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COMMUNICATION

The $R_2^2(8)$ Hydrogen-Bonded Supramolecular Synthon in Two Novel Glycoluril Derivatives

Li-Ping Cao · Xiang-Gao Meng · Jiao-Yang Ding · Hai-Ling Xi · An-Xin Wu

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Abstract Two new glycoluril derivatives, namely 6-phenyl-1,4-dioxo-2,2a,3,4,6,7-hexahydro-1H,5H-2,3,4a,6,7a-pentaazacyclopenta[cd]indene-2a,7b-dicarboxylate (**1**), and diethyl 6-(2,4-dichorophenyl)-1,4-dioxo-2,2a,3,4,6,7-hexahydro-1H,5H-2,3,4a,6,7a-pentaazacyclopenta[cd]indene-2a,7b-dicarboxylate (**2**) have been synthesized and structurally determined by X-ray diffraction analysis. Compound **1** is, monoclinic, space group *C2/c*, with $a = 20.0784(7)$, $b = 9.0316(3)$, $c = 23.0980(8)$ Å, $\beta = 98.3930(10)$, $V = 4143.7(2)$ Å^3, with $Z = 8$ for $d_{calc} = 1.338$ Mg/m^3. The analog **2** is, Triclinic, space group *P-1*, with $a = 8.9353(18)$, $b = 10.466(2)$, $c = 14.679(3)$ Å, $\beta = 73.60(3)$, $V = 1268.1(4)$ Å^3, with $Z = 2$ for $d_{calc} = 1.533$ Mg/m^3. X-ray analysis reveals that both glycoluril derivatives bearing two free *syn*-urea NH groups and two ureidyl C=O, assemble the same one-dimensional chains in the solid-state running parallel to the [110], [1–10] and [010] directions via N–H···O hydrogen bonds.

Keywords Glycoluril · Crystal structure · Hydrogen bonding

L.-P. Cao (✉) · X.-G. Meng · J.-Y. Ding · A.-X. Wu
Key Laboratory of Pesticide and Chemical Biology, Ministry of Education, Central China Normal University, Wuhan 430079, People's Republic of China
e-mail: chlpcao@mails.ccnu.edu.cn

H.-L. Xi
6th Department, Research Institute of Chemical Defence, Beijing 102205, People's Republic of China

Introduction

Glycoluril and its derivatives, due to their special precaved structure and a richness of hydrogen-bonding sites, are widely used as building blocks to construct a series of compounds with more sophisticated structures [1, 2] and anion sensors [3–5]. As a result of its curved but rigid skeleton and its multiplicity of hydrogen bond donating (NH) and accepting (ureidyl C=O) groups, glycoluril and its derivatives have recently emerged as a versatile building block for studies of crystal engineering [6–11]. In continuation of our effort in hydrogen-bonding interactions in crystal engineering using glycoluril derivatives as building blocks [12–14], we report here the two-dimensional hydrogen-bonded layer and three-dimensional hydrogen-bonded network formed by the two novel glycoluril derivatives **1** and **2**, in which kernel of crystal structures is the same supramolecular synthon [15].

Experimental

X-ray Crystallography

Single of **1** and **2** suitable for X-ray diffraction were grown from the $CHCl_3$ or $ClCH_2CH_2Cl$ and MeOH, respectively. The intensities of 4078 and 4961 independent reflections with $I > 2\sigma(I)$ were measured on a Bruker Smart Apex CCD area-detector and Rigaku R-axis Spider diffractometer with Mo-Kα radiation ($\lambda = 0.71073$ Å), respectively. The structure was solved by direct methods and refined on F^2 using SHELXL-97 [16–18]. All the non-hydrogen atoms were refined anisotropically. Carbon bound H-atoms were located at the geometrical positions. The crystal data, intensity collection, and structure refinement are

Table 1 Crystal data and structure refinement

Compound	**1**	**2**
CCDC deposit no.	740030	740031
Color/shape	Colorless/block	Colorless/block
Empirical formula	$C_{19}H_{23}N_5O_6$	$C_{19}H_{21}Cl_2N_5O_6 \cdot ClCH_2CH_2Cl$
Formula weight	417.42	585.26
Crystal system	Monoclinic	Triclinic
Space group	C2/c	*P*-1
a (Å)	20.0784(7)	8.9353(18)
b (Å)	9.0316(3)	10.466(2)
c (Å)	23.0980(8)	14.679(3)
α (°)	90.00	74.74(3)
β (°)	98.3930(10)	73.60(3)
γ (°)	90.00	89.01(3)
V (Å^3)	4143.7(2)	1268.1(4)
Z	8	2
D_c (Mg M^{-3})	1.338	1.533
μ(Mo Kα) (mm^{-1})	0.102	0.514
F(000)	1760	604
Absorption correction	Multi-scan	Multi-scan
T_{min} and T_{max}	0.9770 and 0.9899	0.9041 and 0.9041
θ Range for data collection	1.78 and 26.00	3.00 and 26.00
Index ranges	$-24 \le h \le 24$, $-10 \le k \le 11$, $-28 \le l \le 28$	$-11 \le h \le 11$, $-12 \le k \le 12$, $-17 \le l \le 18$
Reflections collected	16224	10981
Unique reflections	4078	4961
Observed reflections	3163	4537
No. of parameters	299	334
Goodness-of-fit on F^2	1.105	1.061
Final *R* indices [$I > 2\sigma(I)$]	$R_1 = 0.0650$, $\omega R = 0.1348$	$R_1 = 0.0477$, $\omega R = 0.1336$
R indices (all data)	$R_1 = 0.0874$, $\omega R = 0.1452$	$R_1 = 0.0511$, $\omega R = 0.1364$

summarized in Table 1; the hydrogen-bonding geometry is listed in Tables 2 and 3, respectively.

Synthesis

The preparation of glycoluril monomers **1** and **2** followed well established methodology [19, 20], as shown in Scheme 1. When diethoxycarbonyl was combined with equivalent phenyl or 2,4-dichorophenyl methanamine in the presence of anhydrous formaldehyde in ethanol at reflux, the expected compounds, the new glycolurils, were obtained, respectively, in good yields. EtOH and the ethyl amines had to be freshly distilled. A suspension of

Table 2 Hydrogen-bonding geometry for **1** (Å,°)

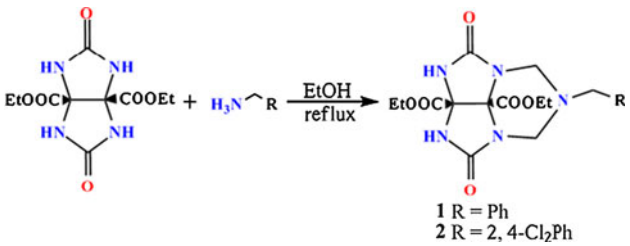
D–H···A	D–H	H···A	D···A	D–H···A
N2–H2···O2^{i}	0.85(2)	2.05(2)	2.876(2)	164(2)
N1–H1···O1^{ii}	0.87(2)	2.05(2)	2.894(2)	165(2)
C17–H17···O1^{iii}	0.93(2)	2.49 (2)	3.417(3)	176(1)

Symmetry code: (i) −x + 1, −y + 2, −z + 1; (ii) −x + 1/2, −y + 3/2, −z + 1; (iii) x + 1/2, y−1/2, z

Table 3 Hydrogen-bonding geometry of **2** (Å,°)

D–H···A	D–H	H···A	D···A	D–H···A
N4–H4A···O1^{i}	0.78(4	2.07(4)	2.845(3)	172(3)
N5–H5A···O2^{ii}	0.82(4)	2.01(4)	2.823(3)	170(3)
C19–H19···Cl1^{iii}	0.96	2.65	3.137(15)	112(3)
C14–H14B···O1^{iii}	0.97	2.55	3.288(3)	133(3)
C7–H7A···O3^{iv}	0.97	2.54	3.337(3)	139(3)

Symmetry code: (i) −x, −y + 2, −z; (ii) −x, −y + 1, −z; (iii) −x + 1, −y + 2, −z; (iv) −x + 1, −y + 1, −z



Scheme 1 Synthesis of the title compounds **1** and **2**

diethoxycarbonyl glycoluril (1.43 g, 5 mmol) with anhydrous formaldehyde (0.3 g, 10 mmol) and EtOH (50 mL) were brought to reflux under Ar. A solution of equivalent phenyl or 2,4-dichorophenyl methanamine (5 mmol) in EtOH (10 mL) was added, dropwise slowly (over 1 h) to the mixture. Then refluxing was continued for 10–12 h, monitored by TLC (the reaction time must be strictly controlled at less 12 h). The solvent was removed under reduced pressure and the products were separated by column chromatography (silica gel). Crystals of **1** and **2** suitable for X-ray data collection were obtained by slow evaporation of a dichloroethane and methanol solution in ratio of 4:1 (v:v) at 293 K. Compound **1**: yield 79%; m.p. 180–181 °C; TLC ($CHCl_3$/MeOH, 30:1) R_f 0.15; IR (KBr, cm^{-1}): 3217m, 3097m, 2985m, 2851m, 1864w, 1844w, 1755s, 1709s, 1653m, 1636m, 1475m, 1457m, 1421m, 1388m, 1339m, 1292s, 1276s, 1193w, 1151m, 1099m, 1048m, 1020m, 993m; ^{1}H NMR (400 MHz, $CDCl_3$): 7.33–7.27 (m, 5H), 6.56 (s, 2H), 4.81 (d, $J = 13.6$, 2H), 4.34 (d, $J = 14.0$, 2H), 4.30–4.24 (m, 4H), 3.66 (s, 2H),

1.32–1.28 (m, 6H); ^{13}C NMR(100 MHz, $CDCl_3$): 166.0, 165.4, 158.1, 136.7, 129.3, 128.4, 127.6,78.4, 74.3, 63.6, 63.2, 59.6, 54.2, 13.9, 13.8. Compound **2**: yield 83%; m.p. 145–146 °C; TLC ($CHCl_3$/MeOH, 50:1) R_f 0.20; IR (KBr, cm^{-1}):3210m, 3096m, 2982w, 2936w, 2854w, 1844w, 1828w, 1764s, 1741s, 1693s, 1651m, 1636w, 1589w, 1474m, 1446m, 1425m, 1395m, 1369m, 1340m, 1308m, 1286m, 1262m, 1224m, 1188m, 1161m, 1082m, 1040m, 986m; ^{1}H NMR (400 MHz, $CDCl_3$):7.42 (d, J = 8.0, 1H), 7.38 (s, 1H), 7.23(d, J = 8.0, 1H),6.75 (s, 2H), 4.82(d, J = 14.0, 2H), 4.33 (d, J = 14.0, 2H), 4.23–4.24 (m, 4H), 3.70(s, 2H), 1.32–1.29 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): 165.9, 165.4, 158.3, 135.8, 134.2, 132.9, 132.1, 129.6, 127.0, 78.4, 74.5, 63.7, 63.3, 59.7, 51.2, 13.9, 13.8.

Result and Discussion

The molecular structures of **1** (Fig. 1) and **2** (Fig. 2) are built up from three fused rings, namely two nearly planar imidazole five-membered rings that adopt envelope conformations, with the ureidyl C=O groups at the flap positions, and one six-membered triazacyclohexane ring that adopts a chair conformation. These rings bear two CO_2Et groups on their 'convex' faces. The bond lengths and bond angles in both the compounds are similar to those reported previously [7, 8, 6, 9, 10, 12]. The =O···O= distances are 5.652(2) Å in (I) and 5.657(2) Å in (II) and all of the C_{sp2}–N distances and C_{sp3}–N distances lie in the range 1.347(3)–1.472(3) Å and 1.444(3) 1.482(3) Å, respectively. Obviously, the N–C(carbonyl) bond distances are much shorter than the other N–C bond distances in three fused rings, indicating some electron delocalization within these rings. Again, the *cis*-fused five-membered rings bearing CO_2Et groups enforce their cup shaped geometry. The angle between the mean planes defined by the five-membered rings amounts to 114.99(10)° in **1** and 114.88(12)° in **2**. The glycoluril units are both almost coplanar, which are indicated by the key torsional angles [in **1**: N1–C1–C2–N3 0.64(2)°, C5–C1–C2–C8 4.5(2)°; in **2**: N2–C12–C16–N4-4.2(2)°, C13–C12–C16–C17-12.6(2)°].

In their supramolecular structures formed via N–H···O hydrogen bonds, the molecules of **1** and **2** are linked into one-dimensional hydrogen-bonded chain (Scheme 2). In **1**, amide N1 and N2 atoms in molecule at (x, y, z) act H-bonding donors, via H1 and H2, respectively, to carboxyl O1 in molecule at (1/2−x, 3/2−y, 1−z) and O2 at (1−x, 2−y, 1−z), both producing one-dimensional chains (Chain A, Fig. 3) running parallel to the [110] direction. These two type [110] chains are interlinked by the approximately centrosymmetric $R_2^2(8)$ [21] H-bonding motif, forming a one-dimensional chain structure along the [110] direction (Table 2). Interestingly, this chain produces

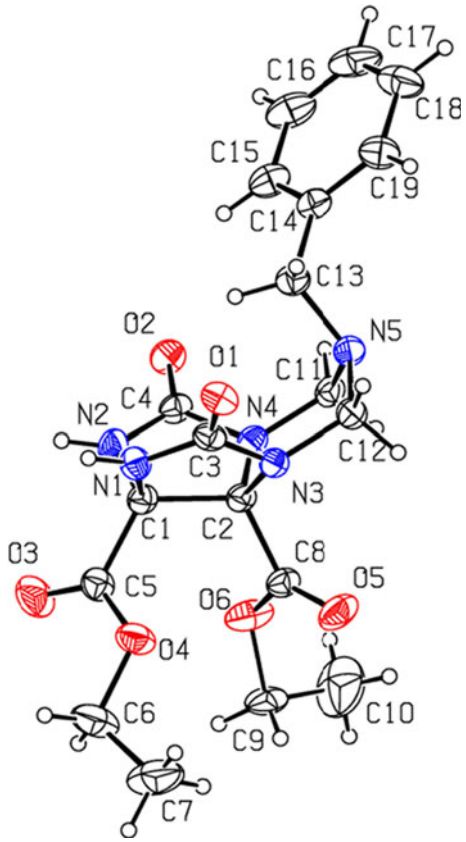


Fig. 1 The molecular structures of **1**, showing 30% probability level and H atoms are shown as small spheres of arbitrary radii. Atoms of the minor disorder components has been omitted for clarity

another different chain generated by the 2_1 screw axis at (1/4, y, 1/4), running parallel to the [1–10] direction (Chain B, Fig. 3). Four chains, including two chain A and two chain B, pass through each unit cell. Some weak nonclassical hydrogen bonds, C17–H17···O2 [C···O = 3.417(3) Å] (Table 2), further consolidate the supramolecular structure.

Similar to compound **1**, molecules in compound **2** also forms the similar one-dimensional hydrogen-bonded tapes in the solid-state along the [010] direction (Fig. 4, Table 3). In **2**, two amide atoms, N4 and N5 in molecule at (x, y, z) act as H-bonding donors, via H4 and H5, respectively, to carboxyl O1 in molecule at (−x, 2−y, 2−z) and O2 at (−x, 1−y, 2−z), both producing the one-dimensional chains running parallel to the [010] direction. These two type [010] chains are interlinked by the approximately centrosymmetric $R_2^2(8)$ [21] H-bonding motif, forming the one-dimensional chain structure along the [010] direction. Furthermore, the second substructure is constructed by way of C–H···O and C–H···Cl hydrogen bonds: C14–H14B···O1 [C···O = 3.288(3) Å], C7–H7A···O3 [C···O = 3.337(3) Å] and C19–H···Cl1 [C···Cl = 3.137(2) Å], forming the other one-dimensional tapes along the [100] direction which suffices to link the [010] tapes into a

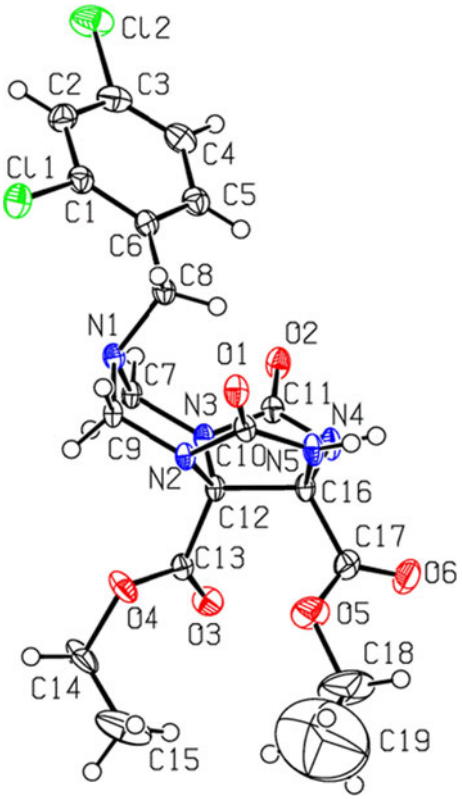
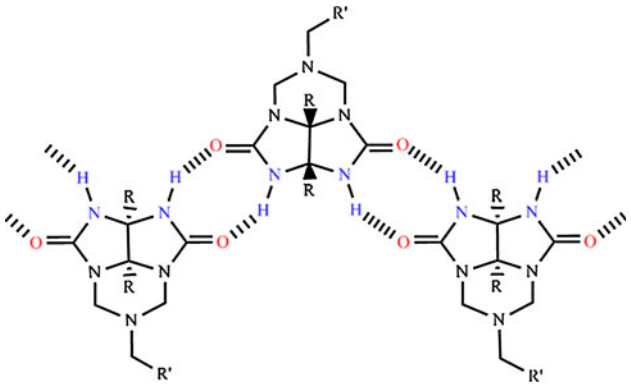


Fig. 2 The molecular structures of **2**, showing 30% probability level and H atoms are shown as small spheres of arbitrary radii. The solvent molecule ($ClCH_2CH_2Cl$) has been omitted for clarity



Scheme 2 $R_2^2(8)$ hydrogen-bonded chain in **1** and **2**

two-dimensional layer running parallel to the (001) direction (Table 3). There are no direction-specific interactions between the adjacent three-dimensional networks, either.

Conclusion

In summary, the same one-dimensional hydrogen-bonded chains along [110], [1–10] and [010] directions are found here for **1** and **2** (Scheme 2). This may be ascribed to the same supramolecular synthon of the two novel glycoluril derivatives, which both bear two free *syn*-urea NH groups and two ureidyl C=O groups. The C–H···O and C–H···Cl hydrogen bonds link these one-dimensional chains into hydrogen-bonded l network in **1** and **2**, respectively.

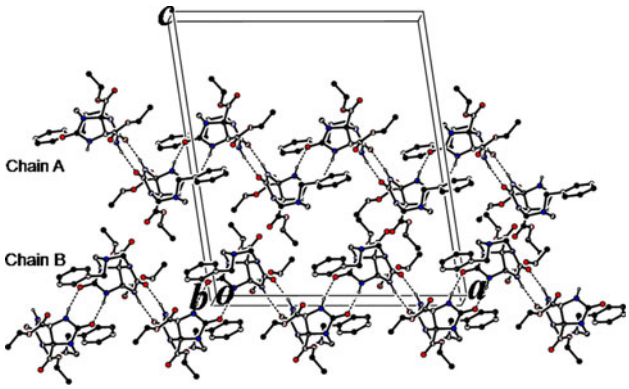


Fig. 3 Packing of **1**, showing the formation of a one-dimensional hydrogen-bonded $R_2^2(8)$ chain along the [110] (*up*) and [1–10] (*down*) directions involving *syn*-NH atoms and C=O. Hydrogen bonds are drawn as *dashed lines*

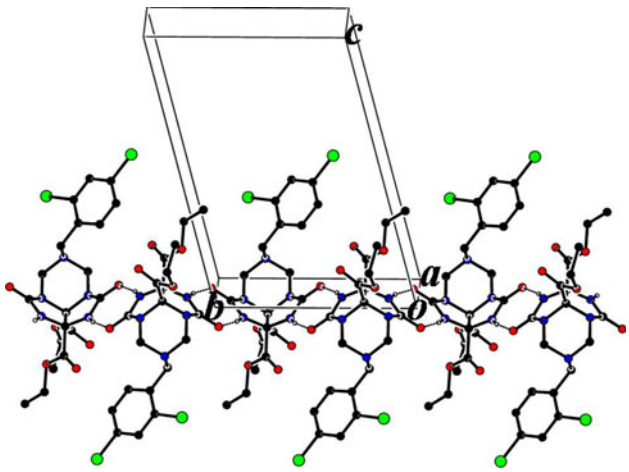


Fig. 4 Packing of **2**, showing the formation of a one-dimensional hydrogen-bonded $R_2^2(8)$ chain along the [010] direction involving *syn*-NH atoms and C=O. Hydrogen bonds are drawn as *dashed lines*

Supplementary Material

CCDC 740030 and 740031 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, by e-mailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44-1223-336033.

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