New preparation, first structure analysis and magnetism of the long-known nickel benzoate trihydrate: A linear Ni···Ni···Ni polymer and its parallels to the active site of urease

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Abstract: Nickel benzoate trihydrate (**1**) was prepared in single-crystalline form by the reaction of nickel carbonate with benzoic acid in boiling aqueous solution. Its crystal structure comprises positively charged $[Ni(Bz)(H_2O)_2]_n^{n+}$ chains, benzoate anions and one independent water molecule of solvation. The hexacoordinated Ni(II) centres in the chains are triply bridged by one *syn-syn* carboxylato and two aqua bridges. Adjacent chains are linked by O-H···O hydrogen bonds [O···O distances in the range 2.647(3) - 2.684(3) Å] through solvate water molecules and benzoate anions. Thermal analysis revealed that **1** is stable up to 100 °C; further heating leads to full dehydration accompanied by an additional decomposition reaction, as characterized by IR spectra of the intermediates. Geometrical features about the Ni centers are compared to similar features at the active sites of urease. The effective magnetic moment per formula unit μ_{eff} has a value of 3.17 μ_B at room temperature and upon cooling reaches a maximum value of 12.39 μ_B at T = 4.6 K, indicating ferromagnetic coupling between the nearest Ni(II) atoms [3.0671(1) Å] within the chains; at lower temperature this is counteracted by zero-field splitting.

Introduction

If chemical simplicity could be conflated reliably with ease of preparation and characterization, then various forms of nickel benzoate, whose trihydrate is the subject of this report, would have been characterized many decades ago. The trihydrate has long been known, its preparation reported by Ephraim and Pfister[1] in 1925 and by Pfeiffer and Müllenheim[2] in 1933. From that time several partial studies of different forms of nickel benzoate (trihydrate, tetrahydrate, anhydrous) were reported.[3,4,5] More recently the crystal structure of the dinuclear "paddle wheel" type complex $[Ni_2(\mu_2\text{-}Bz)_4(HBz)_2]$, formed fortuitously under solvothermal conditions beginning with nickel(II) nitrate, sodium benzoate and 2,2′-bipyridine, was reported.[6] However, a structure analysis of the title trihydrate by diffraction methods, the present-day *sine qua non* standard for characterizing new coordination compounds, has remained elusive.

As one of the simpler and more easily handled carboxylates, benzoate has been used in studies of more complex systems in which carboxylates are common, such as MOFs[7] and magnetic solids.[8] The ubiquity of carboxylates in natural compounds is well known, including in enzymes[9] in which, *inter alia*, they participate at the active sites for biocatalytic processes.

The different manners in which a carboxylate function such as that of benzoate can coordinate metal centers -- as a terminal, chelating, or bridging ligand -- permit a wide variability in the processes and structures in which this group is involved. As a bridge, carboxylate participates in discrete molecules and extended nets, and possesses a special capacity for drawing metal centers closer together than do, for example, cyanide or azide bridges. This property propitiates magnetic interactions and can activate the metal centers for catalytic applications.

Among the metals that have been studied in carboxylate complexes, nickel (II) when six-coordinate -- i.e., in octahedral coordination or in a distorted shape derived from the octahedron -- is expected to be paramagnetic with S = 1. Nickel also appears at the active sites of numerous enzymes,[10] including urease, in which the active sites display a pair of nickel atoms bridged by one carboxylate and one water molecule;[11] compounds with two nickel atoms bridged by two carboxylate groups and one water molecule have been used as model systems for understanding the workings of urease.[12,13]

Ni(II) complexes with one-dimensional (1D) polymeric structures and with S = 1 have been the subjects of many experimental and theoretical studies associated with magnetic phenomena.[14-19] The synthesis of 1D Ni(II) coordination polymers is usually mediated by suitable bridging ligands linking Ni(II) central atoms, e.g., pyrazine (*pyr*) in $\{[Ni(pyr)(H_2O)_4](NO_3)_2\cdot 2H_2O\}_n$,[20] bromide anions in $\{[Ni(Br)_2(tz)_2]\}_n$ (*tz* = 1,3-thiazole)[21] or azido anions in $[Ni(3,5\text{-}dmpy)_2(N_3)_2]_n$ (3,5-*dmpy* = 3,5-dimethylpyridine).[22] Using the complex anion $[Ni(CN)_4]^{2-}$ as a bridging unit, we have previously synthesized several chain-like structures, e.g., $Ni(en)_2Ni(CN)_4$[23] and $Ni(dien)(mea)Ni(CN)_4$ (*dien* = diethylenetriamine, *mea* = 2-aminoethanole);[24] the disadvantage of these cyanidocomplexes as regards their magnetism is the large distance between the paramagnetic Ni(II) atoms (approximately 10 Å), resulting in very weak intrachain exchange interactions. Recently, in our quest for 1D Ni(II) systems with shorter separations between Ni(II) centers, we have prepared a microcrystalline sample of the Haldane gap system $[Ni(bpy)(ox)]_n$ (*bpy* = 2,2-bipyridine, *ox* = oxalate), in which the Ni(II) atoms are bridged in bis-chelating fashion by oxalate.[25]

In continuation of our studies on 1D Ni(II) coordination polymers, we report here the preparation of $\{[Ni(Bz)(H_2O)_2]\cdot Bz\cdot H_2O\}_n$ (**1**) (H*Bz* = benzoic acid) in single crystal form, its magnetism and its crystal structure analysis, which reveals a geometrically linear

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Ni···Ni···Ni polymeric structure with a close Ni···Ni separation of 3.0671(1) Å. Within the chain pairs of nickel centers are triply bridged by a carboxylate and two water molecules. The triple bridge presents interesting similarities to the active site of urease including its hydrogen-bonding interactions with uncoordinated water molecules.

Results and Discussion

We have prepared complex **1** in single crystal form by the reaction of nickel(II) carbonate with a slight excess of benzoic acid in boiling water. The product as isolated contained benzoic acid as an impurity, but this can be removed by rinsing with ethanol. The purity and identity of the product were checked by chemical analysis. In addition, the powder diffraction pattern was recorded to confirm the phase identity of the bulk sample as the same phase characterized in the single crystal X-ray study (Supplementary Fig. S1).

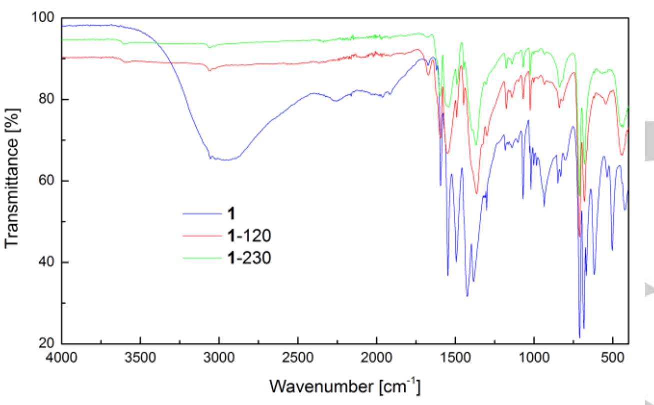
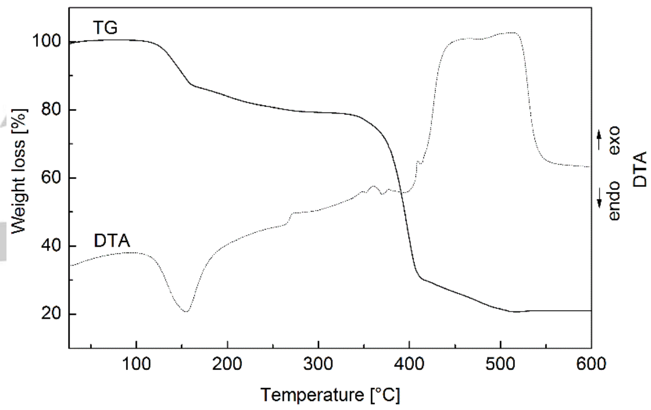


Figure 1. Comparison of the IR spectra of samples **1** (blue trace), **1**-120 (sample heated to 120 °C, red) and **1**-230 (sample heated to 230 °C, green).

The measured IR spectrum of **1** is rich in content (Fig. 1), but some characteristic absorption bands can be identified. A broad absorption band of medium intensity centered around 2965 cm^{-1} can be attributed to *v*(OH) stretching vibrations of the solvate water molecules and aqua ligands. The observed shift of this band to lower wave numbers can be explained by participation of the water molecules in medium to strong hydrogen bonds (HBs; see below). This band has a shoulder, a very weak absorption at 3054 cm^{-1} attributable to a C_{ar}-H stretching vibration as indicated by Nakamoto;[26] in the IR spectrum of benzoic acid this vibration is positioned at 3070 cm^{-1}. The presence of the aromatic rings is also corroborated by the sharp absorption band observed at 1593 cm^{-1}, which can be attributed to the C_{ar}-C_{ar} in-ring stretching vibration. The most characteristic absorption bands are the ones due to the asymmetric (1547, 1494 cm^{-1}) and symmetric (1424, 1384 cm^{-1}) stretching modes of the COO^- groups. We note that Pavkovic reported similar values of 1553, 1500, 1440 and 1392 cm^{-1} for the trihydrate.[3]

Figure 2. Thermal curves of **1**.

In order to check the thermal stability as well as to study the dehydration of **1**, its thermal curves were recorded (Fig. 2). As can be seen from the TG curve in Fig. 2, complex **1** is stable up to 100 °C. Over the broad temperature range 100-330 °C a total weight loss of 21.3% occurs, and can be seen (Fig. 2) to comprise at least two successive processes. The first proceeds in the temperature range 100-160 °C and corresponds to a rapid endothermic weight loss of 14.0%, while the second part, over the larger temperature range of 160-330 °C, manifests itself by a much slower weight loss amounting in the end to 7.3 %. We note that the calculated weight loss for total dehydration of **1** is 15.2%, suggesting that besides dehydration another reaction(s) is taking



place. To obtain more insight into the observed processes, samples of **1** were heated in an oven to 120 °C and to 230 °C for 30 minutes (samples **1**-120 and **1**-230, respectively). The IR spectrum of **1**-120 (Fig. 1) indicates the absence of water molecules in the sample; in addition, substantial changes in the shape and positions of the absorption bands of the asymmetric and symmetric modes of COO^- can be observed. The measured IR spectrum of sample **1**-230 is similar to the spectrum of **1**-120 with a decrease in the intensities of all bands. It is interesting to note the presence of a weak absorption near 3600 cm^{-1} which may correspond to an O-H stretching vibration in the absence of hydrogen bonding. These results suggest that the thermal decomposition of **1** starts with dehydration as was reported for the similar tetrahydrate[27] or the analogous hydrate of the 2-chloro-4-nitrobenzoate of Ni(II).[28] As to the further, much slower decomposition process, several scenarios are possible; among these is partial decarboxylation. We note that it has been reported that benzoic acid can be transformed to phenol by oxidative decarboxylation[29a] (the Dow Phenol Process) in the presence of water over NiO[29b] or using copper benzoate as catalyst.[30] The calculated weight loss for such a combination of processes (3x H_2O and 1x CO_2 with one oxygen atom coming from the atmosphere) is 23.1% which is comparable to the observed weight loss of 21.3%.

Further heating of **1** in the temperature range 320-530 °C leads to a strong exothermic decomposition of its organic component. The residual mass of 20.7% is in good agreement with the calculated residual mass for NiO (21.0%); the formation of NiO was also reported in the case of thermal decomposition of the anhydrous Ni(II) benzoate in air.[31]
As expected, the anhydrous $Ni(Bz)_2$ displayed enhanced thermal stability (230 °C) and upon the observed mass loss the formation of NiO as solid residue was reported.[4] On the other hand, the tetrahydrate $Ni(Bz)_2 \cdot 4H_2O$ is stable only to 100 °C (as was observed for **1**) and the formation of metallic nickel was reported at the end of the thermal decomposition.[5]
The crystal structure of **1** is composed of positively charged $[Ni(Bz)(H_2O)_2]_n^{n+}$ chains, benzoate anions and solvate water molecules (Figs. 3 and 4). The chains are built up of triply bridged pairs of Ni(II) atoms; two bridges are formed by μ_2-aqua ligands and the third by a *syn-syn*-benzoate ligand. Although the Ni···Ni···Ni chains are strictly linear, running parallel to the crystallographic *a*-axis, the axial coordination directions at the Ni(II) atoms -- *i.e.,* the Ni1---O1 and symmetry related bonds -- are tilted by 12.34(7)° with respect to the *b*-axis.
The Ni(II) center (-1 site) is hexacoordinated (donor set O_2O_4) in the form of a compressed bipyramid (Fig. 3). The axial Ni1-O1 bond lengths [1.9654(18) Å; 2x] are shorter than those in the equatorial plane, 2.0979(19) Å and 2.1270(18) Å (Table 1). The observed compression of the octahedron can be expressed by the ratio $\kappa = (Ni\text{-}O)_{ax}/\langle(Ni\text{-}O)_{eq}\rangle = 0.93$. Similar compression of the octahedral coordination of Ni(II) was found in $[Ni(H_2O)_6][Zn(H_2O)_2(phen)_2]_2 \cdot 2BTC \cdot H_2O$ (*phen* = 1,10-phenanthroline; BTC = 1,3,5-benzenetricarboxylate)[32] with the value κ = 0.95; a similar value of κ = 0.94 was found involving the μ_2-bridging aqua ligand in $\{[Ni(cbab)(H_2O)_2] \cdot H_2O\}_n$ (*cbab* = 4-((4-carboxybenzoyl)amino)benzoato).[27] The Ni-O(H_2)-Ni angle in **1** is 93.09(7)°.

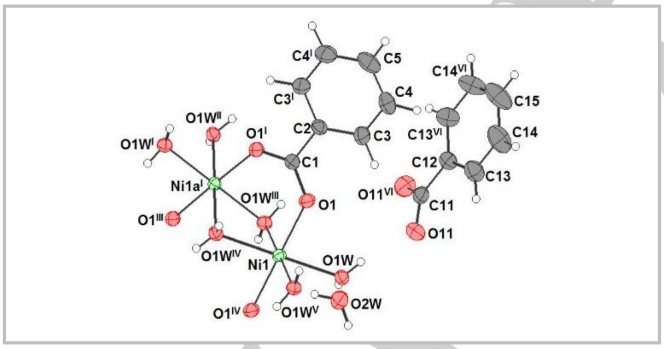


Figure 3. One segment of the structure of 1 with the atom numbering scheme. Displacement ellipsoids are drawn at the 50% probability level. Symmetry codes: i: 1.5-*x*, *y*, 1-*z*; ii: 1+*x*, *y*, *z*; iii: 0.5+*x*, 1-*y*, *z*; iv: 1-*x*, 1-*y*, 1-*z*; v: 0.5-*x*, *y*, 1-*z*; vi: 0.5-*x*, *y*, -*z*.

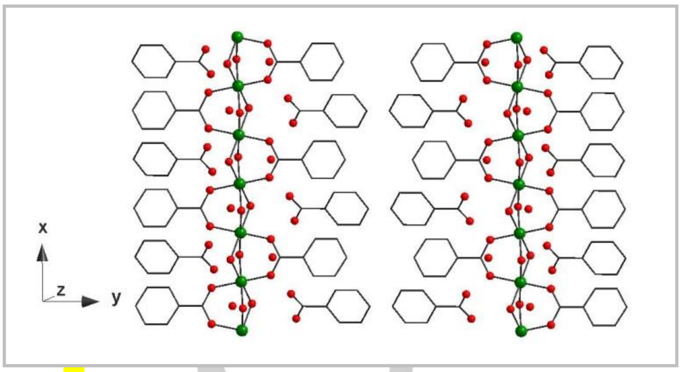


Figure 4. The polymeric structure of **1**.

Reports of Ni compounds with the Ni atoms triply bridged by a carboxylate and two water molecules are scarce, comprising just a single family of hexanickel(II) complexes with Ni···Ni distances between 3.105 and 3.111 Å.[33] The triple bridge in compound **1** coincides with a Ni···Ni separation of 3.0671(1) Å, and the extended chain has Ni···Ni···Ni angles of 180°. Very few linear Ni(II)···Ni(II)···Ni(II) 1D polymers, *i.e.,* with angles of 170-180° and with distances between Ni atoms of less than 4 Å have been reported in metal-organic crystals. In the known examples the bridges are mainly chlorine or bromine atoms, although some structures with S (benzenethiolato: Ni···Ni distance = 3.173 Å)[34] or pyrazolate bridges (Ni···Ni distance = 3.471 Å)[35] have been reported. The Ni···Ni distances in the 1D polymers with halogen bridges depend on the number of bridges (two or three) and the nature of the halogen, the shortest being those with triple chlorine bridges (for instance with an Ni···Ni distance of 3.063 or 3.060 Å)[36] with Ni···Ni separations similar to that in compound **1**.

Table 1. Selected geometric parameters [Å, °] for **1**.

Ni1-O1	1.9654(18)	C1-O1	1.270(2)
Ni1-O1W	2.1270(18)	C1-O1^{v}	1.270(2)
Ni1-O1W^{v}	2.0979(19)	C11-O11	1.261(3)
		C11-O11^{vi}	1.261(3)
O1-Ni1-O1W	87.16(7)	Ni1-O1W-Ni1^{v}	93.09(7)
O1-Ni1-O1W^{v}	90.61(8)	Ni1-O1W^{v}-Ni1^{v}	93.09(7)
O1W-Ni1-O1W^{v}	83.39(8)	O1-C1-O1^{v}	125.3(3)
		O11-C11-O11^{vi}	124.2(4)

Symmetry codes: v: 0.5-*x*, *y*, 1-*z*; vi: 0.5-*x*, *y*, -*z*.

Binuclear nickel compounds with carboxylate and water bridges are of interest as models for the active centers of enzymes.[10,11] While the number of nickel compounds with a carboxylate and two aqua bridges, as in compound **1**, is very small, nickel compounds with one aqua and two carboxylate bridges are more common. Some of those compounds have been used as models for the active site of the enzyme urease,[12] since the active site contains two nickel atoms bridged by a single carboxylate and a single water molecule, with a terminal water molecule at each of the nickel centers, Fig. 5(a). It is not clear whether all of the sites identified as water in urease are indeed water or whether some are hydroxide. Neither is it clear yet how the urease catalyzes the hydrolysis of urea into two ammonia molecules and carbonic acid; but the common first step in all of the proposed mechanisms is the binding of urea to one of the nickel atoms, displacing the terminal water. In Fig. 5 we can see that a similar result would obtain if urea were to coordinate to one of the nickel centers in compound **1**, breaking one of the water bridges. That would leave one terminal and one bridging water, in addition to the newly bound terminal urea. Therefore, compound **1** is of potential interest as a model for studying the mechanism of urease activity, or as a precursor for other, related compounds.

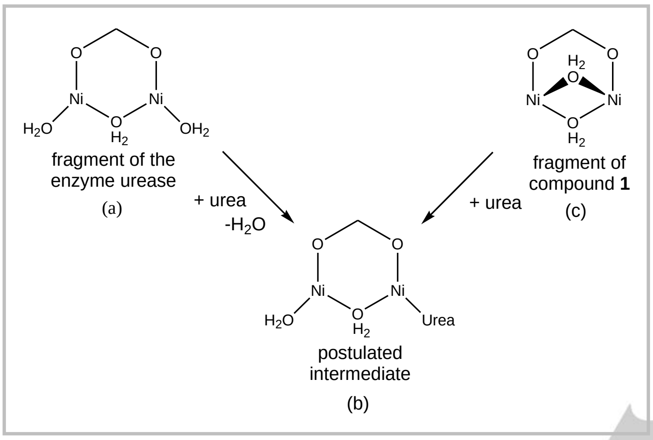


Figure 5. First step in previously proposed mechanism of urease activity [(a) → (b)] and hypothetical parallel reactivity of compound 1 [(c) → (b)].

The water molecules and carboxylate oxygen atoms in **1** are involved in O-H···O hydrogen bonds of considerable strength as indicated by the short O···O distances in the range of 2.647(3) - 2.684(3) Å and O-H···O angles close to linearity (Table 2, Fig. 6). Some of the hydrogen bonds are formed between the bridging water molecules and the free benzoate groups, O1W-H1A···O11, which further polarizes the water O---H bond, favoring a putative deprotonation to give $OH^{(-)}$ groups in compound **1**, in a further possible analogy to the active site of urease.

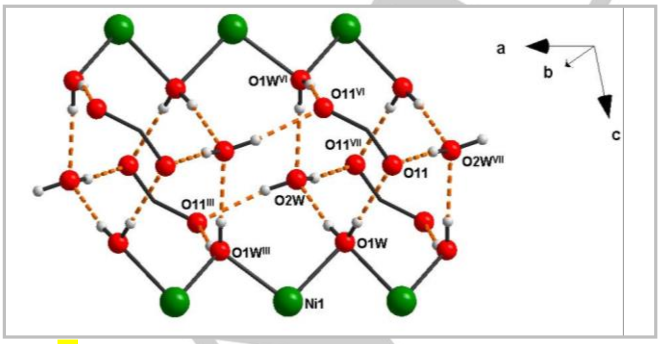


Figure 6. Hydrogen bonding scheme in **1**. Symmtery codes: iii: 0.5+*x*, 1-*y*, *z*; vi: 0.5-*x*, *y*, -*z*; vii: -*x*, 1-*y*, -*z*.

Table 2. Possible hydrogen bonds [Å, °] for **1**.

D-H···A	D-H	H···A	D···A	D-H···A
O1W-H1A···O11	0.76(3)	1.90(3)	2.647(3)	169(3)
O1W-H1B···O2W	0.81(3)	1.88(3)	2.684(3)	172(3)
O2W-H2A···O11^{vii}	0.82(3)	1.86(3)	2.679(2)	172(3)

Symmetry codes: vii: -*x*, 1-*y*, -*z*.

One consequence of the formation of strong H-bonds is the shape of the observed *v*(OH) absorption band in the IR spectrum – all hydrogen atoms are involved in hydrogen bonding – as well as the observed shift of its position to 2965 cm^{-1}. The hydrogen-bonding system connects the covalent chains into supramolecular layers perpendicular to the *b*-axis (Fig. 6). The active site of urease also contains one external water molecule that forms strong hydrogen bonds to the coordinated waters.

For both benzoate fragments the delocalization of π electrons between the aromatic ring and the carboxylate group is hindered, as the ring/$COO^{(-)}$ dihedral angles are 15.17(9)° (benzoate containing C1) and 14.4(3)° (C11). The twist is likely a result of weak C-H···π interactions between neighboring phenyl rings (Fig. 7, Table 3). Evidence of π delocalization was observed in the structure of [Ni_2(μ_2-*Bz*)$_4$(H*Bz*)$_2$], where the dihedral angle between the aromatic ring and the plane defined by the carboxylate group has values of 1.2°, 12.7° and 7.7° for the three independent benzoato ligands.[6]

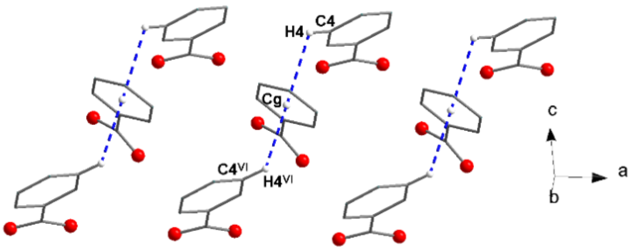


Figure 7. Weak C-H···π interactions between the phenyl rings in the crystal structure of 1. Symmetry code: vi: 0.5-*x*, *y*, -*z*.

Table 3. Possible weak hydrogen bonding interactions [Å, °] for **1**.

C-H···Cg	C-H	H···Cg	C···Cg	C-H···Cg
C4-H4···Cg2^{ii}	0.96(4)	2.93(3)	3.458(4)	116(3)

Symmetry code: ii: 1+*x*, *y*, *z*.

The structure of compound **1** is similar to that of [Cu(H_2O)$_2$(*Bz*)]·H*Bz*·H_2O;[37] however, in **1** the bridging water molecules are essentially symmetrically bonded to the nickel atoms [2.0979(19) and 2.1270(18) Å, O---Ni---O angle 93.09(7)°], while they are quite different in the copper compound (1.972 and 2.504 Å, angle 88.6°) due to the Jahn-Teller effect; this is the origin of a large difference in the unit-cell *β* angles for the two structures [95.331(3)° in compound **1** and 90.0° in the copper analogue]. This is also the origin of the differences in their X-ray powder patterns as noted by Pavkovic.[3]

The evolution of the magnetic properties of **1** (molar magnetic susceptibility, effective magnetic moment, magnetization per formula unit) is shown in Fig. 8. The effective magnetic moment at room temperature possesses a value of μ_{eff} = 3.17 μ_B, in accord with the presence of Ni(II) (S = 1) centers. Upon lowering the temperature the effective magnetic moment increases slowly at first, and then rapidly below 15 K, reaching a maximum of 12.39 μ_B at T = 4.6 K. This is a fingerprint of the ferromagnetic exchange interaction (J > 0). A decrease at lower temperatures is due to single-ion anisotropy, expressed in terms of the zero-field splitting parameter D.

When fitting the magnetic data it must be remembered that analytical formulae for the magnetic susceptibility in the case of J > 0 countermanded by D do not exist. The usual device for dealing with such a case is a finite ring approximation with the spin Hamiltonian

$$\hat{H}_\alpha = -\sum_{A<B}^{N} J(\vec{S}_A \cdot \vec{S}_B) + \sum_{A}^{N} D(\hat{S}_{A,z}^2 - \hat{S}_A^2/3) + \sum_{A}^{N} \mu_B B g \hat{S}_{A,\alpha}$$

where the first summation is restricted to the nearest neighbors for the directions $\alpha = x, z$.

For N = 4 the fitting procedure converged to the following set of magnetic parameters: J/hc = +12.1 cm^{-1}, g = 2.29, D/hc = +9.6 cm^{-1}. The fit is very good for the higher-temperature tail of the magnetic susceptibility, confirming that the Curie-Weiss law holds true in this region. Also, the molar magnetization is well reproduced for higher fields, confirming the value (and also the sign) of the D-parameter. However, the low-temperature region of the magnetic susceptibility and low magnetic field of the magnetization are not reproduced well, which indicates that the magnetic interactions are more complex than the simple model of a finite ring. *N.b.*, the distance between the two neighboring Ni(II) atoms within the chain is much shorter [3.0671(1) Å] than the shortest distance between Ni(II) atoms in neighboring chains [6.9793(2) Å] so that a putative interchain interaction would be weak.

Based on the Ni-O bond distances (Table 1), the structural parameter D_{str} was calculated to be negative,[38] D_{str} = -0.147, in line with the presence of a compressed octahedron in **1**. Thus, one could expect that the zero-field splitting parameter D is negative. (D_{str} is calculated as $\Delta_z - (\Delta_y + \Delta_x)/2$, in which $\Delta_i = d_i - \langle d_i \rangle$, with the average $\langle d_i \rangle$ taken over all three ligand pairs.) Nevertheless, the quality of the fit with D < 0 is much worse than with D > 0.

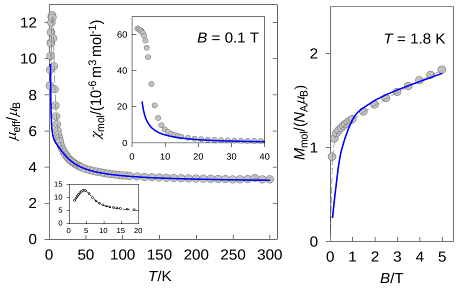


Figure 8. Magnetic functions for **1**. Left – effective magnetic moment (inset: molar magnetic susceptibility). Right – magnetization per formula unit. Solid lines – fitted.

Ferromagnetic interactions between Ni(II) centers are not as common as their antiferromagnetic counterparts; examples of ferromagnetically coupled Ni(II) atoms within chain-like arrangements were reported *e.g.,* in chiral {Ni(L/D-*mand*)(4-MePy)$_3$}$_n$·n(ClO$_4$) (H*mand* = mandelic acid, 4-MePy = 4-methylpyridine)[32] and in [Ni(1-*tza*)$_2$]$_n$ (1-H*tza* = tetrazole-1-acetic acid).[39]

Conclusions

The successful preparation and crystallization of nickel benzoate trihydrate, with moiety formula Ni(BzO)$_2$(H$_2$O)$_3$, has permitted a thorough characterization of this substance, including of its crystal structure, some 90 years after its solubility properties were first reported by Ephraim and Pfister.[1] The 1-dimensional polymer described by the structure analysis, with a rigorously linear Ni···Ni···Ni chain, short inter-metal distances and axially compressed octahedral coordination about the Ni centers, can be correlated well with its magnetic properties, which reveal ferromagnetic intra-chain coupling between the metal atoms and zero-field splitting, possibly alongside inter-chain antiferromagnetic interaction, which takes precedence below T = 4.6 K. In the crystal, with the Ni···Ni···Ni chain parallel to the *a*-axis, supramolecular aggregation mediated by hydrogen bonds extends the structure in the ac-plane; and C---H···π interactions add the third dimension extending along [101].

Experimental Section

CHN analyses were performed on a Perkin Elmer 2400 Series II CHNS/O analyzer. Infrared spectra were recorded on a Perkin Elmer Spectrum 100 CsI DTGS FTIR Spectrometer with UATR 1 bounce-KRS-5 in the range of 4000–300 cm^{-1} (UATR = universal attenuated total reflectance accessory; KRS-5 = thallium bromoiodide). The X-ray powder diffraction pattern of **1** (Supplementary Figure S1) was measured on a RIGAKU D-Max/2500 diffractometer with rotating anode and RINT2000 vertical goniometer, in the 2θ range 2.5 - 40° using Cu K$_{\alpha 1}$ radiation (λ = 1.5406 Å) and a step size of 0.03°; the model powder diffraction pattern was calculated using the program Mercury.[40] TG and DTG curves were recorded on a Netzch STA 409 PC/PG instrument under the following conditions: sample weight = 36.906 mg, heating rate = 10 K/min, dynamic artificial air atmosphere, temperature range 300 – 1174 K, aluminium oxide crucible.

A mixture of solid NiCO$_3$ (1.0 g; 7.7 mmol) and solid benzoic acid (2.0 g, 16.2 mmol) was slowly dissolved in water (250 ml) under heating and stirring, yielding a green solution. Slow boiling was retained until cessation of gas liberation (approx. 45 minutes; the gas is likely CO$_2$). The water loss was continuously compensated by addition of boiling water. The hot solution was filtered and the filtrate was left aside for crystallization at room temperature. Within a few days light green crystals separated (product **1**) along with a few colorless crystals of benzoic acid, which were removed by washing the product in a Buchner funnel with ethanol. The light green crystalline product was dried in air. Yield based on the metal: 72%.

Anal. CHNS/O of **1**: $C_{14}H_{16}NiO_7$ (M = 354.98 g.mol^{-1}): Found (%): C, 46.85; H, 4.68; Calc. (%): C, 47.36; H, 4.55.

IR (UATR) of **1** (in cm^{-1}): 3054(vw); 2965(b); 1593(m); 1547(s); 1494(s); 1424(s); 1384(s); 1301(m); 1070(m); 1020(m); 935(m); 710(s); 683(s); 668(s); 618(s); 504(s); 424(m); 386(m); 291(s); 270(s).

The magnetic properties of **1** were investigated using a commercial Quantum Design SQUID magnetometer in the temperature range of 2 - 300 K at 0.1 T. A powder specimen of 62.130 mg was used. The data were corrected for the diamagnetic contribution with Pascal´s constants using the program MATRA.[41]

Single-crystal X-ray data were collected at 295(2) K on an Oxford Diffraction Xcalibur diffractometer equipped with a Sapphire3 CCD detector and a graphite monochromator, utilizing MoKa radiation ($\lambda_{<\alpha>}$ = 0.71073 Å). The unit cell was chosen in accord with the recommendations of the International Union of Crystallography Commission on Crystallographic Data, using the shortest two axes in the (monoclinic) ac-plane as unit-cell axes. In this case that gives a space group setting of I2/a.[42] Absorption corrections were based on the multi-scan technique using ABSPACK.[43] The structures were solved by SIR92[44] and refined against the F^2 data using full-matrix least squares methods with the program SHELXL-2014/7.[45] Anisotropic displacement parameters were refined for all non-H atoms. The positional parameters of the hydrogen atoms bonded to carbon and oxygen atoms were refined, with isotropic displacement parameters assigned as 1.2 times the U_{eq} values of the corresponding bonding partners. The crystal and experimental data are given in Table 4, and selected geometric parameters are given in Table 1. Possible hydrogen bonds are gathered in Table 2. The structural figures were drawn using Diamond.[46]

Table 4. Crystal data and structure refinement for **1**.

Empirical formula	$C_{14}H_{16}NiO_7$
Molecular weight	354.98
Crystal system	monoclinic
Space group	*I*2/*a*
Unit cell dimensions	
a (Å)	6.1341(2)
b (Å)	34.1797(13)
c (Å)	6.9793(2)
β (°)	95.331(3)
V (Å^3)	1456.96(9)
Z	4
Dcalc (Mg.m^{-3})	1.618
T (K)	295(2)
μ (mm^{-1})	1.364
Crystal dimensions (mm)	0.16 x 0.04 x 0.02
Crystal color / form	light green, needle-like
Index ranges	$-7 \le h \le 7$
	$-43 \le k \le 44$
	$-9 \le l \le 9$
Θ range (°)	4.182 - 27.474
Reflections collected	6276
Independent reflections	1638 (Rint = 0.0391)
Absorption corr. method	multi-scan
T_{min} - T_{max}	0.8438 - 1.0000
Goodness-of-fit on F2	1.118
R indices [$I > 2\Theta(I)$]	*R*1 = 0.0433, w*R*2 = 0.0936
R indices (all data)	*R*1 = 0.0582, w*R*2 = 0.0996

Acknowledgements

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Keywords: Nickel • benzoate • crystal structure • magnetic properties • thermal properties

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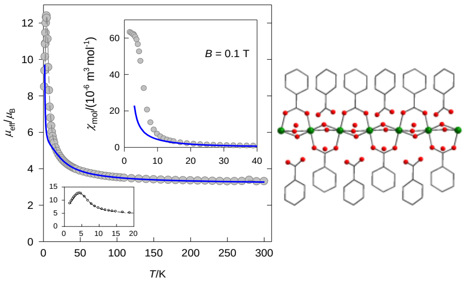
Entry for the Table of Contents

FULL PAPER

Nickel benzoate trihydrate (**1**) was prepared in single-crystalline form by the reaction of nickel carbonate with benzoic acid in boiling aqueous solution. Its crystal structure and magnetic properties were set and commented.



Crystal structure and magnetism

A. Vráblová, L. R. Falvello, J. Campo, J. Miklovič, R. Boča, J. Černák, M. Tomás*

1 – 8

New preparation, first structure analysis and magnetism of the long-known nickel benzoate trihydrate: A rigorously linear Ni···Ni···Ni polymer and its parallels to the active site of urease

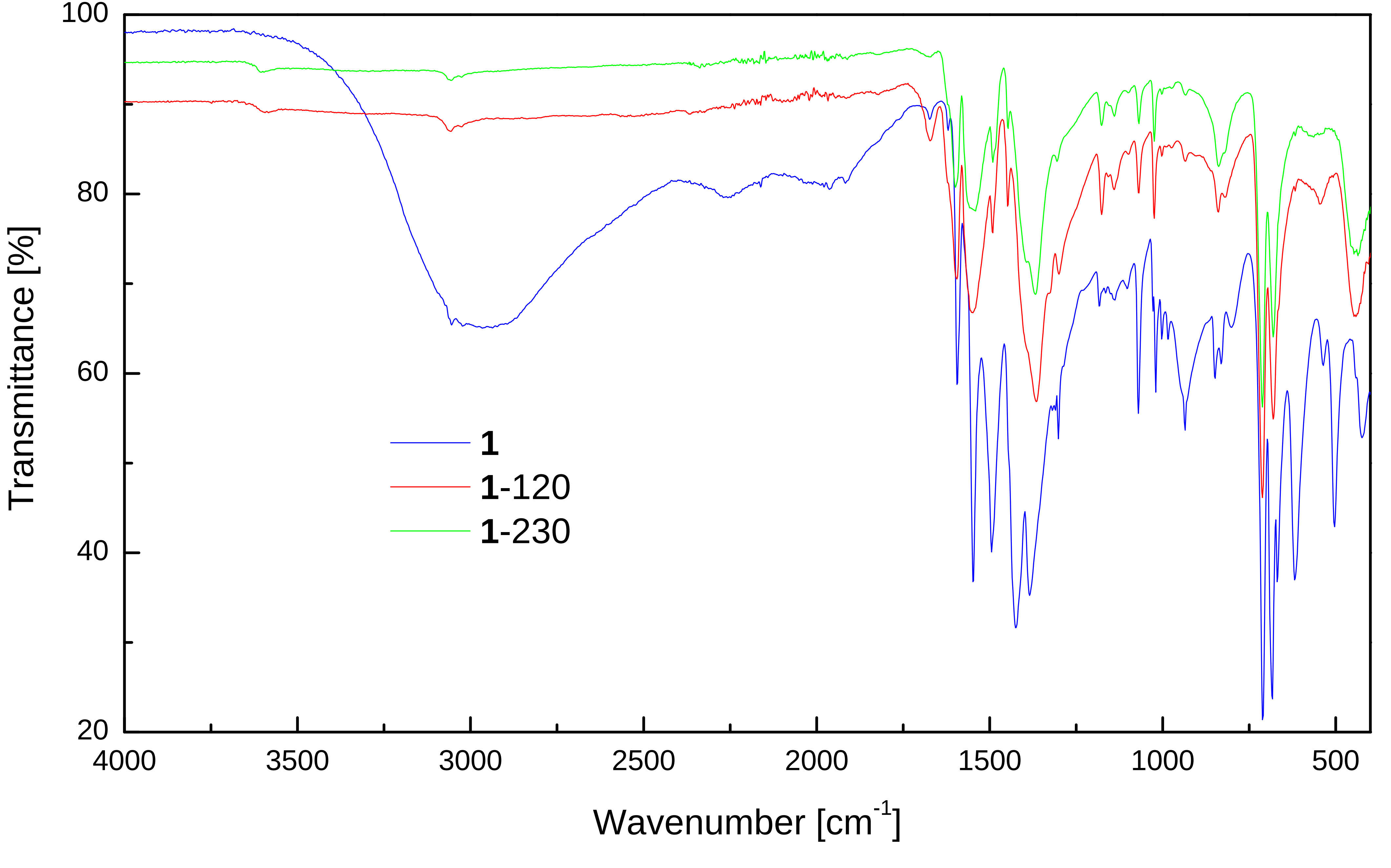


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Figure 2

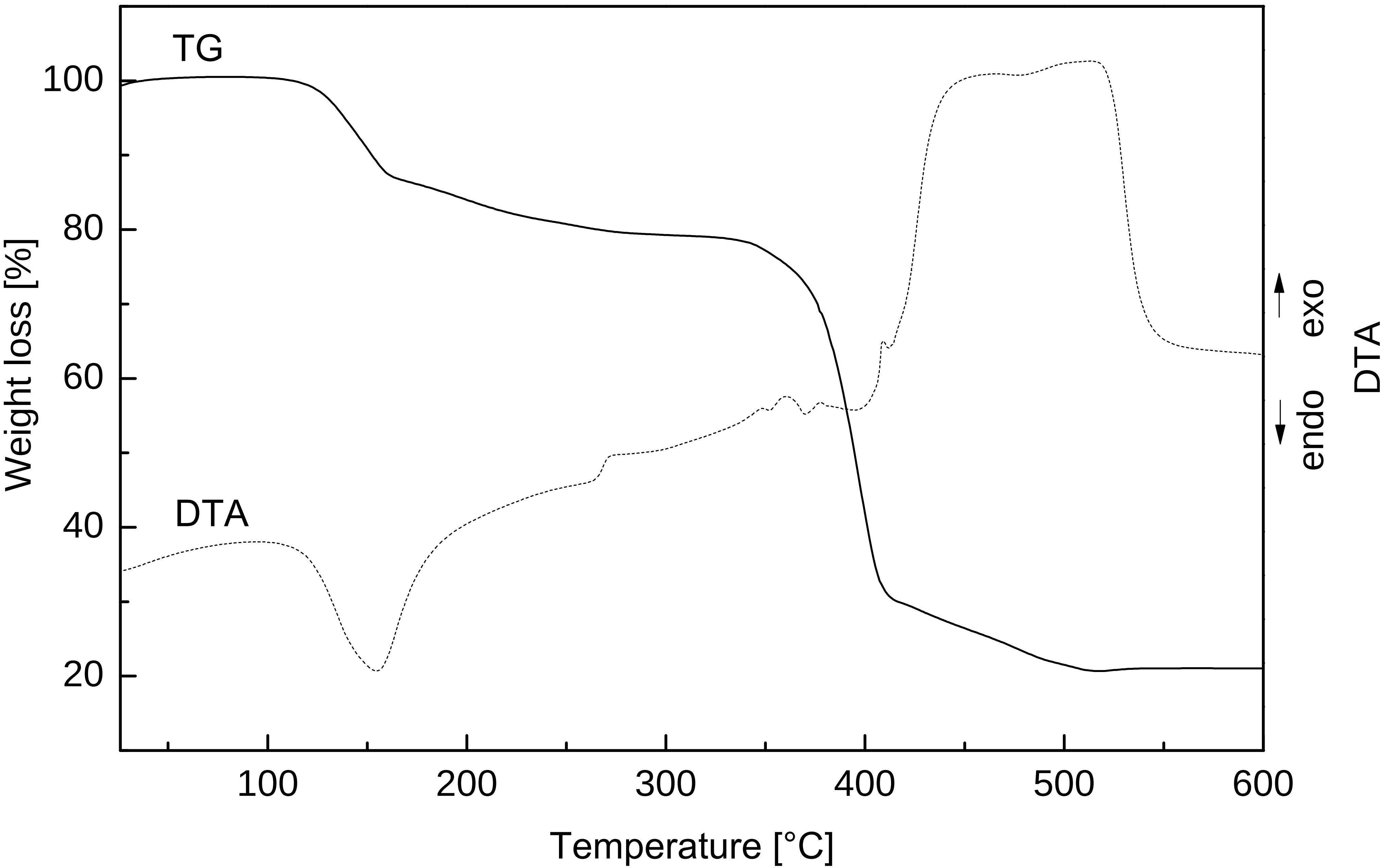
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Figure 3

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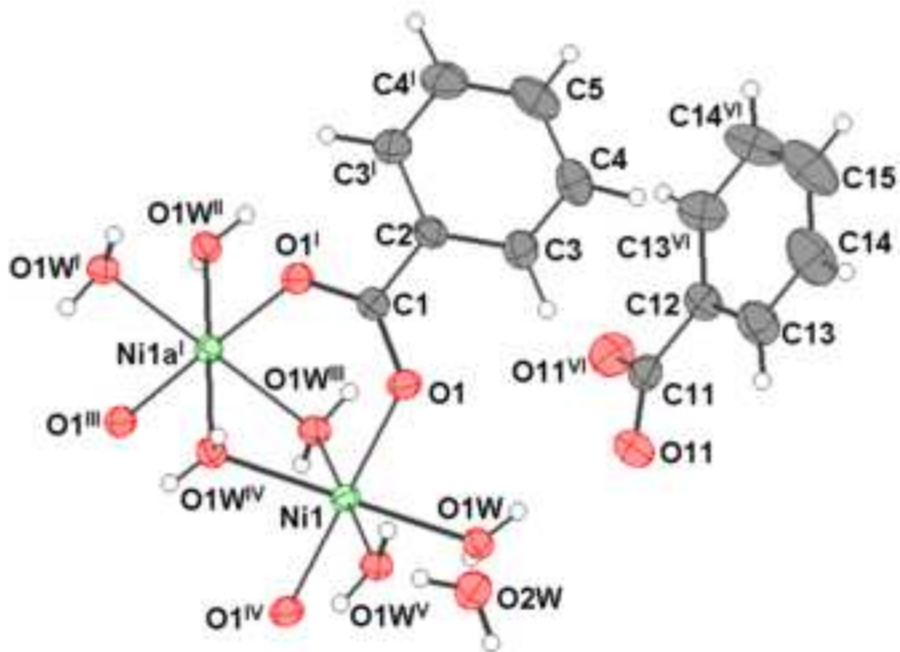

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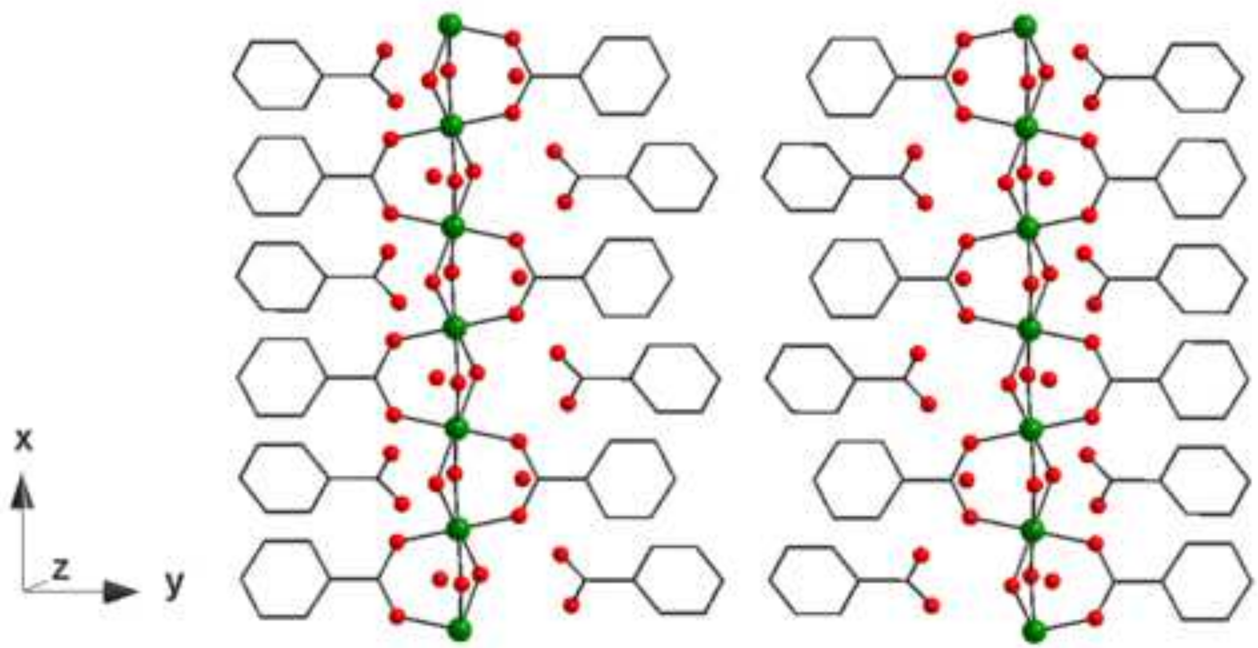

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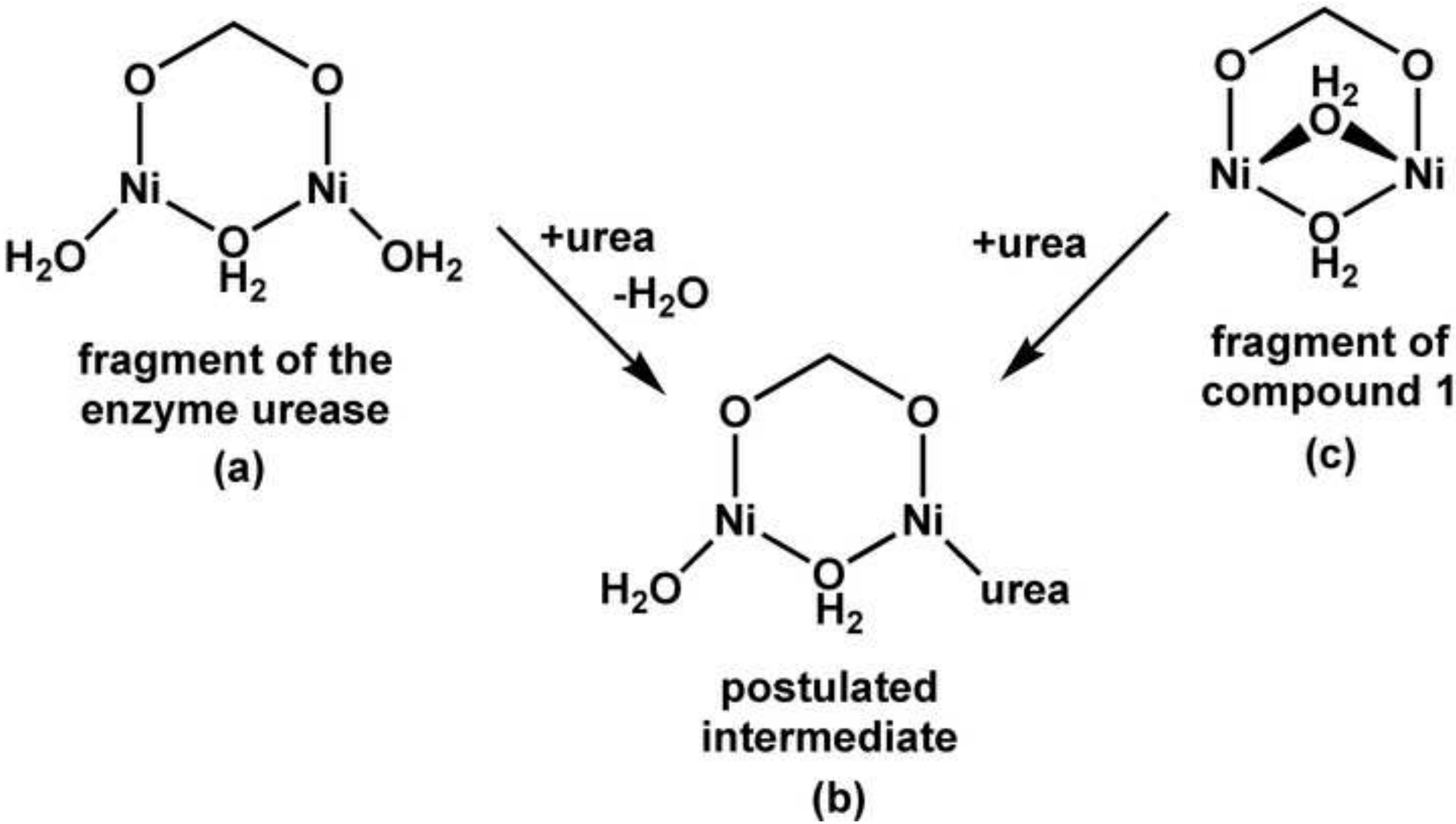
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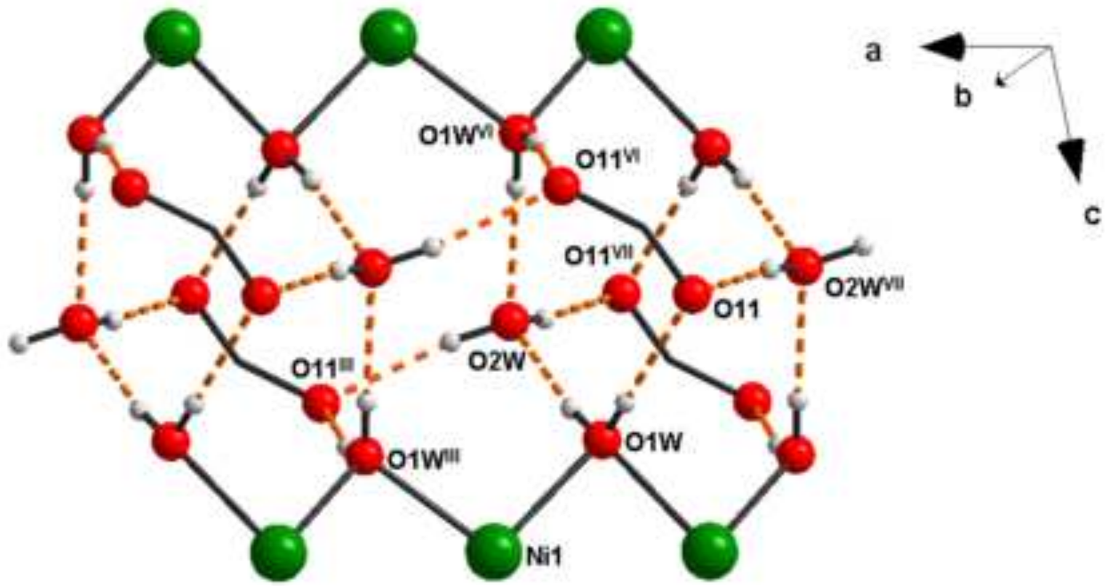

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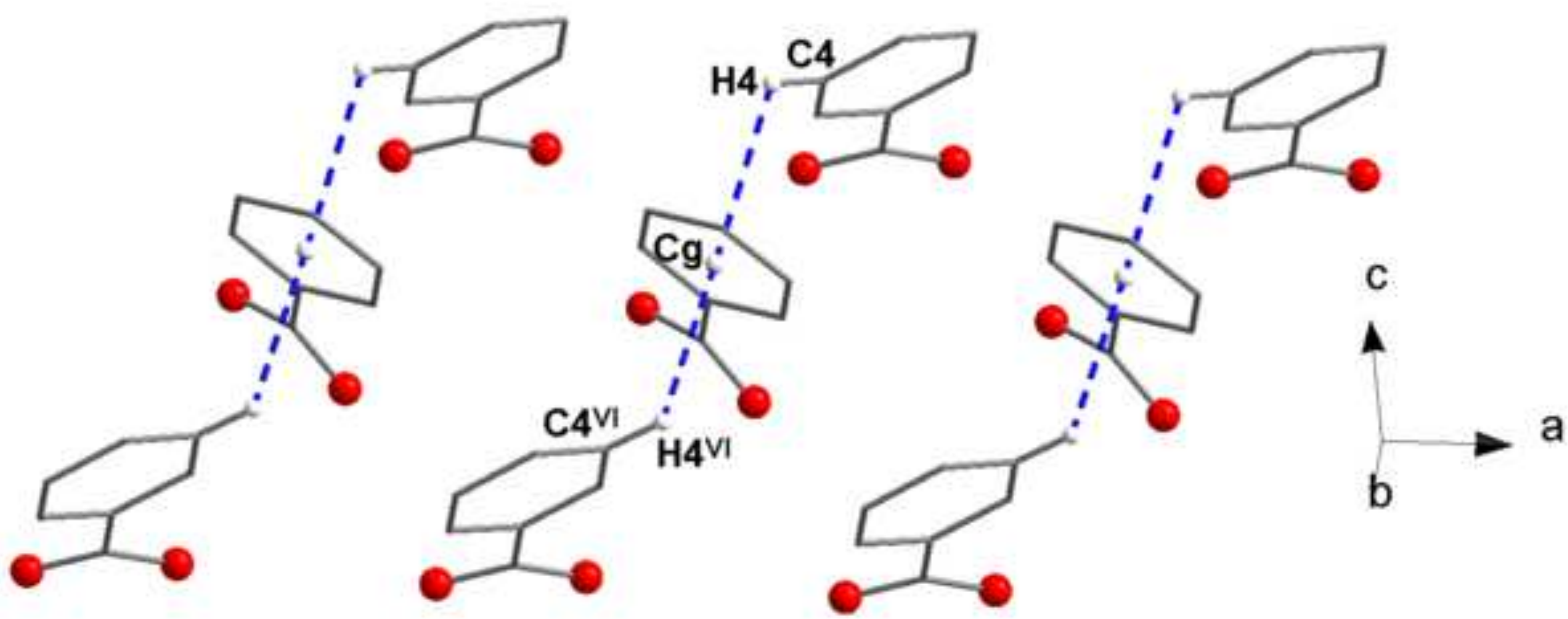

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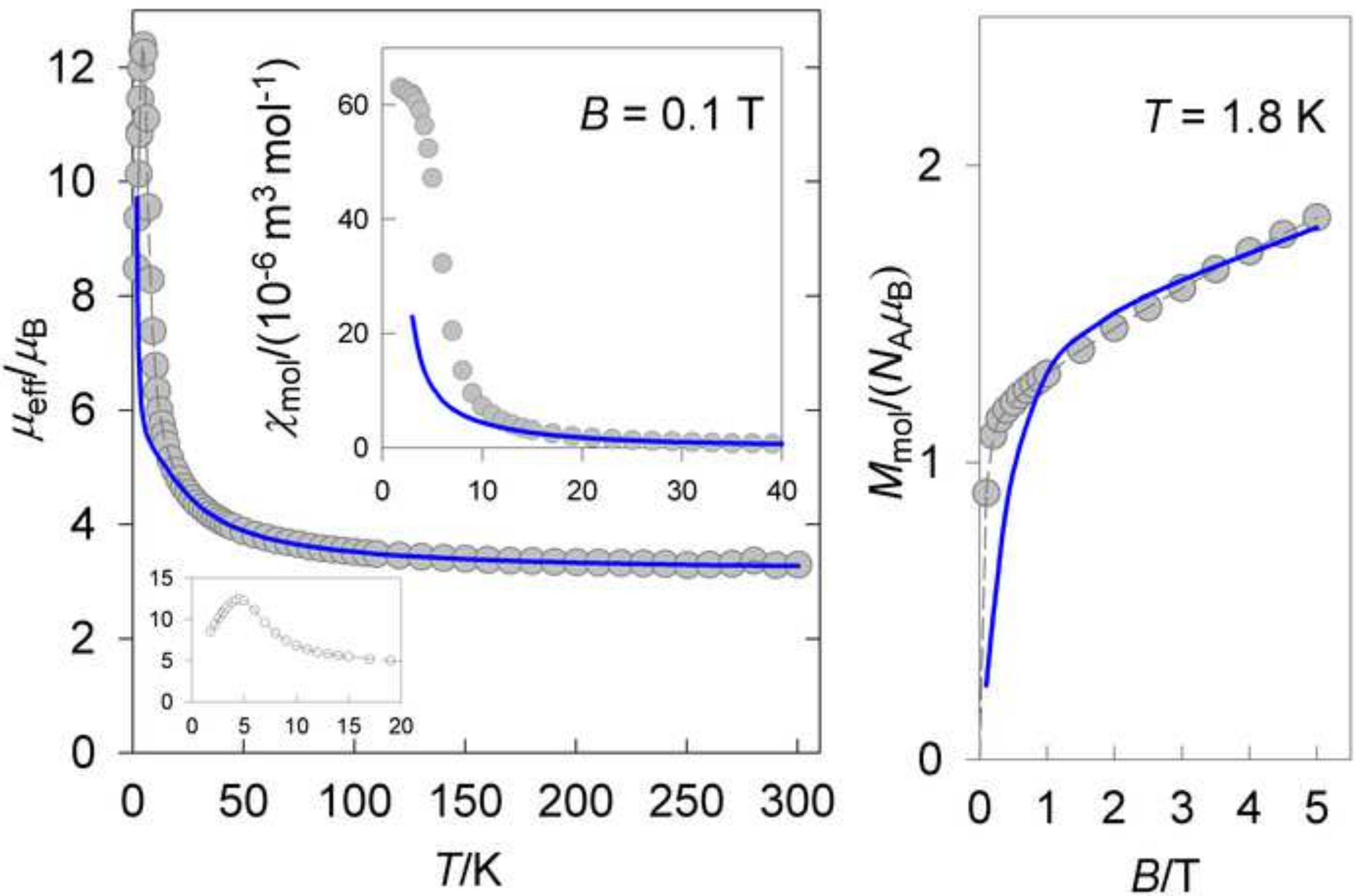

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