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Hydrogen atom disorder in the crystal structure of *o*-phenylenediacetic acid

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Abstract

H_2*opda* (1) (*o*-phenylenediacetic acid) was prepared in the form of single crystals. It exhibits molecular crystal structure. The main feature of the supramolecular structure of 1 is formation of hydrogen bonded dimers *via* a pair of O-H···O hydrogen bonds. The hydrogen atoms in COOH groups are disordered in 0.67(2):0.33(2) ratio. The conformation of the free acid is characterized by *cis* arrangement of the carboxylate groups with respect to the plane of the aromatic ring. The powder diffraction pattern of the bulk sample corroborated the phase identity of the commercial material with that of the studied single crystal.

Introduction

O-phenylenediacetic acid (H_2*opda*) is a dicarboxylic acid which, after partial or full deprotonation, can act, in the form of H*opda*(1-) or *opda*(2-) anions as counter anion in various salts (Imai *et al.* 2007; García-Zarracino *et al.* 2008) as well as O-donor anionic ligand in complexes. Within the complexes variable coordination fashions were reported, like terminal H*opda*(1-) O-donor ligand in [Co(H*opda*)$_2$(*pym*)$_2$] (*pym* = H-pyrazol-4-yl)methane) (Sengupta *et al.* 2012), bridging O,O′-donor ligand in [Cu(*opda*)(*pipm*)]·4H_2O (*pipm* = (piperazine-1,4-diyl)bis[(pyridin-4-yl)methanone) (Czarnecki *et al.* 2019) or bis(chelate) bridging ligand in [Cd(*opda*)(*bimb*)] (*bimb* = benzimidazol-1-ylmethyl)benzene) (Yu *et al.* 2015) to mention few examples. Although the crystal structures containing {*o*-$C_6H_4(CH_2$-$COO)_2$} structural fragment are rather numerous, surprisingly, upon the search in CSD (Groom *et al.* 2016) the crystal structure of the acid alone was not reported up to now. On the other hand, crystal structures of its isomers, namely *m*-phenylenediacetic acid, H_2*mpda* (Ref-code HOFBOU) and *p*-phenylenediacetic acid, H_2*ppda* (RIGXOV) were already reported (Fun *et al.* 2007; Zhu 2008).

It is familiar that carboxylate groups, under certain condition, are able to form polymeric-like catemer chains within crystals (D'Ascenzo and Auffinger 2015). Thus comprehensive structure determination and classification of these supramolecular motifs should be of interest in pharmaceutical industry, biomolecular sciences, or crystal engineering. Similar motifs occur in the form of amino acids or motifs involving ligands bearing carboxylate groups (Modec and Klančar 2012).

Following our experiments with the aim to prepare single crystals of magnetically active Ce(III) complex with *opda*(2-) ligand we have unexpectedly obtained single crystals of the free acid. Here we report identification, crystal, molecular and supramolecular structure of H_2*opda*.

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Experimental

Materials

Cerium(III) nitrate, $Ce(NO_3)_3$, NaOH, H_2*pda* and ethanol (99.8 %) were purchased from commercial sources and used as received.

Synthesis of single crystals of H_2pda

To the colorless aqueous solution of $Ce(NO_3)_3$ (200 mg, 0.46 mmol, 10 mL of H_2O) was added a water (15 mL) solution of H_2*opda* (134 mg, 0.69 mmol). The formed solution with pH adjusted to pH = 3 using 0.1 mol.L^{-1} aqueous solution of NaOH was refluxed 90 min yielding yellow microcrystalline powder which was separated by filtration and the light yellow filtrate was left aside. After one week separated light yellow crystals (LK9) which were separated by filtration, rinsed quickly by small amounts of ethanol and diethylether and dried on air.

IR (cm^{-1}): 3065 (w), 3027 (w), 2977 (w), 2939 (w), 2654 (br), 2548 (br), 1682 (s), 1605 (w), 1493 (m), 1453 (m), 1436 (w), 1416 (m), 1394 (m), 1341 (m), 1314 (w), 1284 (w), 1252 (br), 1209 (m), 1191 (w), 1155 (s), 1095 (w), 1050 (w), 910 (br), 812 (m), 758 (m), 742 (s), 701 (s), 667 (m), 650 (m), 626 (m), 543 (m), 500 (m), 445 (m), 413 (w).

^{1}H NMR: [ppm] 3.6 s(4H), 7.21 s(4H-Ar), 12.15 s(2H-OH)

^{13}CNMR: [ppm] 39.5 (2xCH_2), 126.9 (C4,C5), 130.6 (C3,C6), 134.09 (C1,C2), 172.4 (COOH)

Physical measurements

The IR were recorded on a Nicolet 6700 FT-IR spectrophotometer from Thermo Scientific equipped with a diamond crystal Smart Orbit™ in the range 4000 – 400 cm^{-1}.

NMR data were collected at room temperature on a Varian VNMRS spectrometer operating at 599.87 MHz for ^{1}H, and 150.84 MHz for ^{13}C. Spectra were recorded in DMSO-d_6 and the chemical shifts were referenced to the residual solvent signal (^{1}H NMR 2.50 ppm, ^{13}C NMR 39.5 ppm). The 2D gCOSY, gHSQC and gHMBC (optimized for a long range coupling of 8 Hz) methods were employed.

X–ray crystallography

X–ray experiments were carried out on a four-circle κ-axis Xcalibur2 diffractometer equipped with a CCD detector Sapphire2 (Oxford Diffraction). The CrysAlis software package (Oxford Diffraction 2003) was used for data collection and reduction. Analytical absorption corrections using crystal faces were applied (Clark and Reid 1995). The crystal structure of H_2*opda* was solved by direct methods and further refined using the SHELXTL and SHELXL programs (Sheldrick 2015), respectively, incorporated in the WinGX program package (Farrugia 2012). Hydrogen atoms of the aromatic ring and methylene groups were placed in the calculated positions and allowed to ride on the parent atoms with isotropic thermal parameters tied with the parent atoms (U(H) = 1.2U(CH_2)). Hydrogen atoms H11 and H31 of the COOH groups involving O1 and O3 atoms, resp. were easily found in the difference map and were included in the refinement first as idealized OH groups riding on the parent O atom; their isotropic thermal parameters were tied with the parent O atoms (U(H) = 1.5U(O)). During last cycles of the refinement it was found that the differences in C-O(H) and C=O distances are rather small (see Discussion) and, in addition, in the difference map were present small maxima at the positions attributable to hydrogen atoms near (C=)O2 and (C=)O4 oxygen atoms. These findings indicated possible disorder, i.e. partial protonation of both oxygen atoms within the respective COOH groups. The adoption of this model allowed to refine occupancy factors for both orientations of protonation which converged to ratio 0.67(2):0.33(2) with refinement of the positions of hydrogen atoms; the O-H distances were restrained to 0.82(1) Å. It should be noted that the refinement program did not indicate splitting of the corresponding oxygen atoms.

The structural figures were drawn using the Diamond software (Brandenburg 2008). Some geometric parameters were calculated using the PARST program (Nardelli 1999). Program Mercury CSD 4.2.0 Development (Macrae *et al.* 2006) was used for comparison of molecular structures. The Hirshfeld surface was calculated using the program CrystalExplorer17 (Turner *et al.*

Table 1. Crystal data and structure refinement for H_2*opda*.

Empirical formula	$C_{10} H_{10} O_4$
Formula weight	194.18
Temperature [K]	291(2)
Wavelength [Å]	0.71073 Å
Crystal system	Monoclinic
Space group	$P2_1/n$
Unit cell dimensions [Å, °]	a = 14.5276(15) b = 4.8274(3) c = 14.8183(13) β =118.058(13)
Volume [$Å^3$]	917.08(17)
Z	4
Density (calculated) [$g.cm^{-3}$]	1.406
Absorption coefficient [mm^{-1}]	0.110
Crystal dimensions [mm^3]	0.867 x 0.193 x 0.057
θ range for data collection [°]	3.116 to 26.493
Index ranges	$-9 \le h \le 17$, $-5 \le k \le 5$, $-17 \le l \le 12$
Reflections coll./ obs.	3078/1709
Absorption correction	analytical
T_{min}/T_{max}	0.942 / 0.994
Goodness-of-fit on F^2 (all/obs.)	1.035/1.034
Final R indices [$I>2\sigma(I)$]	$R1$ = 0.0349, $wR2$ = 0.0802
R indices (all data)	$R1$ = 0.0508, $wR2$ = 0.0900
Largest diff. peak and hole [e $Å^{-3}$]	0.160 and –0.145

2017). Crystal data and final parameters of the structure refinement are summarized in Table 1, while selected geometric parameters are given in Table 2. Possible hydrogen bonds are gathered in Table 3.

Results and Discussion

Synthesis and spectroscopic characterization

Single crystals of the H_2*opda* suitable for single crystal study were obtained unexpectedly by crystallization from the reaction mixture containing cerium nitrate, NaOH and H_2*opda*. We note that our effort to prepare single crystals by simple recrystallization of the commercially obtained H_2*opda* from various solvents were unsuccessful; the “best” results were obtained by recrystallization from acetone but the tiny dendritic needles were not suitable for single crystal study. The obtained single crystals of H_2*opda* were checked by FT-IR, ^{1}H and ^{13}C NMR spectroscopies; the observed absorption bands and positions of the resonance pics are gathered in the experimental part.

Crystal structure

The crystal structure of H_2*opda* is molecular (Fig. 1) and the unit cell contains 4 molecules of H_2*opda*.There are three points concerning the structural results which merit some comments. The first issue concerns the C-O(H) and C=O bond distances. In H_2*opda* the mean experimental C-O(H) and C=O bond distances are 1.277 Å and 1.248 Å, resp. (Table 2). The search in CSD (Groom *et al.* 2016) has shown that these values are from the ranges found for corresponding bond

Table 2. Selected geometric parameters [Å, °] for H_2*opda*.

C8-O1	1.2824(17)	C10-O3	1.2695(18)
C8-O2	1.2473(17)	C10-O4	1.2477(19)
C7-C8	1.496(2)	C9-C10	1.507(2)
C1-C7	1.5123(19)	C2-C9	1.516(2)
O1-C8-O2	123.51(13)	O3-C10-O4	123.50(14)

Table 3. Hydrogen bonds [Å, °] in H_2*opda*; only the thus with higher occupied hydrogen atoms are shown.

D-H...A	*d*(D-H)	*d*(H···A)	*d*(D···A)	<(DHA)
O1-H11···O4^{i}	0.827(10)	1.884(11)	2.7053(15)	172(3)
O3-H31···O2^{i}	0.819(10)	1.841(10)	2.6598(15)	177(3)

Symmetry code: i: 1 - *x*, 1 - *y*, 1 - *z*.

distances in structures containing {C_6-CH_2-COOH} structural fragment (C_6 is an aromatic ring with any substituent; organic structures, 198 hits), e.g. similar values of 1.279 Å and 1.247 Å were found in (2,3-dihydro-1H-benzo[b]cyclo-penta[d]furan-8-yl)acetic acid (WIDYAM) (Sun *et al.* 2018). On the other hand, the mean values of 1.31(2) and 1.22(2) Å for C-O(H) and C=O bonds, resp., in carboxyl-*syn* structural fragment were reported (D'Ascenzo and Auffinger 2015). Results of our refinement (see the Experimental part) suggest that the rather small observed differences between the C-O(H) and C=O bonds can be explained by hydrogen atom disorder within both COOH groups. Analogous hydrogen atom disorder associated with variation of the corresponding C-O(H) and C=O bonds studied by means of neutron diffraction was reported for benzoic acid (Wilson *et al.* 1996).

The second point worth of discussion is the conformation of the H_2*opda* molecule, more specifically, the positions of the carboxylate groups with respect to the plane of the aromatic ring. While C7 and C9 methylene carbon atoms lie almost in the plane of the aromatic ring (the distances of these C7 and C9 atoms from the aromatic plane are 0.0055(16) Å (C7) and 0.0140(16) Å (C9), the C8 and C10 atoms of the carboxylate groups are both above the plane formed by the aromatic ring (*cis* arrangement). These positions of the carboxylate groups can be expressed by torsion angles C6-C1-C7-C8 and C1-C2-C9-C10 with values of 94.61(17) and 75.75(18)°, respectively. We note that the planes formed by carboxylate groups deviate only slightly from co-planarity as can be seen from the value of 10.74(17)° for the angle between the two planes formed by the respective {COO} groups.

It may be interesting to compare the conformation of the H_2*opda* molecule, more precisely the positions of the carboxylate groups with respect to the plane of the aromatic ring, with the corresponding structural entities in potassium salt, K(H*opda*) (García-Zarracino *et al.* 2008) and four reported salts containing organic cations (Imai *et al.* 2007; Modec and Klačnar 2012; Liu *et al.* 2016; Lin *et al.* 2017). In the potassium salt, like in the free acid, both COO and COOH groups are placed in *cis* arrangement with respect to the aromatic plane, like in the free acid, and the

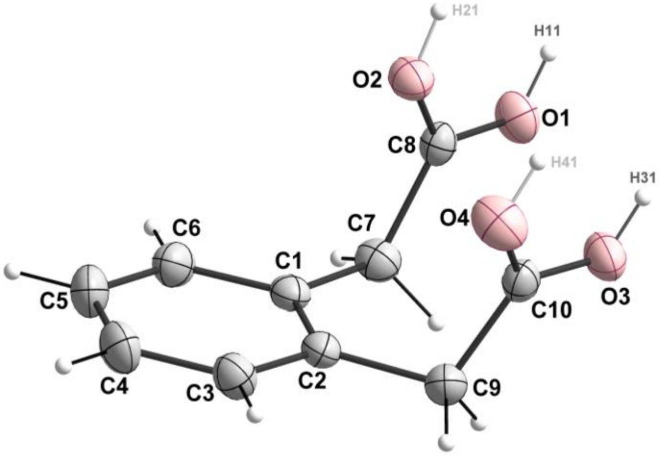

Fig. 1. Thermal ellipsoid plot of the molecular structure of H_2*opda* along with atoms numbering scheme. The thermal ellipsoids are drawn on 30 % probability level. Hydrogen atoms within the carboxylate groups are disordered (H11/H21 and H31/H41) with occupation factors in the 0.67(2):0.33(2) ratio.

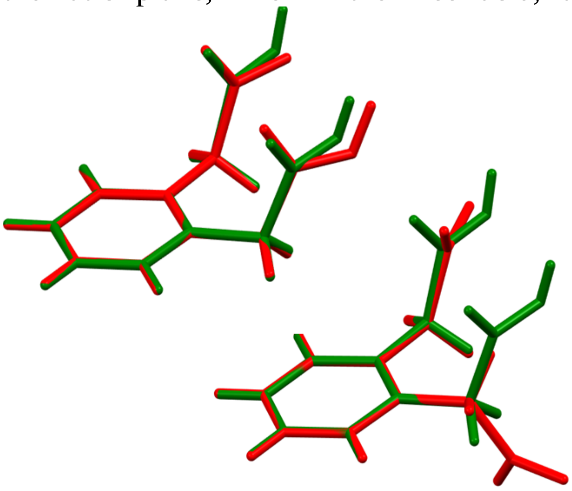

Fig. 2. Comparison of the molecular structures of H_2*opda* molecule (green) and H*opda*(-) anion in K(H*opda*) (red) (left), and H_2*opda* molecule (green) and *opda*(2-) anion in (*dpen*H_2)(*opda*)·CH_3OH (red) (right). The structures were superimposed in such a way that the aromatic rings are overlapped as close as possible.

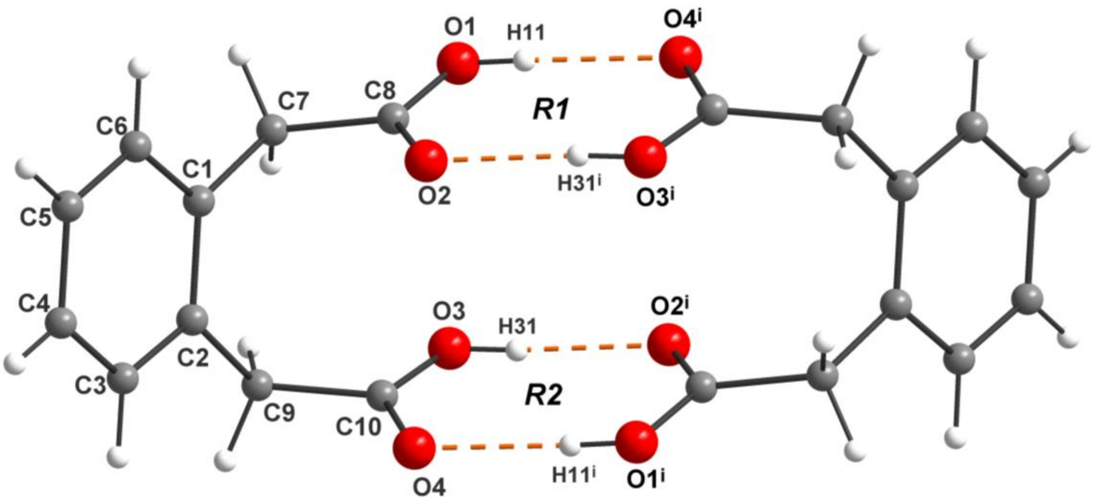

Fig. 3. View on the supramolecular hydrogen bonded dimers of H_2*opda*. Only hydrogen atoms with higher s.o.f.s are shown for clarity. *R*1 and *R*2 are hydrogen bonded rings, both exhibit descriptor $R_2^2(8)$. Symmetry code: i: 1 - *x*, 1 - *y*, 1 - *z*.

corresponding torsion angles of 97.3(2) and 72.1(3)° are comparable with those found in H_2*opda*; the only difference is the slight rotation of both COO groups around the C-C single bond (see Fig. 2, left). On the other hand, in all four salts with organic cations, the two acetate groups are oriented in the space oppositely, i.e. one is situated above and the second below the plane of the aromatic ring (*trans* arrangement). As an example we can mention (*dpen*H_2)(*opda*)·CH_3OH (*dpen*H_2^{2+} = (1R,2R)-1,2-diphenylethylenediammonium dication) (Imai *et al.* 2007) in which the corresponding torsion angles are 97.83 and -83.12°; the structure overlay of the anion *opda*(2-) in this salt with H_2*opda* is shown on Fig. 2 (right). It seems the {*opda*} structural fragment due to its flexibility as to the rotation around methylene group is enough flexible to form in the crystalline state conformation leading to maximization of the lattice energy.

The third point to mention is the formed supramolecular structure. Two molecules of H_2*opda*, the asymmetric one and its congener by center of symmetry, are linked by a pair of relatively strong hydrogen bonds of the O-H···O type yielding supramolecular dimers (H_2*opda*)$_2$ (Table 3, Fig. 3); the hydrogen bonded ring systems can be described using descriptor $R_2^2(8)$ according to Graph Set Analysis (Bernstein *et al.* 1995). We note that no stacking interactions (the shortest distance between the centers of gravity of the aromatic ring is 4.7856(5) Å) nor C_{ar}-H···O weak hydrogen bonds were found, so the formed supramolecular dimers interact only by weak intermolecular interactions of van der Waals nature. The shortest contact is the distance of 2.60 Å between (C7-)H7A hydrogen atom from methylene group and O2^{ii} (ii: *x*, 1 + *y*, *z*) atom from carboxylate group (C7···O2 distance is 3.4884(4) Å). Accordingly, the calculated Hirshfeld surface of the supramolecular dimer is featureless and the very weak pink colored circles correspond to the above mentioned contacts (Fig. 4, upper).

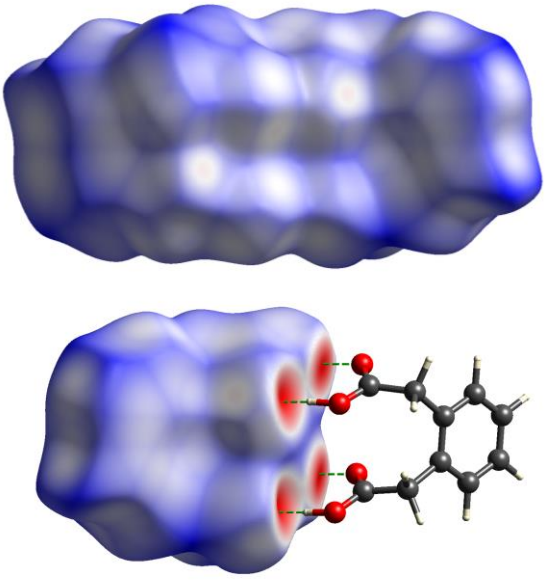

Fig. 4. Upper: Hirshfeld surface of the hydrogen bonded dimers [H_2*opda*]$_2$. Lower: Hirshfeld surface of the H_2*opda* molecule. The hydrogen bonded congener molecule (ball model) is also shown. Hydrogen bonds leading to dimerization are shown as green dashed lines.

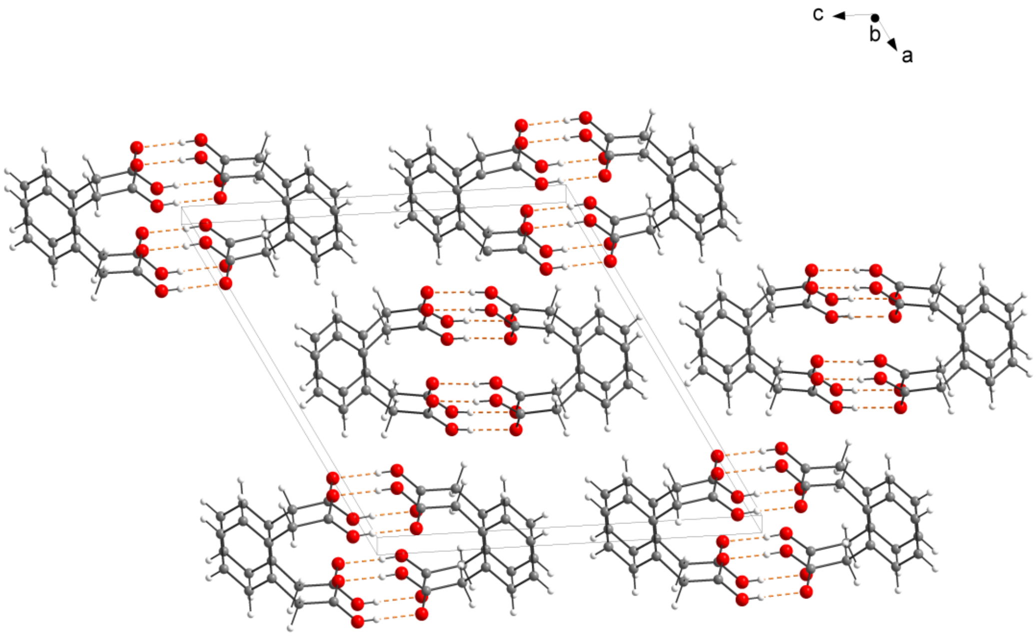

Fig. 5. Packing diagram of H_2*opda*.

On the Fig. 4 (lower) is shown the Hirshfeld surface of the H_2*opda* molecule alone clearly displaying the red spots which reflect the formation of O-H···O type hydrogen bonds. The Fig. 5 shows the packing of the supramolecular dimers.

Conclusions

Single crystals of H_2*opda* crystallized from the reaction mixture formed of cerium(III) nitrate, NaOH and H_2*opda*. Their chemical identity was corroborated by spectroscopic methods. Single crystal X-ray structure analysis confirmed the molecular structure of the free acid with *cis* arrangement of the two acetate groups with respect to the aromatic plane. Results of the structure analysis indicate hydrogen atom disorder in ratio 33 and 67 % within the carboxylate groups. Two H_2*opda* molecules are linked by a pair of O-H···O type hydrogen bonds yielding supramolecular dimers, which are linked only by weak intermolecular interactions.

Supporting Information

Crystallographic data for the compound H_2*opda* has been deposited with the Cambridge Crystallographic Data Centre, CCDC 1981160. Copies of the information may be obtained free of charge from The Director, CCDC, 12 Union Road, Cambridge, CB21EZ, UK (fax: +44–1223–336033; e-mail: deposit@ccdc.cam.ac.uk or www: http://www.ccdc.cam.ac.uk).

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Conflict of Interest

The authors declare that they have no conflict of interest.

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