Frameworks of amino acids: synthesis and characterization of two zinc phosphono-amino-carboxylates with extended structures

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Received (in Columbia, MO, USA) 7th February 2000, Accepted 18th May 2000

Two α-amino acids, 3-phosphono-2-aminopropionic and 4-phosphono-2-aminobutyric, are used to link zinc atoms in three-dimensional structures where the three phosphonic and one of the carboxylic oxygen atoms coordinate to the metal, while the protonated amino groups and the second carboxylic oxygen atom are not coordinated and remain terminal in the voids of the framework.

Multifunctional ligands have attracted much interest in recent years mainly due to the possibility to build infinite frameworks by coordination to metal centers.[1] Such hybrid inorganic–organic compounds have the potential for use in shape recognition,[2] and more importantly, in stereoselectivity when chiral linkers are used.[3] Linkers with two or more different functional groups are even more interesting since they can provide different modes of coordination, different stability, and different structural dimensionality and motifs. Extended structures of such organic moieties with two different end groups that are both coordinated to the metal centers are actually quite rare. Known and structurally characterized are one such amino-phosphonate with a zeolite-like structure,[4] three carboxylate-phosphonates with layered structures,[5] and three of the latter type but with three-dimensional framework structures.[6] We have now taken one step further in the complexity, and have studied organic linkers with three different functional groups, *i.e.* species with an amino, carboxylic and phosphonic groups. Reported here are the structures and the IR and TGA characteristics of two framework compounds of zinc and phosphonated α-amino acids, $Zn(O_3PCH_2CH(NH_3)COO)$ (**1**) and $Zn(O_3PCH_2CH_2CH(NH_3)COO)$ (**2**), where the zinc atoms are coordinated by oxygen from the phosphonic and the carboxylic groups. Our ultimate goal is to achieve layered compounds with non-coordinated carboxylic and amino groups that are potential candidates for stereoselective intercalation due to the chiral α-carbon. In the pursuit of this same goal, layered inorganic compounds such as zirconium phosphate have been intercalated with amino acids where the latter interact electrostatically or van der Waals-like with the host.[7]

Compounds **1** and **2** were synthesized hydrothermally in autoclaves at 130 °C (2 d) from $Zn(NO_3)_2\cdot 6H_2O$, and DL-2-amino-3-phosphonopropionic or DL-2-amino-4-phosphonobutyric acids (from Sigma), respectively, in molar ratio 1 : 4 and resulting pH of about 1.5. The latter is perhaps very near the isoelectric point of these very acidic amino acids, and as a result they exist as zwitterions in the product. The resulting solids were filtered, washed with water, ethanol and acetone, and were dried at room temperature. Compound **1** crystallizes as large polyhedral crystals, while the crystals of **2** are extremely small and very thin rectangular plates. Correspondingly, the structure of **1** was determined from X-ray diffraction data collected on a regular four-circle diffractometer, while a CCD area detector was used for the structure of **2**.†

The structure of compound **1** is a hybrid of alternating inorganic and organic layers (Fig. 1). The inorganic layers, made of oxygen-connected tetrahedra centered by phosphorus and zinc, are linked by the amino acid molecules. The connectivity is achieved *via* the carbon–phosphorus bond of the phosphonated amino acid and with the coordination of one of the carboxylic oxygens to Zn (Fig. 1 and in the TOC). The other oxygen of the latter is noncoordinated as is the protonated amino group of the amino acid. Thus, unlike other examples of bi-coordinated organic moieties such as diphosphonates or carboxylates-phosphonates and poly-carboxylates, the organic species here are highly functionalized with hydrophilic groups, *i.e.* with the $>C{=}O$ and NH_3^+ functionalities. These functional groups point toward the one-dimensional inter-linker apertures (4.36 Å O–O diameter) that exist along the *b* direction (Fig. 1), and are hydrogen bonded between themselves.

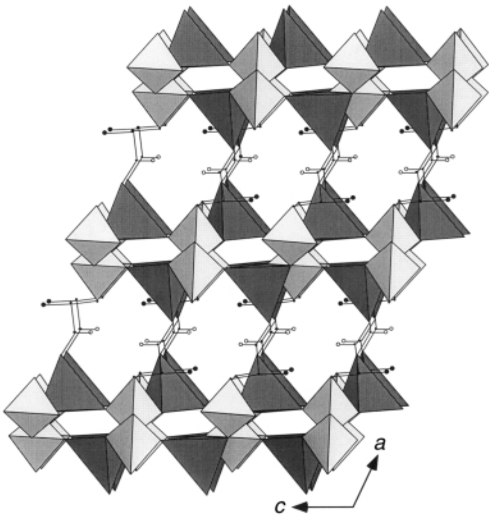

Fig. 1 A general view of the structure of compound **1**, $Zn(O_3PCH_2CH(NH_3)COO)$, along the *b* axis. The carbon and nitrogen atoms are shown as small and large black circles, respectively, while the non-coordinated oxygen of the carboxylic group is shown as an open circle. The darker and lighter shaded tetrahedra are centered by Zn and P, respectively.

The structure of compound **2** presents very similar features. Its carboxylic groups are also coordinated *via* only one oxygen atom, and therefore, the second one is terminal, and the amino groups are again protonated to $-NH_3^+$ (Fig. 2 and in the TOC). Crystallographically, there are two different phosphono-amino acids as well as zinc atoms in this structure but they are all nearly identical in coordination, bond distances and angles. Similar to **1**, the structure of **2** (Fig. 2) contains phosphonate–zinc inorganic layers that are grafted by the amino acid moieties. Nevertheless, there is an additional feature in this structure, inorganic chains of PO_3/ZnO_4 running along the *a* axis (the viewing direction of Fig. 2). The chains are positioned between the inorganic layers and are linked to the two neighboring layers by the amino acids. This leads to increased separation between the layers, 17.5 Å (half the *b* axis), since they are formally connected by amino acid–PO_3–ZnO_4–amino acid composite linker. These linkers are not perpendicular to the layers but are rather tilted, most likely due to the rigidity of the carbon angles, and give the impression that the layers are offset or shifted along the *c* direction with respect to each other. Long narrow gaps of about 19.3 Å (measured in O–O distance) are formed between

DOI: 10.1039/b001275k

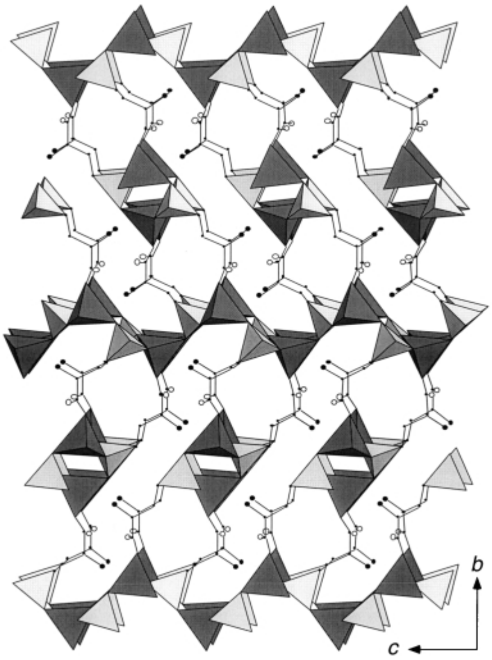

Fig. 2 A general view of the structure of compound **2**, Zn($O_3PCH_2CH_2CH(NH_3)COO$), along the *a* axis. The carbon and nitrogen atoms are shown as small and large black circles, respectively, while the non-coordinated oxygen of the carboxylic group is shown as an open circle. The darker and lighter shaded tetrahedra are centered by Zn and P, respectively.

the composite linkers. All pendant amino groups and carboxyl oxygen atoms point into these gaps and are extensively hydrogen bonded through that space (3 bonds per amino group and one bond per carboxylic oxygen). Both structures are centrosymmetric and contain racemic mixtures of the corresponding amino acids.

The compounds are thermally stable up to about 350 °C in a flow of air, according to TGA measurements. At this temperature, in a single sharp step, they lose the organic fraction in the form of CO_2, NH_3 and H_2O, and end up as $ZnHPO_4$. The IR spectra of the compounds (in KBr pressed pellets) show the antisymmetric and symmetric vibrations of the carboxylic groups. For compound **1** they are observed at 1627 and 1414 cm^{-1}, respectively, while doublets at 1636 and 1621 cm^{-1} for the antisymmetric and at 1446 and 1429 cm^{-1} for the symmetric vibrations are observed for compound **2**. The splitting is due to the two crystallographically different amino acids, *i.e.* the two slightly differently bonded carboxylic groups in the compound. The vibrations of the phosphonic groups are observed in the region 900–1200 cm^{-1}, as expected.

The existence of these framework compounds proves that it is possible sometimes to teach ‘an old dog’, the amino acids, ‘new tricks’. The next step is to find a way to anchor only the phosphonic groups in a layer-type compound, and use the two functionalities COOH and NH_3, and the chiral α-carbon for a variety of intercalation and chiral molecular recognition reactions.

Such supported amino acids can be used for a number of organic reactions in the interlayer spacing, including formation of peptide bonds and longer chains of different residues. The two compounds presented here are not layered or microporous, and guest molecules can not access the inside of the structures, but they clearly have the right structural motifs and are on the right track towards more open frameworks.

We thank Chris Cahill for help with the data collection, and the National Science Foundation (DMR-9701550) for the financial support and for the Summer Program in Solid State Chemistry.

Notes and references

† *Crystal data* for Zn($O_3PCH_2CH(NH_3)COO$) **1**: Mw = 232.4, monoclinic, $P2_1/c$, Z = 4, a = 8.234(1), b = 9.768(2), c = 8.850(2) Å, β = 109.5(1)°, V = 670.9(2) Å^3, μ = 38.69 cm^{-1}. A hemisphere of data was collected on a CAD4 single crystal diffractometer with graphite-monochromated Mo-Kα radiation at room temperature (crystal size 0.35 × 0.25 × 0.20 mm, ω-2θ scans, $2\theta_{max}$ = 50°, 2328 and 1182° collected and independent reflections, respectively). *Crystal data* for Zn($O_3PCH_2CH_2CH(NH_3)COO$) **2**: Mw = 246.4, monoclinic, $P2_1/n$, Z = 8, a = 5.2022(6), b = 35.000(3), c = 8.1165(4) Å, β = 94.16(1)°, V = 1473.9(2) Å^3, μ = 35.30 cm^{-1}. Nearly a full sphere of data was collected on a Bruker SMART system with a CCD area detector (graphite-monochromated Mo-Kα radiation, room temperature, crystal size 0.16 × 0.06 × < 0.01 mm, 60 seconds/frame, $2\theta_{max}$ = 56.5°, 9719 and 3549 collected and independent reflections, respectively). The structures were solved by direct methods and refined with the aid of the SHELXTL-V5.1 package. XABS empirical absorption corrections were applied to the data of **2** after the structure was refined with isotropic thermal parameters. Final residual values: compound **1**, $R1/wR2$ = 4.74/14.30% for 968 reflections with $I \geqslant 2\sigma I$ and 99 refined parameters; compound **2**, $R1/wR2$ = 8.45/15.95% for 1092 reflections with $I \geqslant 2\sigma I$ and 225 refined parameters. The somewhat higher R-values for **2** are due to absorption problems resulting from the extremely anisotropic crystals (plates, 0.16 × 0.06 × < 0.01 mm). CCDC 182/1661. See http://www.rsc.org/suppdata/cc/b0/b001275k/ for crystallographic files in .cif format.

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Typeset and printed by Black Bear Press Limited, Cambridge, England