Directionality of $\pi$-holes in nitro compounds†

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Intermolecular interactions determine how molecules interact with one another, and are thus fundamental to inquiries in areas like supramolecular chemistry and molecular biology.$^1$ It is well-appreciated that even weak interactions (e.g., hydrogen bonding involving C–H) can bear functional relevance, especially when several such forces work in concert.$^2$ This begs the question what weak interactions can be identified as possibly functionally relevant.

Hydrogen (H) and halogen (Hlg) bonds are by far the best established intermolecular forces.$^3$ The regions of electropositive potential on R–H and R–Hlg (Fig. 1a and b, phenol and bromobenzene, respectively) can be described as unpopulated $\sigma^*$ antibonding orbitals along the R–H/Hlg vector.$^{7,9}$ These ‘$\sigma$-holes’ have also been identified on atoms that belong to the oxygen, nitrogen and carbon families, and their binding to electron-rich entities is referred to as chalcogen-,$^4$ pnicogen-,$^5$ and tetrel-bonding,$^6$ respectively.

In analogy to the $\sigma$-hole, a $\pi$-hole can be seen as an electropositive potential located on an unpopulated $\pi^*$-orbital. The best-known $\pi$-hole interactions involve carbonyl compounds (e.g., $p$-quinone, as shown in Fig. 1c): Bürgi and Dunitz$^7$ uncovered the trajectory along which a nucleophile attacks the $\pi$-hole of a carbonyls’ C-atom, and $\pi$-hole interactions involving amides are known to persist in protein structures.$^8$ Aromatic rings bearing electron withdrawing substituents, such as hexafluorobenzene (Fig. 1d), can also function as $\pi$-holes.$^9$ Interactions involving such $\pi$ acidic aromatic rings are generally referred to as anion- or lone pair-$\pi$ interactions.$^{10}$

A recent theoretical study revealed that a $\pi$-hole can also be found on a nitro group.$^{11}$ Association of this $\pi$-hole with electron-rich entities (ElR, e.g., H$_2$O and Cl$^-$) was estimated to vary in strength between $-0.5$ and $-27.9$ kcal mol$^{-1}$ Fig. 1e and f illustrate the $\pi$-holes in nitromethane and nitrobenzene, respectively. One might thus wonder if the ‘NO$_2$–ElR’ interaction bears any functional relevance. The first step towards answering this question is to establish whether this intermolecular force is actually directional. Analysis of the data compiled within the Cambridge Structural Database (CSD)$^{12}$ has proven to be an exquisite tool for revealing the directional nature of traditional and non-canonical intermolecular forces. We thus set out to evaluate the CSD using a methodology that is particularly apt for ascertaining the directional character of weak intermolecular forces.$^7$

Aliphatic and aromatic C–NO$_2$ compounds that are abundant within the CSD were considered: there are 900 crystallographic information files (CIFs) containing nitromethane, and 14 227 CIFs containing an aromatic nitro compound where the NO$_2$ moiety is flanked by two ortho-H’s (this allows the NO$_2$ and C$_6$H$_5$ moieties to be relatively coplanar). Fig. 2a illustrates the query used to obtain initial datasets from the CSD.

An entry was considered a hit when the intermolecular distance (D) between the C–N centroid (blue) and any electron-rich atom (red, ElR = N, P, As, O, S, Se, Te, F, Cl, Br, I or At) was $\leq 5$ Å. The initial dataset was thus confined within a sphere with a radius of 5 Å, centred on the C-N centroid. The spatial separation (d) between ElR and the CNO$_2$ plane was also retrieved from the CSD. The $xy$ coordinates relative to this plane were determined as described elsewhere.$^{13}$ By virtue of Pythagoras’s theorem, the parallel displacement parameter $r$ could be derived.

Fig. 1 Some $\sigma$- and $\pi$-holes with their electropositive potential in kcal mol$^{-1}$ (MP2/6-311+G**).

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from $D$ and $d$. The $CN_{\text{centroid}}$–$N$–ElR angle ($\alpha$) was measured as well.

For this study, only the data characterized by $y = \pm 2$ Å were considered, which are therefore located within the 4 Å wide spherical segment, as illustrated in Fig. 2b–d. The data can thus be characterized by the parallel displacement ($r$) within this spherical segment, either towards the NO$_2$ group ($\alpha < 90^\circ$) or towards the other atoms attached to C ($\alpha > 90^\circ$). To analyse directionality, we applied a method described in detail elsewhere.$^9,13,14$ This method entails computing the parameter $P(r)$, which signifies the distribution of the data along $r$ that is corrected for the volume occupied by the host and for a random scattering of data. When $P \neq 1$, non-accidental clustering of data is established and $P > 1$ is indicative of an attractive interaction.

The $P$ versus $r$ plots for CH$_3$NO$_2$ (black circles) and C$_6$H$_2$NO$_2$ (open circles) are shown on the left hand side of Fig. 3. For both ‘hosts’, $P > 1$ around $r = 0$, indicating some directionality of the $\pi$-hole. The $P$ values of 2–3 are similar to those observed for C–H–$\pi$phenyl hydrogen bonding.$^{15}$ In the case of CH$_3$NO$_2$, the observed clustering is spread out over the region ranging from $r = -1$ to $+1$ Å. It is likely that CH–EIR hydrogen bonding also contributes to the observed distribution. The clustering observed for aromatic NO$_2$ is spread out over the region from $r = 0$ to $+1$ Å, and hydrogen bonding cannot contribute in this case. It was further assessed how exactly the data are distributed within the data characterized by $-1 > r < 1$ Å. Thus, the relative hit fraction was plotted as a function of the van der Waals corrected $CN_{\text{centroid}}$–EIR distance, as shown on the right hand side of Fig. 3. For both central groups, roughly $20\%$ van der Waals overlap is present. These two plots together indeed show that a nitro moiety can be a directional $\pi$-hole donor.

We have theoretically analysed (see the ESI† for details) several representative complexes between electron-rich moieties and nitrobenzene (Fig. 4a; a similar study with nitromethane is reported elsewhere).$^11$ The interaction energies and some geometric features of the complexes are summarized in Table 1. The interaction energies are similar for nearly all complexes ranging from $-2.3$ to $-6.6$ kcal mol$^{-1}$ and the most favourable one corresponds to chlorine complex 7. The $\pi$-hole in nitrobenzene is located along the C–N bond and close to the nitrogen atom (see Fig. 1f and 4b). We have included both EIR–N and EIR–C distances (denoted as $D_N$ and $D_C$, respectively) in Table 1. All complexes exhibit similar $D_N$ and $D_C$ distances and in all cases the electron-rich atom is located over the C–N bond, in agreement with results of the MEP analysis. The interaction energy is modest in complex 6 due to the low basicity of the sp-hybridized nitrogen atom of the HCN molecule.

![Fig. 2](image1.png)

**Fig. 2** Illustrations of the method used to analyse directionality of intermolecular interactions between an electron-rich atom (EIR, N, P, As, O, S, Se, F, Cl, Br, I or At) and a nitro group (in this illustration nitromethane).

![Fig. 3](image2.png)

**Fig. 3** Analysis of the directional nature of NO$_2$ $\pi$-holes. Left: directionality plots of $P$ vs. $r$ for CH$_3$NO$_2$–EIR (●, $N_{\text{cut}} = 6,680$) and C$_6$H$_2$NO$_2$–EIR (○, $N_{\text{cut}} = 33,523$) of the data characterized by $D \leq 5$ Å and $y \pm 2$ Å; right: $N_{\text{relative}}$ vs. $vdW$ van der Waals corrected $CN_{\text{centroid}}$–EIR distance (assuming $(\text{vdW}_C + \text{vdW}_N)/2 = 1.625$ Å) for CH$_3$NO$_2$–EIR (●, $N_{\text{cut}} = 1,231$) and C$_6$H$_2$NO$_2$–EIR (○, $N_{\text{cut}} = 4,727$) of the data characterized by $D \leq 5$ Å and $r \pm 1$ Å.

![Fig. 4](image3.png)

**Fig. 4** (a) Complexes 1–7 studied in this work. (b) A pictorial representation of the complementarity of the MEP surfaces of nitrobenzene and trimethylenimine.

![Table 1](image4.png)

**Table 1** BSSE corrected interaction energies ($E$, kcal mol$^{-1}$) and equilibrium distances from the electron-rich atom to the N ($D_N$) and C ($D_C$) atoms of the C–NO$_2$ moiety (in Å) of complexes 1–7 at the RI-MP2/def2-TZVPD//PB86-D3/def2-TZVPD level of theory.

| Complex | $E$ | $D_N$ | $D_C$ |
|---------|-----|-------|-------|
| 1       | -6.2| 2.770 | 2.932 |
| 2       | -4.3| 3.636 | 3.547 |
| 3       | -4.4| 2.823 | 2.931 |
| 4       | -4.7| 3.416 | 3.448 |
| 5       | -4.7| 2.956 | 3.001 |
| 6       | -2.3| 3.181 | 3.191 |
| 7       | -6.6| 3.204 | 3.047 |
The optimized geometries of some complexes are shown in Fig. 5, including the “atoms-in-molecules” AIM distribution of critical points computed for complexes 1 (lone pair donor EIR) and 5 (anionic EIR). The optimized geometries and critical point distribution for the rest of the complexes are included in the ESL†. It can be clearly observed in Fig. 5 and Fig. S1 (ESI†) that the position of the EIR atom of the interacting molecule coincides with the location of the π-hole in all complexes, indicating that the interaction is basically electrostatic in nature. The AIM analysis of 1 is complicated since it shows five bond critical points symmetrically distributed for the rest of the complexes are included in the ESI.

Fig. 5 (a–c) Optimized π-hole complexes 1, 3 and 7 studied in this work. (d and e) Distribution of critical points in complexes 1 and 7 (bond and ring critical points are represented by red and yellow spheres, respectively). Bond paths connecting bond critical points are represented.

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Thus reasonable to anticipate an experimental study unveiling the functional relevance of this novel π-hole interaction.

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