

N,N'-Dicyclohexyl-*N*-[4-(1*H*-indol-3-yl)butanoyl]urea

Sharmila Basu,^a Soumen Ghosh,^a Somnath Ghosh,^b
Madeleine Helliwell^c and Alok K. Mukherjee^{a*}^aDepartment of Physics, Jadavpur University, Kolkata 700 032, India, ^bDepartment of Chemistry, Jadavpur University, Kolkata 700 032, India, and ^cDepartment of Chemistry, University of Manchester, Manchester M13 9PL, England
Correspondence e-mail: akm_ju@rediffmail.comReceived 9 September 2008
Accepted 1 October 2008
Online 18 October 2008

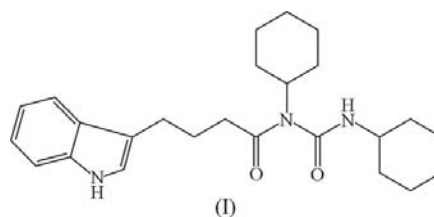
The title compound, C₂₅H₃₅N₃O₂, is a novel urea derivative. Pairs of intermolecular N—H···O hydrogen bonds join the molecules into centrosymmetric R₂²(12) and R₂²(18) dimeric rings, which are alternately linked into one-dimensional polymeric chains along the [010] direction. The parallel chains are connected *via* C—H···O hydrogen bonds to generate a two-dimensional framework structure parallel to the (001) plane. The title compound was also modelled by solid-state density functional theory (DFT) calculations. A comparison of the molecular conformation and hydrogen-bond geometry obtained from the X-ray structure analysis and the theoretical study clearly indicates that the DFT calculation agrees closely with the X-ray structure.

Comment

In the molecular recognition and self-assembly process, relatively simple building blocks recognize one another, associate, and form one-, two- and three-dimensional supramolecular frameworks. The phenomenon of specific recognition is facilitated by a combination of different noncovalent interactions, which include electrostatic interactions, hydrogen bonds, hydrophobic interactions and aromatic stacking interactions. The overall combination of various molecular forces, which are quite weak individually, results in the process of self-organization from simple blocks into complex supramolecular structures. In this context, substituted ureas having multiple hydrogen-bonding potential are of considerable current interest (Allen *et al.*, 1997; Gale & Quesada, 2006; Custelcean, 2008). Several urea derivatives have been found to contain a one-dimensional α networks, which in turn are linked to form two-dimensional β sheets through N—H···O hydrogen bonds. Many of these compounds also exhibit a wide range of biological activities as herbicides, pesticides and fungicides (Bessard & Crettaz, 2000; Sun & Zhang, 2006).

As part of an ongoing programme on the synthesis and structural characterization of novel urea derivatives, we

synthesized *N,N'*-dicyclohexyl-*N*-[4-(1*H*-indol-3-yl)butanoyl]urea, (I), designed for self-complexation, and the crystal structure of (I) was established by single-crystal X-ray analysis. Since the positions of H atoms in molecular systems are usually determined with limited accuracy by an X-ray study, a solid-state density functional theory (DFT) calculation has been performed for a better understanding of the intra- and intermolecular hydrogen-bond geometry in the title compound. The advantage of the DFT method over X-ray structure refinement is that the positions of the H atoms are optimized simultaneously along with the positions of the non-H atoms, thus providing a more reliable hydrogen-bond geometry.



The asymmetric unit of (I) (Fig. 1) consists of a planar indole group (C1–C8/N1), with an r.m.s. deviation of 0.013 Å, and a dicyclohexylurea unit joined through a butanoyl chain. The two cyclohexyl groups are in a *syn-syn* conformation with respect to the urea group; the O2–C13–N3–C14 and O2–C13–N2–C20 torsion angles are 4.5 (2) and 48.7 (1)°, respectively. The extended molecular conformation of (I) is indicated by the C9–C10–C11–C12 torsion angle of –174.9 (2)°. Each of the cyclohexyl groups in (I) adopts a chair conformation, with ring-puckering parameters (Cremer & Pople, 1975) Q , θ and φ of 0.569 (2) Å, 180.0 (2)° and 344 (53)°, respectively, for the C14–C19 ring, and 0.579 (2) Å, 2.9 (2)° and 54 (3)°, respectively, for the C20–C25 ring. The two carbonyl groups in the *N*-acylureido unit are twisted substantially at the central N2 atom, with a dihedral angle of

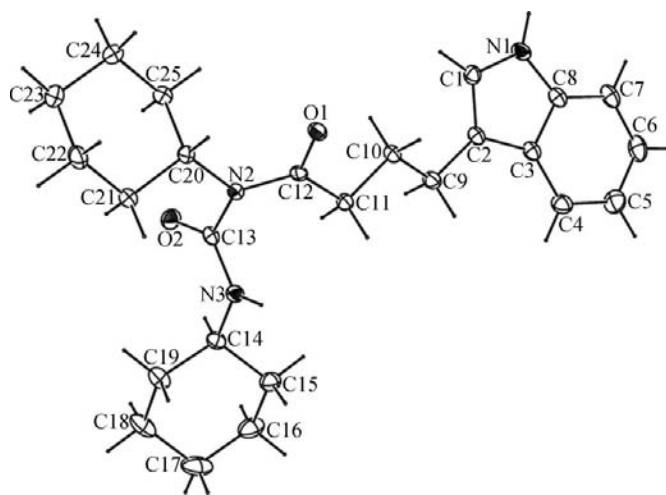


Figure 1
A view of (I), showing the atom-numbering scheme. Displacement ellipsoids are drawn at the 40% probability level and H atoms are shown as small spheres of arbitrary radii.

58.3 (1)° between the O1/C12/N2 and N2/C13/O2 planes, which increases the distance between atoms O1 and N3. Therefore, as expected, no intramolecular N3—H3N···O1 hydrogen bond is formed.

The observed bond distances from the X-ray analysis are in accord with the corresponding values reported for other dicyclohexylurea derivatives (Gallagher *et al.*, 1999; Sun & Zhang, 2006; Wu *et al.*, 2006). The shortening of the N3—C13 and N2—C12 bond lengths with the corresponding lengthening of the N2—C13 bond distance (Table 1) can be attributed to π -conjugation in the O1/C12/N2/C13 and O2/C13/N3/C14 fragments of the molecule.

Molecules of (I) are linked by a combination of N—H···O and C—H···O hydrogen bonds (Table 2) into a two-dimensional framework, whose formation is readily analysed in terms of substructures of lower dimensionality with finite zero-dimensional dimeric units as the building blocks within the structure. A pair of intermolecular N—H···O hydrogen bonds with the urea N3 atom in the molecule at (x, y, z) acting as a donor to the butanoyl O1 atom in the molecule at $(1-x, 1-y, 1-z)$ generates a centrosymmetric dimeric ring (A) with graph-set motif (Etter, 1990) $R_2^2(12)$, centred at $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2})$. Similarly, a pair of intermolecular N1—H1N···O1ⁱⁱ hydrogen bonds in (I) interconnects two molecules at (x, y, z) and $(1-x, -y, 1-z)$, producing a centrosymmetric $R_2^2(18)$ dimeric ring (B) centred at $(\frac{1}{2}, 0, \frac{1}{2})$. The $R_2^2(12)$ and $R_2^2(18)$ rings are alternately linked into an infinite one-dimensional $ABAB\dots$ polymeric chain propagating along the [010] direction (Fig. 2). Adjacent one-dimensional chains are connected *via* pairs of C11—H11A···O2 $(-x, -y+1, -z+1)$ hydrogen bonds,

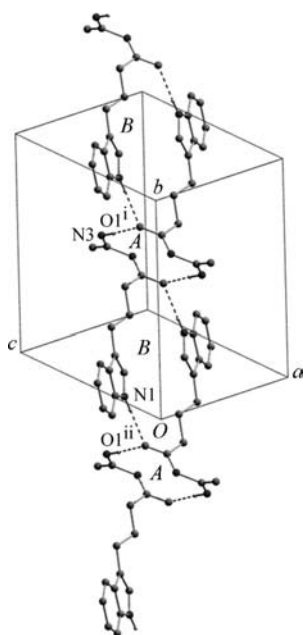


Figure 2
Part of the crystal structure of (I), showing the combination of $R_2^2(12)$ and $R_2^2(18)$ rings forming a one-dimensional chain running along the [010] direction. For the sake of clarity, the cyclohexyl groups and H atoms not involved in the hydrogen bonding shown have been omitted. [Symmetry codes: (i) $-x+1, -y+1, -z+1$; (ii) $-x+1, -y, -z+1$.]

producing $R_2^2(12)$ motifs which propagate along the [100] direction. The combination of [010] and [100] chains suffices to generate a continuous two-dimensional framework structure (Fig. 3).

Solid-state DFT calculations have been performed using the *Dmol*³ code (Delly, 1996, 1998) of the *Materials Studio* system of programs (Accelrys Inc., Princeton, New Jersey, USA) in the framework of a generalized-gradient approximation. The starting atomic coordinates were taken from the final X-ray refinement cycle. Since the resulting molecular geometry depends on the choice of functionals, theoretical calculations were carried out with the BLYP (Becke, 1988; Lee *et al.*, 1988) and HCTH (Hamprecht *et al.*, 1998; Boese *et al.*, 2000; Boese & Handy, 2001) levels of theory using the numeric DNP basis set. The cell parameters were kept fixed during the DFT calculations. Different functionals describe different classes of molecules with varying degrees of accuracy. Between the two functionals used for the DFT calculation, the results with the HCTH functional agree more closely with the X-ray analysis of the title compound. A comparison of the molecular conformation of (I) as established by the X-ray study and quantum mechanical calculations shows an excellent agreement (Fig. 4); the r.m.s. deviation between the coordinates obtained by geometry optimization and X-ray structure analysis is 0.013 Å. The elongation of the DFT-calculated N2—C13 bond length compared with the N2—C12 and N3—

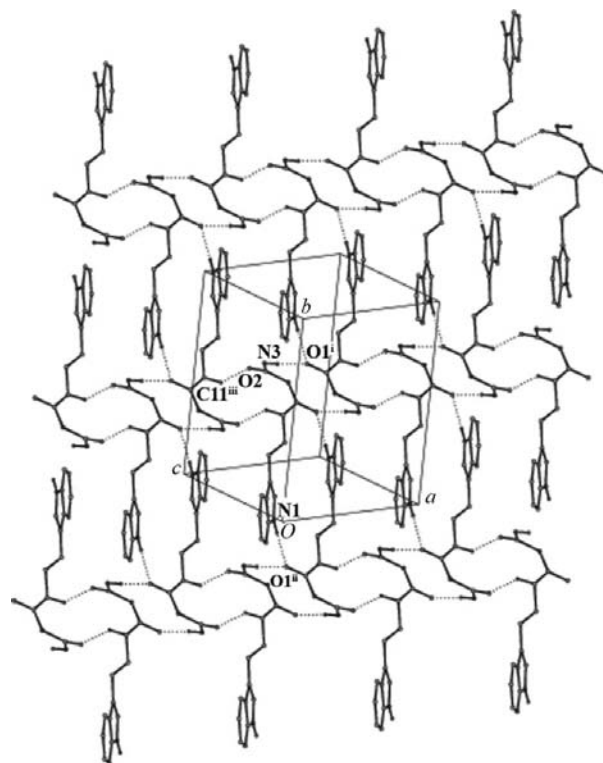


Figure 3
Part of the crystal structure of (I), showing the generation of the two-dimensional framework structure. For the sake of clarity, the cyclohexyl groups and H atoms not involved in the motif shown have been omitted. [Symmetry codes: (i) $-x+1, -y+1, -z+1$; (ii) $-x+1, -y, -z+1$; (iii) $-x, -y+1, -z+1$.]

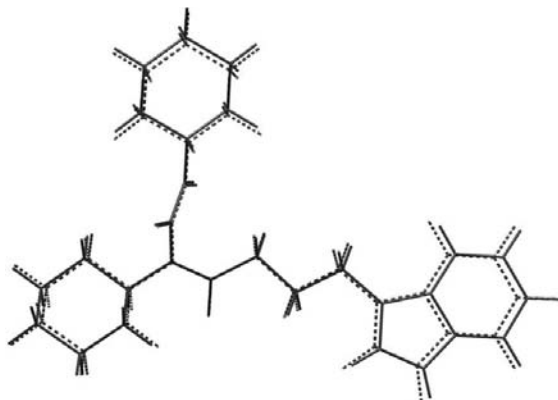


Figure 4
Comparison of the molecular conformation of (I) as established from X-ray study (solid line) and solid-state DFT calculation (dotted line).

C13 bond distances is consistent with the X-ray analysis of the title compound. The calculated O \cdots H distances (1.831–1.898 Å) in (I) lie in the range of normal N–H \cdots O hydrogen bonds (Lyssenko & Antipin, 2006). The geometries of the hydrogen bonds (Table 2) calculated from the DFT method closely resemble those obtained from the X-ray analysis (X –H bond lengths normalized to neutron distances), with the formation of characteristic $R_2^2(12)$ and $R_2^2(18)$ rings, polymeric chains and finally a two-dimensional supramolecular assembly.

It is of interest to compare briefly the supramolecular structure of (I) with those of other N,N' -disubstituted ureas (Custelcean, 2008). Disubstituted urea derivatives tend to form one-dimensional hydrogen-bonded chains by employing their two NH H-atom donors and the C=O acceptors. The NH H atoms normally adopt an *anti* conformation with respect to the carbonyl group and form three-centre bonds to the urea carbonyl groups. The resulting hydrogen-bonded motif can be described by using the graph-set notation as $C(4)[R_2^1(6)]$ (Chang *et al.*, 1993; Hollingsworth *et al.*, 1994). Bulky substituents at the urea N atoms of (I), however, prohibit the formation of short NH \cdots O–C interactions, and consequently the urea planes are twisted relative to one another. The propensity of ureas to form hydrogen-bonded chains and cyclic dimers has been utilized in the design of two-dimensional layered networks (Kane *et al.*, 1995; Wu *et al.*, 2006). In the structure of (I), a two-dimensional supramolecular network based on cyclic $R_2^2(12)$ and $R_2^2(18)$ motifs has been established from urea–butanoyl NH \cdots O–C, indole–butanoyl NH \cdots O–C and butanoyl–urea CH \cdots O–C interactions.

Experimental

A suspension of 4-(indol-3-yl)butyric acid (1.02 g, 5 mmol) and dicyclohexyl diimide (1.03 g, 5 mmol) in dry benzene (20 ml) was refluxed for 3 h using a Dean–Stark water separator. Removal of the solvent *in vacuo* afforded a colourless crystalline solid, which was recrystallized from an acetone/*n*-hexane mixture (1:1 *v/v*) to obtain diffraction quality single crystals of the title compound (yield 0.48 g, 23.5%; m.p. 413 K). Analysis found: C 73.38, H 8.55, N 10.30%; calculated for $C_{25}H_{35}N_3O_2$: C 73.31, H 8.61, N 10.26%. 1H NMR

($CDCl_3$): δ 1.23 (*m*, 11H, –NH– C_6H_{11}), 1.74 [*m*, 11H, –CO–N(C_6H_{11})–CO–], 2.07 (*m*, 2H, –CH $_2$ –CH $_2$ –CH $_2$), 2.45 (2H, *t*, J = 7.2 Hz, –H $_2$ C–CH $_2$ –CO–), 2.84 (2H, *t*, J = 7.2 Hz, In–CH $_2$ –CH $_2$ –), 6.78 (1H, *br s*, –CO–NH– C_6H_{11}), 7.01 (1H, *br s*, C $_2$ –H), 7.11 (1H, *t*, J = 7.5 Hz, C $_6$ –H), 7.19 (1H, *t*, J = 7.5 Hz, C $_5$ –H), 7.36 (1H, *d*, J = 8.1 Hz, C $_7$ –H), 7.60 (1H, *d*, J = 7.8 Hz, C $_4$ –H), 8.02 (1H, *br s*, –NH).

Crystal data

$C_{25}H_{35}N_3O_2$	γ = 72.289 (1) $^\circ$
M_r = 409.56	V = 1135.83 (16) Å 3
Triclinic, $P\bar{1}$	Z = 2
a = 8.4655 (7) Å	Mo $K\alpha$ radiation
b = 11.5938 (9) Å	μ = 0.08 mm $^{-1}$
c = 13.0982 (11) Å	T = 100 (2) K
α = 68.331 (2) $^\circ$	0.50 \times 0.46 \times 0.40 mm
β = 86.752 (1) $^\circ$	

Data collection

Bruker SMART CCD area-detector diffractometer	5965 measured reflections
Absorption correction: multi-scan (<i>SADABS</i> ; Bruker, 2001)	3945 independent reflections
T_{min} = 0.964, T_{max} = 0.975	3297 reflections with $I > 2\sigma(I)$
	R_{int} = 0.029

Refinement

$R[F^2 > 2\sigma(F^2)]$ = 0.036	H atoms treated by a mixture of independent and constrained refinement
$wR(F^2)$ = 0.100	$\Delta\rho_{max}$ = 0.19 e Å $^{-3}$
S = 1.03	$\Delta\rho_{min}$ = –0.19 e Å $^{-3}$
3945 reflections	
279 parameters	

Table 1

Selected geometric parameters (Å, $^\circ$) for (I).

	X-ray	DFT
C1–N1	1.3758 (16)	1.376
N1–C8	1.3709 (17)	1.370
C12–N2	1.3629 (15)	1.363
C20–N2	1.4874 (15)	1.487
C13–N2	1.4474 (15)	1.448
C13–N3	1.3295 (16)	1.329
C13–O2	1.2154 (15)	1.215
C14–N3	1.4619 (16)	1.462
C8–N1–C1	108.57 (11)	108.6
C3–C8–N1	107.65 (11)	107.6
C9–C10–C11–C12	–174.86 (10)	–174.9
O2–C13–N3–C14	4.45 (18)	4.5
O2–C13–N2–C20	48.75 (15)	48.8

Table 2

Hydrogen-bonding geometry (Å, $^\circ$) for (I).

D –H \cdots A		D –H	H \cdots A	$D\cdots A$	D –H \cdots A
N3–H3N \cdots O1 i	X-ray	0.885 (15)	2.049 (16)	2.9326 (14)	176 (1)
N3–H3N \cdots O1 i	Pseudo-neutron	1.01	1.93	2.933 (2)	176
N3–H3N \cdots O1 i	DFT	1.10	1.83	2.933	172
N1–H1N \cdots O1 ii	X-ray	0.882 (16)	2.06 (2)	2.914 (1)	162.7 (14)
N1–H1N \cdots O1 ii	Pseudo-neutron	1.01	1.94	2.914 (2)	162
N1–H1N \cdots O1 ii	DFT	1.10	1.90	2.915	150
C11–H11A \cdots O2 iii	X-ray	0.97	2.23	2.970 (2)	126
C11–H11A \cdots O2 iii	Pseudo-neutron	1.08	2.23	2.970 (2)	123
C11–H11A \cdots O2 iii	DFT	1.14	2.19	2.969	123

Symmetry codes: (i) $-x + 1, -y + 1, -z + 1$; (ii) $-x + 1, -y, -z + 1$; (iii) $-x, -y + 1, -z + 1$.

The NH H-atom positions obtained from a difference Fourier map were refined freely, while the C-bound H atoms were placed in idealized positions using the riding method, with bond distances ranging from 0.93 to 0.98 Å and $U_{\text{iso}}(\text{H})$ values set at $1.5U_{\text{eq}}$ of the parent atoms.

Data collection: *SMART* (Bruker, 2001); cell refinement: *SAINT* (Bruker, 2002); data reduction: *SAINT*; program(s) used to solve structure: *SHELXS97* (Sheldrick, 2008); program(s) used to refine structure: *SHELXL97* (Sheldrick, 2008); molecular graphics: *ORTEP-3 for Windows* (Farrugia, 1997), *CAMERON* (Watkin *et al.*, 1993) and *DIAMOND* (Bergerhoff, 1996); software used to prepare material for publication: *SHELXL97* and *PARST95* (Nardelli, 1995).

Soumen Ghosh thanks Jadavpur University, Kolkata, India, for a research fellowship. The authors are grateful to Basab Chattopadhyay, IACS, Kolkata, for helping with the DFT calculations.

Supplementary data for this paper are available from the IUCr electronic archives (Reference: SK3261). Services for accessing these data are described at the back of the journal.

References

- Allen, F. H., Bird, C. M., Rowland, R. S. & Raithby, P. R. (1997). *Acta Cryst.* **B53**, 680–695.
- Becke, A. D. (1988). *Phys. Rev. A*, **38**, 3098–3100.
- Bergerhoff, G. (1996). *DIAMOND*. Crystal Impact GbR, Bonn, Germany.
- Bessard, Y. & Crettaz, R. (2000). *Tetrahedron*, **56**, 4739–4746.
- Boese, A. D., Doltsinis, N. L., Handy, N. C. & Sprik, M. (2000). *J. Chem. Phys.* **112**, 1670–1678.
- Boese, A. D. & Handy, N. (2001). *J. Chem. Phys.* **114**, 5497–5503.
- Bruker (2001). *SMART* and *SADABS*. Bruker AXS Inc., Madison, Wisconsin, USA.
- Bruker (2002). *SAINT*. Bruker AXS Inc., Madison, Wisconsin, USA.
- Chang, Y. L., West, M. A., Fowler, F. W. & Lauher, J. W. (1993). *J. Am. Chem. Soc.* **115**, 5991–6000.
- Cremer, D. & Pople, J. A. (1975). *J. Am. Chem. Soc.* **97**, 1354–1358.
- Custelcean, R. (2008). *Chem. Commun.* pp. 295–307.
- Delly, B. (1996). *J. Phys. Chem.* **100**, 6107–6110.
- Delly, B. (1998). *Int. J. Quantum Chem.* **69**, 423–433.
- Etter, M. C. (1990). *Acc. Chem. Res.* **23**, 120–126.
- Farrugia, L. J. (1997). *J. Appl. Cryst.* **30**, 565.
- Gale, P. A. & Quesada, R. (2006). *Coord. Chem. Rev.* **250**, 3219–3244.
- Gallagher, J. F., Kenny, P. T. M. & Sheehy, M. J. (1999). *Acta Cryst.* **C55**, 1607–1610.
- Hamprecht, D. T. F. A., Cohem, A. J. & Handy, N. (1998). *J. Chem. Phys.* **109**, 6264–6271.
- Hollingsworth, M. D., Brown, M. E., Santarsiero, B. D., Huffman, J. C. & Goss, C. R. (1994). *Chem. Mater.* **6**, 1227–1244.
- Kane, J. J., Liao, R.-F., Lauher, J. W. & Fowler, F. W. (1995). *J. Am. Chem. Soc.* **117**, 12003–12004.
- Lee, C., Yang, W. & Parr, R. G. (1988). *Phys. Rev. B*, **37**, 785–789.
- Lyssenko, K. A. & Antipin, M. Yu. (2006). *Russ. Chem. Bull.* **55**, 1–14.
- Nardelli, M. (1995). *J. Appl. Cryst.* **28**, 659.
- Sheldrick, G. M. (2008). *Acta Cryst.* **A64**, 112–122.
- Sun, C.-W. & Zhang, X.-D. (2006). *Acta Cryst.* **E62**, o2700–o2701.
- Watkin, D. M., Pearce, L. & Prout, C. K. (1993). *CAMERON*. Chemical Crystallography Laboratory, University of Oxford, England.
- Wu, L., Liu, H.-M., Zhao, W.-T. & Zhang, W.-Q. (2006). *Acta Cryst.* **C62**, o435–o437.