Crystal Structure of Holmium Aspartate Chloride Hydrate, Ho(L-Asp)$Cl_2 \cdot 6H_2O$

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As part of a research program concerning the structural aspects of interactions between lanthanoid cations and amino acids in the solid state, the complex Ho[OOC–CH(NH_3)–CH_2–COO]$Cl_2 \cdot 6H_2O$ has been studied by single-crystal X-ray diffraction. The symmetry is trigonal ($P3_1$) with $Z = 3$. The unit cell dimensions using the hexagonal coordinate system are $a = 10.0708(3)$ and $c = 11.8450(4)$ Å. The structural model has been refined to a final linear R value of 0.035 for 2582 reflections. Statistical tests of the crystallographic R values confirms the L configuration of the aspartic acid residues. The Ho^{3+} cations are eight-coordinated by five water oxygens and three carboxyl oxygens of three different aspartate moieties. The crystal structure consists of parallel polymeric chains of holmium–L-aspartate–hydrate. The chloride anions and the sixth, non-coordinating water molecule reside in the cavities between the chains, and stabilize the crystal packing by forming hydrogen bonds.

Divalent calcium plays an important role in living organisms. Many Ca^{2+}-related processes occur by means of calcium-protein interactions.[1] Because of the similarity of rare earth coordination chemistry to that of calcium (size, preference for oxygen donors, variability in coordination number, lack of strong directionality),[2] X-ray studies of lanthanoid–amino acid complexes may give valuable information about structural characteristics of calcium-binding sites in complicated bioorganic systems. As part of a research program concerning the structural and spectroscopic aspects of interactions between trivalent lanthanoid cations and amino acids in the solid state, the structures of the L-glutamate complexes of praseodymium,[3,4] dysprosium[4] and holmium[4] have been studied previously, and we now report the crystal structure of a holmium aspartate complex, Ho(L-Asp)$Cl_2 \cdot 6H_2O$. Further stimulus for these investigations comes from the finding that Ca(II) in biological systems often occurs bonded to protein via aspartate or glutamate residues.

Experimental

Sample preparation. The holmium aspartate chloride complex was prepared by dissolving $HoCl_3 \cdot 6H_2O$ (crystallized from a solution of holmium oxide [Merck] in hydrochloric acid) in excess in an acidic solution ($1.4 < pH < 3.3$) of L-aspartic acid (Reanal, Hungary). The crystal density, measured by the flotation method in a mixture of bromoform and 1,2-dibromomethane, was found to be 2.27 g cm^{-3}.

X-Ray data collection and reduction. Intensity data were obtained for a light yellow single crystal of the title complex [Ho($C_4H_6O_4N$)$Cl_2 \cdot 6H_2O$, $M_w = 476.02$, $D_c = 2.279$ g cm^{-3}] with the approximate dimensions $0.21 \times 0.36 \times 0.49$ mm, sealed in epoxy glue. The measurements were carried out at room temperature on a Siemens STOE/AED2 diffractometer using graphite-monochromated Mo$K\alpha$ radiation ($\lambda = 0.7107$ Å, $\theta_{max} = 30°$) and ω-2θ scan technique. Four reference reflections (6 1 2, 0 – 6 – 3, 2 2 8 and 3 3 6) were measured every 60 min. No systematic variation was detected. The net intensities of a total of 4095 reflections were corrected for Lorentz, polarization and absorption effects ($\mu = 61.99$ cm^{-1}), and the final refinement calculations also involved refinement of an empirical extinction correction factor.[5] The absorption corrections were based on ψ scans of 8 reflections with $75° < \chi < 90°$ and different 2θ values (the transmission factors varied between 0.060 and 0.258).

The crystal symmetry is trigonal. The systematic absences were consistent with the space groups $P3_1$ and $P3_2$. In the course of the final refinement calculations, the $P3_1$ symmetry proved to be the more suitable one (see below). The unit cell dimensions using the hexagonal coordinate system are $a = 10.0708(3)$ and $c = 11.8450(4)$ Å. There are three formula units per cell. The cell dimensions were refined against angular settings of 58 carefully centered reflections with $30° < 2\theta < 58°$.

Solution and refinement of the structure. The structure was solved and refined with the programs of the SHELX system.[5] Only the reflections with $F > 6\sigma(F)$ were used in the

Table 1. Fractional atomic coordinates and equivalent isotropic temperature factors[a] of the non-hydrogen atoms. The e.s.d.'s are given in parentheses. The atoms are numbered as in Fig. 1.

Atom	*x/a*	*y/b*	*z/c*	U_{eq}[a]/Å^2
Ho	−0.27536(3)	−0.23693(3)	−0.06850	0.0157(1)
Cl(1)	−0.0757(4)	−0.6257(3)	0.2335(2)	0.046(1)
Cl(2)	−0.6386(3)	−0.4686(3)	0.2326(2)	0.036(1)
O(W1)	−0.1168(8)	−0.3351(7)	0.0057(6)	0.028(2)
O(W2)	−0.4862(7)	−0.4579(7)	0.0038(5)	0.031(2)
O(W3)	−0.4852(7)	−0.2846(9)	−0.1940(6)	0.034(3)
O(W4)	−0.2970(9)	−0.4319(8)	−0.1862(6)	0.038(3)
O(W5)	−0.3471(8)	−0.0539(9)	−0.0273(6)	0.034(3)
O(1)	−0.2723(6)	−0.2168(7)	0.1315(5)	0.023(2)
O(2)	−0.3352(9)	−0.0451(8)	0.1916(6)	0.033(3)
C(1)	−0.3004(8)	−0.1465(9)	0.2068(6)	0.021(2)
C(2)	−0.2971(8)	−0.1910(9)	0.3300(6)	0.022(3)
N(2)	−0.2534(8)	−0.3099(8)	0.3348(6)	0.027(3)
C(3)	−0.1966(8)	−0.0544(9)	0.4076(6)	0.023(3)
C(4)	−0.0287(8)	0.0338(8)	0.3804(6)	0.018(2)
O(4)	0.0197(6)	−0.0237(7)	0.3081(5)	0.022(2)
O(5)	0.0546(6)	0.1593(6)	0.4308(5)	0.022(2)
O(W6)	−0.3448(12)	−0.5746(9)	0.1835(8)	0.050(4)

[a] $U_{eq} = \frac{1}{3}\sum_i \sum_j U_{ij} \mathbf{a}_i^* \cdot \mathbf{a}_j^* \cdot a_i a_j$.

calculations. The holmium cation was located from a Patterson synthesis. The positions of all the remaining atoms, except for three carbon-bonded H atoms of the aspartic residue which were assigned assumed positions after each cycle of the refinement, were derived from difference electron density calculations. The structural model was refined by the full-matrix least-squares method. In the last stage of the refinement calculations the non-hydrogen atomic positions were refined together with their anisotropic thermal parameters, and two isotropic group temperature factors were refined for the hydrogens: one for the O- and N-bonded hydrogens, riding on their respective mother atoms and one for the calculated H atoms. The atomic scattering factors for the C, O, N and Cl atoms were taken from Cromer and Mann,[6] those for the Ho^{3+} ion from Cromer and Waber,[7] and those for the H atoms from Stewart, Davidson and Simpson.[8] The corrections for the anomalous dispersion of the non-H atoms were taken from Cromer and Liberman.[12]

The final refinement calculation was carried out twice: first with $P3_1$ symmetry and L absolute configuration for the aspartic acid residues, and then with $P3_2$ symmetry and with D-aspartate moieties. These calculations, in which 166 variables were refined using 2582 observations, converged to the final reliability indices $R[=\Sigma|\Delta F|/\Sigma|F_0|] = 0.035$ and 0.042, $R_w[=\Sigma\sqrt{w}|\Delta F|/\Sigma\sqrt{w}|F_0|] = 0.038$ and 0.046 and $R_G[=(\Sigma w|\Delta F|^2/\Sigma w|F_0|^2)^{1/2}] = 0.045$ and 0.057 for the first and the second refinement, respectively. The weights were calculated as $w = 15.0/[\sigma^2(F)+0.000074(F^2)]$ and $w = 12.6/[\sigma^2(F)+0.000027(F^2)]$, respectively. From these results we may conclude that the space group symmetry is $P3_1$ and that the aspartic acid residues thus have the L configuration, as expected. This can be confirmed to a significance level of 0.001 by statistical tests made on the crystallographic R_G values, according to Hamilton[9] and Rogers.[10] The final atomic coordinates, listed in Table 1,

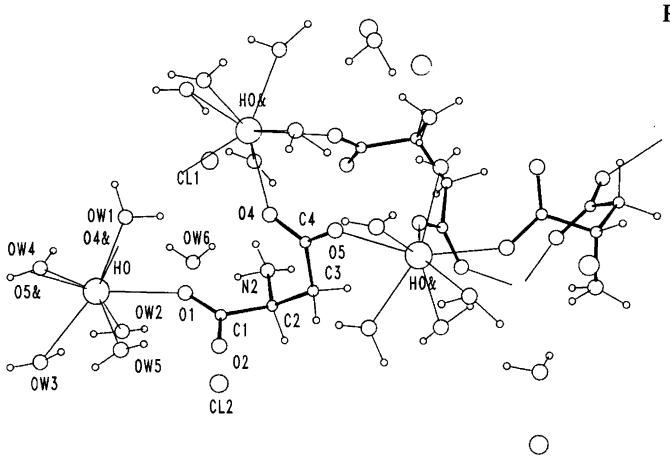

Fig. 1. Characteristic fragment of the polymeric $Ho(L\text{-}Asp)Cl_2 \cdot 6H_2O$ structure. The atoms of the crystallographic asymmetric unit are labelled as in the test ('&' means equivalent atomic positions, generated from the coordinates of Table 1 by using one of the possible symmetry operations).

Table 2. The geometry of the coordination around the Ho(III) ion, Ho–O distances and O–Ho–O angles with e.s.d.'s in parentheses. The atoms are numbered as in Fig. 1. The oxygen positions are generated using the coordinates in Table 1 together with the symmetry operations given in the footnote, below.[a,b]

Atoms	Distance/Å	Atoms	Distance/Å
Ho–O(W1)	2.425(9)	Ho–O(W2)	2.338(5)
Ho–O(W3)	2.427(8)	Ho–O(W4)	2.327(9)
Ho–O(W5)	2.342(10)	Ho–O(1)	2.376(6)
Ho–O(4)[b]	2.323(6)	Ho–O(5)[a]	2.351(6)
Atoms involved	**Angle/°**	**Atoms involved**	**Angle/°**
O(W5)–Ho–O(1)	73.8(3)	O(W4)–Ho–O(1)	131.4(3)
O(W4)–Ho–O(W5)	148.5(3)	O(W5)–Ho–O(1)	126.9(3)
O(W3)–Ho–O(W5)	72.7(3)	O(W3)–Ho–O(W4)	76.2(3)
O(W2)–Ho–O(1)	71.5(2)	O(W2)–Ho–O(W5)	100.5(3)
O(W2)–Ho–O(W4)	76.1(3)	O(W2)–Ho–O(W3)	75.5(3)
O(W1)–Ho–O(1)	72.0(3)	O(W1)–Ho–O(W5)	140.4(3)
O(W1)–Ho–O(W4)	71.1(3)	O(W1)–Ho–O(W3)	145.8(3)
O(W1)–Ho–O(W2)	87.1(2)	O(W1)–Ho–O(4)[b]	75.3(3)
O(W1)–Ho–O(5)[a]	107.2(3)	O(W2)–Ho–O(4)[b]	145.2(2)
O(W2)–Ho–O(5)[a]	143.7(2)	O(W3)–Ho–O(4)[b]	133.5(2)
O(W3)–Ho–O(5)[a]	74.4(2)	O(W4)–Ho–O(4)[b]	123.6(3)
O(W4)–Ho–O(5)[a]	77.4(2)	O(W5)–Ho–O(4)[b]	76.9(2)
O(W5)–Ho–O(5)[a]	89.6(2)	O(1) –Ho–O(4)[b]	74.6(2)
O(1) –Ho–O(5)[a]	144.3(2)	O(4)[b] –Ho–O(5)[a]	71.0(2)

[a]Atoms at −y, x−y, z+0.333. [b]Atoms at −x+y, −x, z+0.667. Atoms without superscript at *x, y, z.*

refer to the correct enantiomer with L-aspartate moieties (cf. Fig. 1).

Lists of fractional atomic coordinates of the hydrogen atoms and anisotropic thermal parameters of the non-hydrogen atoms have been deposited with the British Library Lending Division. Copies may be obtained through The Executive Secretary, International Union of Crystallography, 5 Abbey Square, Chester CH1 2HY, England or from the authors. A copy of the list of the structure factors is available directly from the authors (I.C. and P.K.) upon request.

Crystallographic description of the structure, and discussion. Fig. 1 shows a perspective view of a characteristic fraction of the title structure and the labelling of the atoms of the crystallographic asymmetric unit. The geometric data for the coordination around the holmium cation are listed in Table 2, and Fig. 2 is a stereoscopic view of the coordination polyhedron. Table 3 shows the covalent bond lengths and bond angles within the aspartic acid residue, and Table 4 lists the possible H-bonds to the chloride anions and to the non-coordinating water molecule, $O(W6)H_2$. The packing in the crystal structure is illustrated in Fig. 3.

The holmium cation is eight-coordinated by five water molecules and three carboxyl oxygens of three aspartic acid residues. The Ho–O distances range between 2.32 and 2.43 Å, with an average value of 2.36[4] Å (the r.m.s.

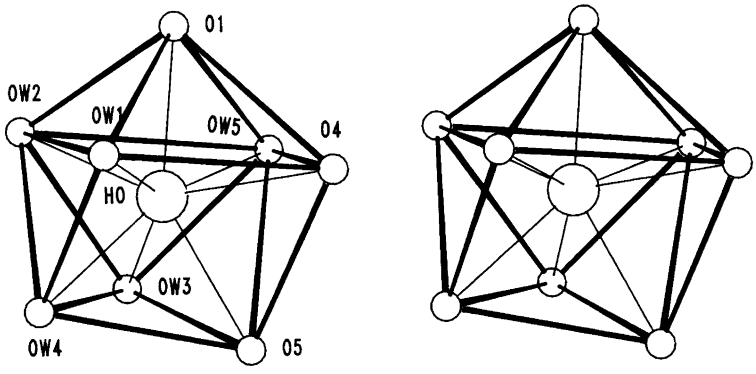

Fig. 2. Stereoscopic view of the coordination polyhedron around the eight-coordinated holmium cation.

Table 3. Intramolecular bond lengths and bond angles involving the non-hydrogen atoms of the aspartic residue. The e.s.d.'s are given in parentheses.

Atoms	Distance/Å	Atoms	Distance/Å
O(1)–C(1)	1.26(1)	O(2)–C(1)	1.25(2)
C(1)–C(2)	1.53(1)	C(2)–N(2)	1.47(2)
C(2)–C(3)	1.54(1)	C(3)–C(4)	1.50(1)
C(4)–O(4)	1.26(1)	C(4)–O(5)	1.26(1)
Atoms involved	**Angle/°**	**Atoms involved**	**Angle/°**
O(1)–C(1)–O(2)	126.4(7)	O(2)–C(1)–C(2)	115.6(7)
O(1)–C(1)–C(2)	117.9(7)	C(1)–C(2)–C(3)	114.1(6)
C(1)–C(2)–N(2)	109.5(6)	N(2)–C(2)–C(3)	111.9(7)
C(2)–C(3)–C(4)	116.3(6)	C(3)–C(4)–O(5)	118.6(7)
C(3)–C(4)–O(4)	117.0(7)	O(4)–C(4)–O(5)	124.4(8)

Table 4. List of possible hydrogen bonds to the chloride anions and to the non-coordinating water molecule.

Atoms	Symmetry	Distance/Å
Cl(1)–O(W6)	*x, y, z*	3.06(1)
Cl(1)–O(W4)	$-x+y, -x-1, z+0.667$	3.01(1)
Cl(1)–O(W5)	$-y, x-y, z+0.333$	3.05(1)
Cl(1)–N(2)	$-x+y, -x-1, z+0.667-1$	3.05(1)
Cl(2)–O(W2)	*x, y, z*	3.09(1)
O(W6)–N(2)	*x, y, z*	2.95(1)
O(W6)–O(W4)	$-y-1, x-y-1, z+0.333$	2.69(1)

deviation is given in angular brackets). The coordination polyhedron can possibly be approximated by a distorted bicapped trigonal prism.

The bond distances and bond angles within the aspartic acid residue conform to the expected values. The C–O distances clearly show the two carboxyl groups to be ionized.

The results of the X-ray study show the coordination of the aspartate moiety to the lanthanoid cation to be very different from that of the glutamic acid residue,[3,4] thus supporting the suggestion made earlier on the basis of spectroscopic investigations.[11] In the crystals of the lanthanoid glutamate perchlorate complexes the cations occur in pairs bridged by four carboxyl groups. The bifunctional glutamic acid residues interlink the pairs of metal ions by coordinating with their two carboxyl groups to two pairs of cations, thus forming infinite layers. The two functional groups of the aspartic acid residues, however, behave very differently: the β-COO^- group coordinates through both of its oxygens to two Ho(II) ions, whereas only one of the α-carboxylic O atoms has direct contact to a third cation. The non-coordinating O(2) atom (*cf.* Fig. 1) is 3.840(7) Å away from the nearest cation and seems to be involved in two hydrogen bonds from two water molecules [O(2)···$O(W5)_{x,y,z}$ = 2.594(9) and O(2)···$O(W2)_{-x+y-1,\ -x-1,\ z-0.333}$ = 2.772(8) Å]. Accordingly, each aspartic acid residue is coordinated to three cations so as to form infinite chains in the crystallographic *c* direction. Within the chains the cations are linked together by an O-C-O group and an O-C-C-C-C-O fragment of two aspartic acid residues in such a way that eleven-membered rings are formed.

The crystal structure consists of parallel holmium–L-aspartate–hydrate chains. The chloride anions and the sixth, non-coordinating water molecule reside in the cavities between the chains and stabilize the crystal packing by forming hydrogen bonds (*cf.* Table 4).

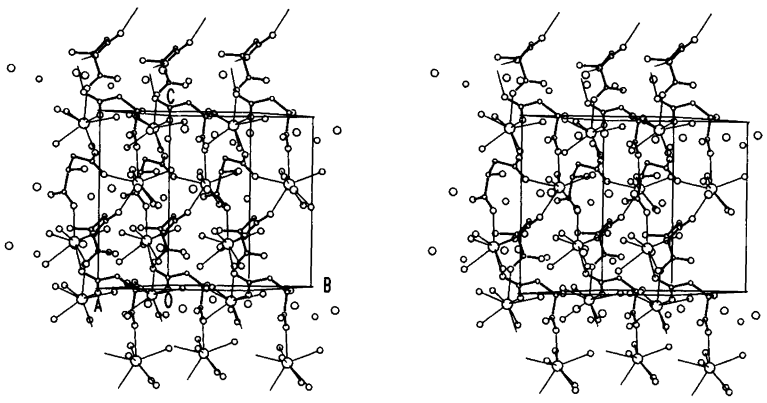

Fig. 3. Stereoscopic packing diagram of the crystal structure viewed along the *a* axis. The hydrogens are omitted for clarity.

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