

Dipolar $C\equiv N \cdots C\equiv N$ interactions in organic crystal structures: database analysis and calculation of interaction energies

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The Cambridge Structural Database (CSD) has been used to study nonbonded interactions between dipolar cyano groups. The analysis shows that $C\equiv N \cdots C\equiv N$ interactions form in an analogous manner to those involving carbonyl groups, and with the same interaction motifs: a dominant antiparallel dimer (57.5%) together with smaller populations of perpendicular (19.4%) and sheared parallel (23.0%) motifs. *Ab initio* calculations using intermolecular perturbation theory (IMPT) show an attractive $C\equiv N \cdots C\equiv N$ interaction in the dominant antiparallel dimer, with $E_t = -20.0 \text{ kJ mol}^{-1}$ at $d(C \cdots N) = 3.30 \text{ \AA}$ and with the motif having a shear angle close to 102° . The antiparallel $C\equiv N \cdots C\equiv N$ interaction is therefore slightly weaker than the analogous $C=O \cdots C=O$ dimer ($-23.5 \text{ kJ mol}^{-1}$), but both interactions have attractive energies similar to that of a medium-strength hydrogen bond and, where sterically favoured, they are important in the stabilization of extended crystal structures.

1. Introduction

The importance of non-covalent interactions between strongly dipolar groups was highlighted nearly 40 years ago in an important review by Bent (1968). Recently the twin growth of crystal engineering and rational molecular design has led to a resurgence of interest in non-covalent interactions of all kinds, and there has been renewed interest in dipolar interactions and their effects in organic (Taylor *et al.*, 1990; Allen *et al.*, 1998; Lee *et al.*, 2004), metal-organic (Braga & Grepioni, 1994, 1997; Sparkes *et al.*, 2006) and macromolecular (Maccallum *et al.*, 1995a,b; Deane *et al.*, 1999; Bergner *et al.*, 2002) crystal structures, culminating in an extensive new review of the area (Paulini *et al.*, 2005). Much of the work of the past 20 years has involved surveys of available experimental data in the Cambridge Structural Database (CSD: Allen, 2002; Bruno *et al.*, 2002) and in the Protein Data Bank (PDB: Berman *et al.*, 2002), allied to computational studies of interaction energies.

Chemically, much of this interest has focused on interactions between dipolar carbonyl groups, due to their high incidence, and structural importance across the broad spectrum of compounds noted above. However, many other chemical bonds and groups exhibit local dipole moments which are similar to that of the carbonyl group, and whose interactions may also have implications in crystal engineering. Among these is the cyano group $-C^{\delta+}\equiv N^{\delta-}$, and here we explore the experimental evidence for $C\equiv N \cdots C\equiv N$ interactions, and compare the interaction motifs and interaction energies of this simple dipole with data already assembled for the analogous carbonyl dipole $-C^{\delta+}=O^{\delta-}$ (Allen *et al.*, 1998).

We note at the outset that our CSD survey and calculations overlap to some extent with the work of Lee *et al.* (2004). While these authors acknowledge and report the large number of centrosymmetric antiparallel dimers that form in crystal structures [see *e.g.* Allen *et al.* (1998) for analysis of $C=O \cdots C=O$ data for ketones], their primary concern has been the orientational effects of dipolar interactions, and they chose to exclude symmetrical forms of the interaction motifs in their computational studies. Our own interest is to examine the role of dipolar interactions in all crystal structures, to assess the relative strengths of the interactions and to examine their potential role in crystal design. It is in this context that we present our database

Table 1

 Motif formation via $C\equiv N \cdots C\equiv N$ interactions in crystal structures compared with analogous information for $C=O \cdots C=O$ interactions.

Geometrical parameters are defined in Fig. 1. N_{ref} is the no. of CSD recodes and N_{frag} is the no. of chemical fragments of types now defined: *A*: Any $-C\equiv N$ or $C_2-C=O$ group within the CSD secondary search criteria and then for the following $C\equiv N \cdots C\equiv N$ or $C=O \cdots C=O$ interactions. *B*: Any interactions having $D1 \leq 3.6$ Å. *C*: Interactions (*B*) forming any of the three classifiable motifs (I), (II), (III) of Fig. 2. (I) Interactions (*B*) forming the antiparallel motif (I): $D1 \leq 3.6$ Å, $D2 \leq 3.6$ Å. (II) Interactions (*B*) forming the perpendicular motif (II): $D1 \leq 3.6$ Å, $A4$ 140–180°. (III) Interactions (*B*) forming the sheared parallel motif (III): $D1 \leq 3.6$ Å, $T1$ 160–180°, $A1$ and $A4$ 65–115°, $A2$ and $A3$ 30–80°.

C≡N...C≡N interactions						C=O...C=O interactions				
Type	N_{ref}	N_{frag}	%A	%B	%C	N_{ref}	N_{frag}	%A	%B	%C
A	5082	9599	100.0			15 493	22 102	100.0		
B	1615	3539	36.9	100.0		2189	3088	14.0	100.0	
C	1266	1992	20.8	56.3	100.0	1627	1926	8.7	62.4	100.0
(I)	932	1146	11.9	32.4	57.5	1112	1233	5.6	39.9	64.0
(II)	267	387	4.0	10.9	19.4	363	418	1.9	13.5	21.7
(III)	242	459	4.8	13.0	23.0	239	275	1.2	8.9	14.3

Table 2

 Mean angular geometries for the classifiable motifs [Fig. 2: (I), (II) and (III)] for $C\equiv N \cdots C\equiv N$ interactions compared with analogous data for $C=O \cdots C=O$ interactions.

 The no. of observations contributing to each mean is the relevant N_{frag} value from Table 1, the standard deviation of each mean is given in parentheses.

Motif	(I)		(II)		(III)	
	C≡N	C=O	C≡N	C=O	C≡N	C=O
angle						
A1	86.3 (4)	83.1 (3)	98.3 (6)	96.8 (7)	89.3 (4)	97.2 (5)
A2	91.9 (4)	95.6 (3)	67.5 (6)	68.6 (7)	57.6 (3)	50.2 (4)
A3	†	†	22.2 (6)	23.1 (6)	56.5 (4)	48.0 (3)
A4	†	†	152.9 (5)	153.2 (5)	90.5 (5)	99.4 (5)

† Motif (I) has topological symmetry such that $A1 \equiv A3$ and $A2 \equiv A4$. The $2N_{frag}$ instances of each independent angle have been averaged together to yield the means for $A1$ and $A2$ cited here.

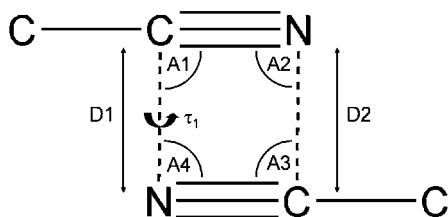
analysis and computational results for cyano...cyano interactions in organic crystal structures.

2. Experimental

2.1. Database study

Database analyses used CSD Version 5.28 (November 2006: 390 081 entries). The chemical fragment used is depicted in Fig. 1 and the primary intermolecular distance constraint used in the search for relevant intermolecular interactions required $D1$ to be ≤ 3.6 Å. Location of specific interaction motifs required additional torsional or angular constraints, as noted in Table 1. Comparison data for $C=O \cdots C=O$ interactions were obtained using identical geometrical criteria. For all searches, the following secondary acceptance criteria restricted searches to structures:

- having no crystallographic disorder,
- without polymeric (*catena*) bonding,
- having no residual errors following CSD validation procedures,


Figure 1

Search fragment and geometrical parameters used in this analysis. Full details of the search process and distance criteria are given in §2.

(iv) determined using single-crystal techniques (no powder diffraction structures),

(v) having $R \leq 0.075$, and which were

(vi) organic structures according to CSD definitions (Allen, 2002; Bruno *et al.*, 2002).

2.2. Ab initio calculations

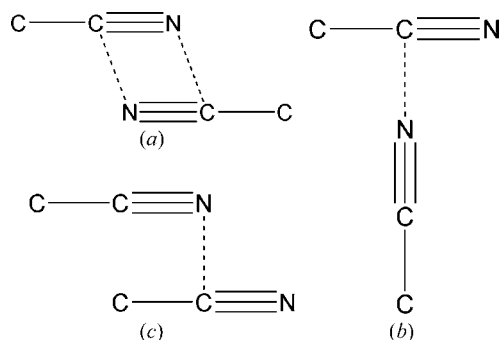
The intermolecular perturbation theory (IMPT) of Hayes & Stone (1984) as implemented in the *CADPAC6.5* program package (Amos, 1998) was used to calculate intermolecular $C\equiv N \cdots C\equiv N$ interaction energies, as described by Allen *et al.* (1998) and using the acetonitrile (CH_3CN) dimer as the model system. The IMPT methodology yields separate interaction energy components (first order: electrostatic and exchange–repulsion energies; second order: polarization, charge-transfer and dispersion energies) which sum to a total interaction energy (E_i) that is free from basis-set superposition errors (Stone, 1993).

3. Results and discussion

3.1. Database analysis

Results of the CSD analysis of $C\equiv N \cdots C\equiv N$ interactions are summarized in Tables 1 and 2, which also include the contemporary comparative data for $C=O \cdots C=O$ interactions. The results show that the crystal structure statistics for the two interactions are closely similar.

Table 1 shows that a higher percentage ($\%A = 36.9\%$) of cyano groups exhibit group–group interactions within the 3.6 Å distance limit than keto groups ($\%A = 14.0\%$). This is almost certainly due to the increased steric availability of the cyano group. The


Figure 2

 The three commonly observed $C\equiv N \cdots C\equiv N$ interaction motifs: (I) sheared antiparallel motif, (II) perpendicular motif and (III) sheared parallel motif.

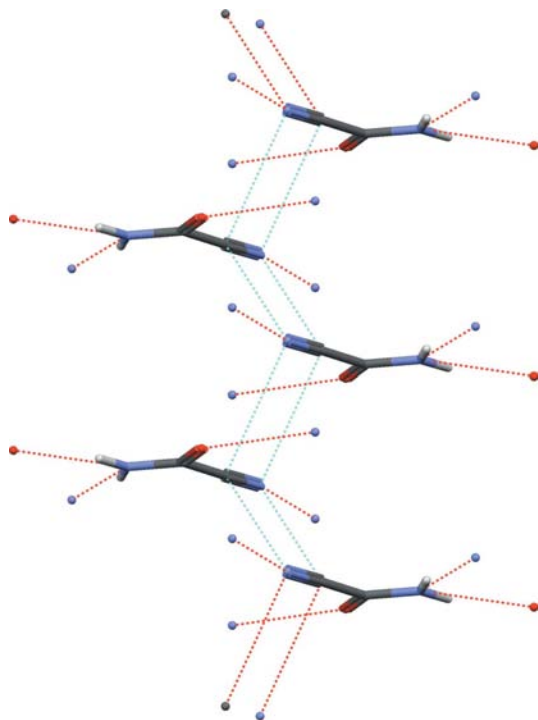


Figure 3
Crystal structure of cyanoformamide (CSD refcode CISNEX: Druck *et al.*, 1984) showing centrosymmetric $\text{C}\equiv\text{N}\cdots\text{C}\equiv\text{N}$ interactions with $d(\text{C}\cdots\text{N}) = 3.44$ Å operating together with $\text{N}-\text{H}\cdots\text{N}$ and $\text{N}-\text{H}\cdots\text{O}$ hydrogen bonds.

$\text{C}\equiv\text{N}\cdots\text{C}\equiv\text{N}$ interactions can be classified into the three motifs identified in the previous analysis of $\text{C}=\text{O}\cdots\text{C}=\text{O}$ interactions (Allen *et al.*, 1998) and depicted in Fig. 2. The percentage of $\text{C}\equiv\text{N}$

groups that form the antiparallel self-interactions of Fig. 2 is 56.3% (%*B*; Table 1), broadly similar to the percentage of $\text{C}=\text{O}\cdots\text{C}=\text{O}$ that form classifiable interactions (%*B* = 62.4%), taking account of the softness of the geometrical classification criteria used in these analyses.

The percentages of each of the classifiable motifs (I), (II) and (III) (Fig. 2) are also broadly similar for both functional groups, with the sheared antiparallel motif (I) dominant in both cases. Beyond that, the slight preference for the sheared parallel motif (III), rather than the perpendicular motif (II), to be formed by cyano groups may be real and, again, linked to the increased steric availability of $-\text{C}\equiv\text{N}$. Mean angular parameters for the three motifs (I), (II) and (III) are very similar for both functional groups (Table 2). However, there is evidence that the degree of shear in the well characterized motif (I) for the cyano group [mean value of $A2 = 91.9$ (4)°] is less than that observed for the keto group [mean $A2 = 95.6$ (3)°].

The majority of examples of the dominant antiparallel motif (I) involve symmetry-related pairs of $\text{C}\equiv\text{N}$ groups. The torsion angle τ_1 about the constrained $\text{C}\cdots\text{N}$ contact is exactly 0° in 594 (51.8%) of the 1146 examples of (I). Most of the examples of (I) that do not involve symmetry are also close to planar, so that examples of motif I having values of $\tau_1 < 10^\circ$ and $< 20^\circ$ are 83.0 and 86.3%, respectively. The corresponding percentages of $\text{C}=\text{O}\cdots\text{C}=\text{O}$ antiparallel motifs that have $\tau_1 = 0, < 10$ and $< 20^\circ$ are very closely comparable at 52.4, 84.8 and 87.3%, respectively. As an illustration of the interactions analysed here, Fig. 3 shows the antiparallel $\text{C}\equiv\text{N}\cdots\text{C}\equiv\text{N}$ interaction (I) operating in concert with $\text{N}-\text{H}\cdots\text{N}$ and $\text{N}-\text{H}\cdots\text{O}$ hydrogen bonds in cyanoformamide (CSD refcode CISNEX: Druck *et al.*, 1984).

3.2. IMPT calculations

IMPT calculations were carried out using the acetonitrile ($\text{CH}_3\text{C}\equiv\text{N}$) dimer as the model system, with the internal monomer geometry optimized using the 6-31G** basis set. In order to provide energy data comparable to those calculated for $\text{C}=\text{O}\cdots\text{C}=\text{O}$ interactions (Allen *et al.*, 1998), our IMPT calculations concentrated on the antiparallel dimer [(I), Fig. 2]. The dimer was constructed as a perfect rectangle (Fig. 1 with angles $A1-A4 = 90^\circ$, and $D1 = D2 = d$) and IMPT calculations were performed for values of the non-bonded $\text{C}\equiv\text{N}$ group separation (d) ranging from 2.80 to 3.80 Å in 0.1 Å increments. The results are illustrated in Fig. 4(a), which shows minima in the E_t curve of -16.0 kJ mol⁻¹ at 3.20 Å, -16.2 kJ mol⁻¹ at $d = 3.30$ Å, and -16.0 kJ mol⁻¹ at $d = 3.40$ Å. The minimum E_t for the unsheared antiparallel $\text{C}=\text{O}\cdots\text{C}=\text{O}$ motif was -23.4 kJ mol⁻¹ at $d(\text{C}\cdots\text{O}) = 3.02$ Å.

To complete the comparison with $\text{C}=\text{O}\cdots\text{C}=\text{O}$ interactions, IMPT calculations were performed varying the shear angle, $A2$, in the antiparallel $\text{C}\equiv\text{N}\cdots\text{C}\equiv\text{N}$ dimer from 70–110° in 5° increments for each of three values

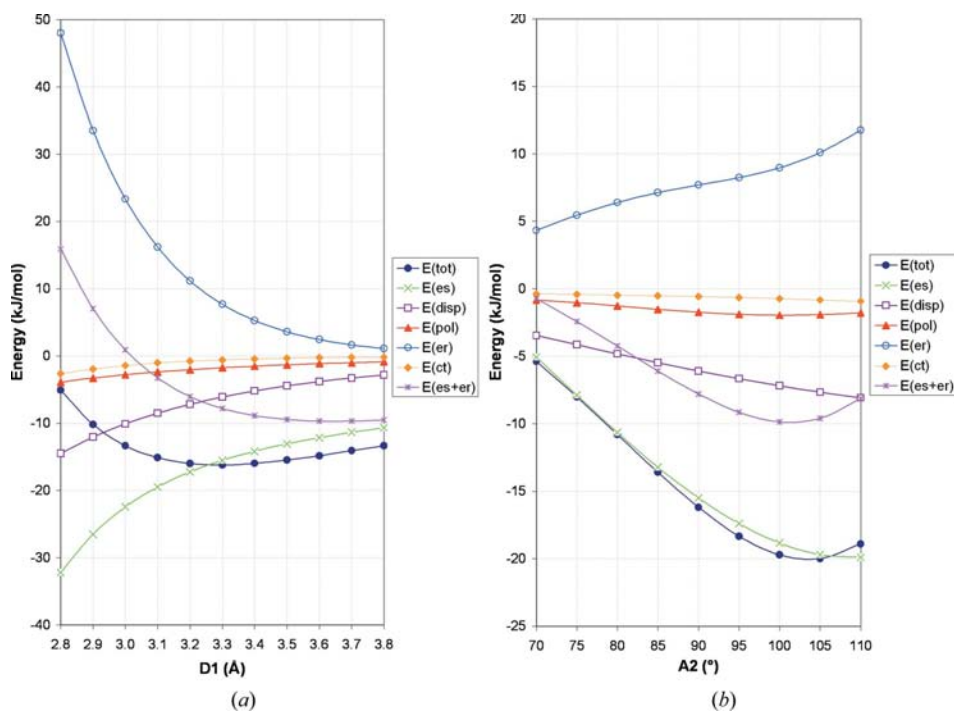


Figure 4
IMPT results for the antiparallel $\text{C}\equiv\text{N}\cdots\text{C}\equiv\text{N}$ interaction (I): (a) for a rectangular motif, varying the $d(\text{C}\cdots\text{N})$ distance only, and (b) varying the shear angle, $A2$, for a fixed value of $d(\text{C}\cdots\text{N})$ of 3.30 Å.

of the inter-cyano distance, $d = 3.20, 3.30$ and 3.40 \AA . The energy minima, E_t , occurred at $A2$ between 100 and 105° in each case, respectively, with the overall minimum of $-20.0 \text{ kJ mol}^{-1}$ occurring at $d = 3.30 \text{ \AA}$ and $A2 = 105.0^\circ$. The IMPT component energies for this sheared geometry are shown in Fig. 4(b) and, as for the analogous carbonyl system, the interaction is dominated by electrostatic effects. By comparison, the minimum E_t is $-23.5 \text{ kJ mol}^{-1}$ for $\text{C}=\text{O} \cdots \text{C}=\text{O}$, with a shear angle very close to 90° (Allen *et al.*, 1998). These IMPT data would indicate that the $\text{C}\equiv\text{N} \cdots \text{C}\equiv\text{N}$ interaction is significantly strengthened by shearing away from 90° to a value close to 102° , but that this is not reflected in the mean shear angle, $A2$, determined from the crystal structure data. However, we note that the distribution of $A2$ is very broad, with values ranging from 75 to 125° , and the correspondingly broad IMPT E_t profile confirms the softness of the interaction.

4. Conclusion

This work has shown that $\text{C}\equiv\text{N} \cdots \text{C}\equiv\text{N}$ interactions are commonly observed in crystal structures, and that the dominant antiparallel motif has an interaction energy that is similar to that of a moderately strong hydrogen bond. The results closely parallel those from a similar study (Allen *et al.*, 1998) of $\text{C}=\text{O} \cdots \text{C}=\text{O}$ interactions, but these latter interactions are shown here to be stronger than those for $\text{C}\equiv\text{N} \cdots \text{C}\equiv\text{N}$ by *ca* 3.5 kJ mol^{-1} . Given that both interactions are primarily electrostatic in nature (Figs. 4a and b), this difference almost certainly reflects differences in the electrostatic nature of $\text{C}=\text{O}$ and $\text{C}\equiv\text{N}$ groups. To provide some independent computational evidence for the reliability of the energy difference between $\text{C}=\text{O} \cdots \text{C}=\text{O}$ and $\text{C}\equiv\text{N} \cdots \text{C}\equiv\text{N}$ interactions, atomic point charges have been calculated *via* Mulliken analysis using *GAMESS* (Schmidt *et al.*, 1993) and an MP2/6-31G** basis set. These data show $\text{C}(+0.51 \text{ e})=\text{O}(-0.53 \text{ e})$ in acetone and $\text{C}(+0.30 \text{ e})\equiv\text{N}(-0.46 \text{ e})$ in acetonitrile, in agreement with the relative interaction energies. Nevertheless, despite their slightly weaker nature, it is clear that $\text{C}\equiv\text{N} \cdots \text{C}\equiv\text{N}$ interactions can play a significant role in stabilizing the extended structures of cyano compounds, and this role may be greater than for the analogous $\text{C}=\text{O} \cdots \text{C}=\text{O}$ interactions owing to the increased steric availability of cyano substituents.

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References

- Allen, F. H. (2002). *Acta Cryst.* **B58**, 380–388.
 Allen, F. H., Baalham, C. A., Lommerse, J. P. M. & Raithby, P. R. (1998). *Acta Cryst.* **B54**, 320–329.
 Amos, R. D. *et al.* (1998). *CADPAC6.5*. Chemistry Department, Cambridge University, England.
 Bent, H. A. (1968). *Chem. Rev.* **68**, 588–648.
 Bergner, A., Günther, J., Hendlich, M., Klebe, G. & Verdonk, M. (2002). *Biopolymers (Nucleic Acid Sci.)*, **61**, 99–110.
 Berman, H. M., Battistuz, T., Bhat, T. N., Bluhm, W. F., Bourne, P. E., Burkhardt, K., Feng, Z., Gilliland, G. L., Iype, L., Jain, S., Fagan, P., Marvin, J., Padilla, D., Ravichandran, V., Schneider, B., Thanki, N., Weissig, H., Westbrook, J. D. & Zardecki, C. (2002). *Acta Cryst.* **D58**, 899–907.
 Braga, D. & Grepioni, F. (1994). *Acc. Chem. Res.* **27**, 51–56.
 Braga, D. & Grepioni, F. (1997). *Acc. Chem. Res.* **30**, 81–87.
 Bruno, I. J., Cole, J. C., Edgington, P. R., Kessler, M., Macrae, C. F., McCabe, P., Pearson, J. & Taylor, R. (2002). *Acta Cryst.* **B58**, 389–397.
 Deane, C. M., Allen, F. H., Taylor, R. & Blundell, T. L. (1999). *Protein Eng.* **12**, 1025–1028.
 Druck, E., Becker, W. & Becker, G. (1984). *Z. Kristallogr.* **167**, 131–138.
 Hayes, I. C. & Stone, A. J. (1984). *J. Mol. Phys.* **53**, 83–105.
 Lee, S., Mallik, A. B. & Fredrickson, D. C. (2004). *Cryst. Growth Des.* **4**, 279–290.
 Maccallum, P. H., Poet, R. & Milner-White, E. J. (1995a). *J. Mol. Biol.* **248**, 361–373.
 Maccallum, P. H., Poet, R. & Milner-White, E. J. (1995b). *J. Mol. Biol.* **248**, 374–384.
 Paulini, R., Muller, K. & Diederich, F. (2005). *Angew. Chem. Int. Ed. Engl.* **44**, 1788–1805.
 Schmidt, M. W., Baldrige, K. K., Boatz, J. A., Elbert, S. T., Gordon, M. S., Jensen, J. H., Koseki, S., Matsunaga, N., Nguyen, K. A., Su, S., Windus, T. L., Dupuis, M. & Montgomery, J. A. (1993). *J. Comput. Chem.* **14**, 1347–1363.
 Sparkes, H. A., Raithby, P. R., Clot, E., Shields, G. P., Chisholm, J. A. & Allen, F. H. (2006). *CrystEngComm*, **8**, 563–570.
 Stone, A. J. (1993). *Chem. Phys. Lett.* **211**, 101–109.
 Taylor, R., Mullaley, A. & Mullier, G. W. (1990). *Pestic. Sci.* **29**, 197–213.