](H_2O)_{2.25}$. The analogous sodium salt is also known [78].

When analogous reactions were carried out with sodium cresotate at pH 11.5 without exclusion of carbon dioxide, a crystalline material was isolated which was shown to be a mixed hydroxo cresotate carbonate the trianion of which is shown in Fig. 13 [77]. The Be atoms of the dinuclear complex are chelated by cresotate dianions and bridged by one hydroxo and one carbonate unit to form a six-membered ring. The compound is an octahydrate. Its water molecules are not involved in Be complexation.

The above results have several implications:

1. The experiment has shown that beryllate solutions will take up CO_2 to form carbonato complexes. Inert gas protection is therefore required if carbonate formation is to be excluded.
2. In physiological solutions with their bicarbonate buffer, the HCO_3^-/CO_3^{2-} anions will compete with other oxygen donor molecules for any beryllium present in the system.
3. If several different donors are available, mixed complexes must be considered. The above trianion is composed of hydroxide, carbonate and 3-methyl-salicylate ligands for two beryllium atoms.

7. Beryllium complexes of enols and polyols

The behavior of salicylic acid towards beryllium salts suggested investigations with catechol with its two phenolic groups in the *ortho* position. Such studies are also of interest because of the role of catecholamines as bioregulators in biological systems, where beryllium may interfere.

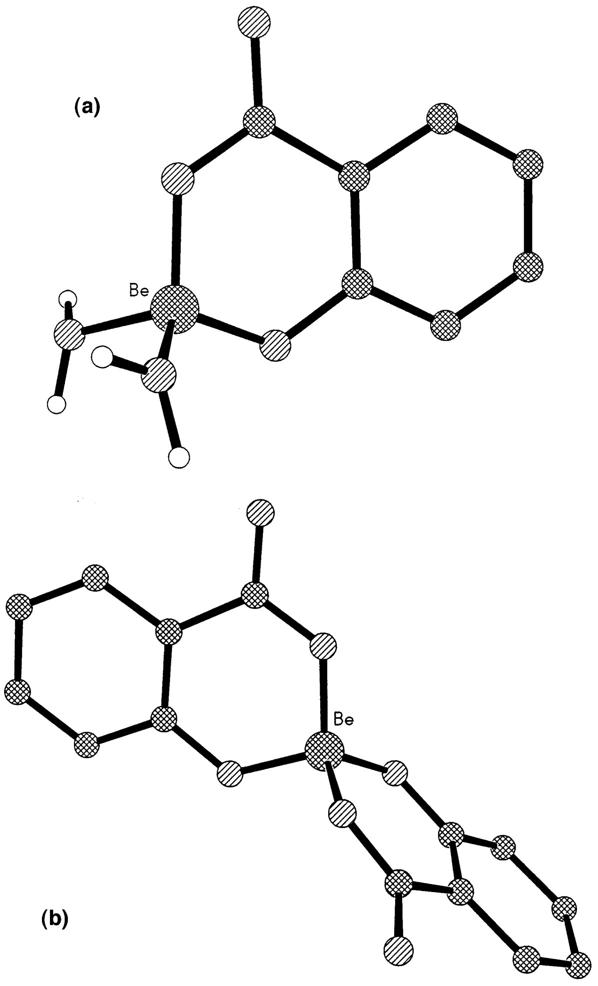

Fig. 12. Beryllium salicylates. (a) Molecular structure of Diaquo-beryllium-salicylate. (b) Structure of the bis(salicylato)beryllate dianion in the ammonium salt.

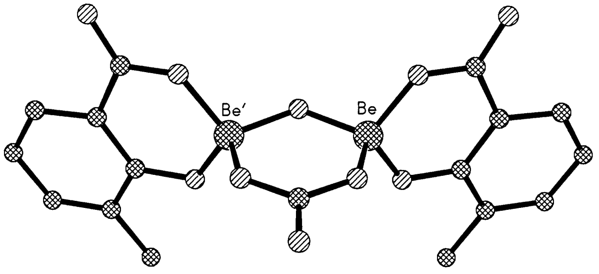

Fig. 13. Structure of the di-beryllium-hydroxo-carbonato-bis(cresotate) trianion in the sodium salt.

From aqueous solutions of beryllium salts and catechol at pH greater than 11, salts with the bis-chelated dianions can be isolated. The crystal structure was determined for $Na_2[Be(OC_5H_4O)_2](H_2O)_5$ which contains the beryllium atom as a spiro-center of two five-membered rings (Fig. 14) [78]. At lower pH the diaquo complex $[OC_6H_4O)Be(OH_2)_2]$ is likely to be present, but the complex could not be isolated.

Beryllium bis(acetylacetonate) was described in very early studies and its crystal structure has subsequently been determined [79–81]. It is completely analogous to that of many related metal(II) 'acac' complexes (Fig. 15).

Investigations in the beryllium chemistry of aliphatic polyols have been rare, but a well-defined complex of a cyclic diol (anhydroerithritol) has recently been obtained and fully characterized (Fig. 16) [82]. The structure of the trinuclear beryllium complex of a trideoxy-*cis*-inositol is more complicated, but follows the same principle [83]. These important results are proof for the affinity of beryllium dications for simple aliphatic alcoholic groups if some chelate assistance is provided. They indicate that natural carbohydrates (sugars) may be targets for beryllium complexation under physiological conditions.

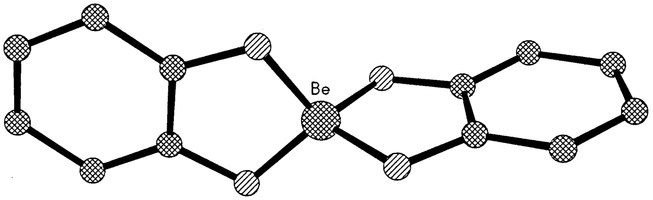

Fig. 14. Structure of the bis(catecholato)beryllate dianion in the sodium salt pentahydrate.

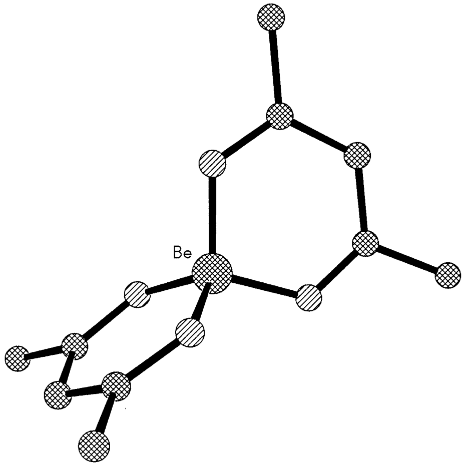

Fig. 15. Molecular structure of beryllium-bis(acetylacetonate).

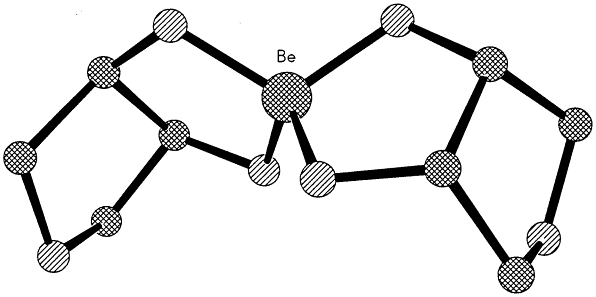

Fig. 16. Structure of the beryllium-bis(anhydroerithritolate) dianion.

8. Miscellaneous

While there is evidence for direct interaction of beryllium salts with carboxylic acids, hydroxycarboxylic acids and polyols, the mode of complexation with amino acids is still unknown [11,14]. No discrete complex of beryllium with a standard amino acid could be isolated and structurally characterized. This is also true for aspartic and glutamic acid [84,85], for which there is ample information regarding the coordination to all other earth alkaline metals, magnesium, calcium, strontium, and barium [86]. Aspartate and glutamate are known to be the prime binding sites for hard metal atoms at proteins [87]. A whole series of preparative, analytical, and spectroscopic studies of the systems beryllium/aspartic and glutamic acid in water or mixed solvents have not given any clue regarding the nature of interaction between the components [11,85]. Therefore, there is as yet no model system for the binding of beryllium cations to peptides and proteins.

Beryllium salts of common mineral acids crystallize as hydrates in which the anions have no contact with the beryllium atom. This has been demonstrated for the perchlorate, sulfate and nitrate by structure analyses [16–19]. However, for precipitates obtained with phosphoric acids (*ortho*-, pyro-, poly-, *meta*-phosphoric acids, phosphonic and phosphinic acids etc.) the situation is less clear [1–4,14]. Only very few structural details are available [5]. Because of the relevance of phosphate buffers as well as mono-, di- and triphosphates to biological systems, this area requires more research attention in the future [87].

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