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PAPER

On the directionality of anion–π interactions†

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The directionality of two important noncovalent interactions involving aromatic rings (namely anion–π and cation–π) is investigated. It has been recently published that the anion–π interactions observed in X-ray structures where the anion is located exactly over the center of the ring are scarce compared to cation–π interactions. To explain this behavior, we have analyzed how the interaction energy (RI-MP2/aug-cc-pVDZ level of theory) is affected by moving the anion from the center of the ring to several directions in anion–π complexes of chloride with either hexafluorobenzene or trifluoro-*s*-triazine. We have compared the results with the directionality of the cation–π interaction in the sodium–benzene complex. The results are useful to explain the experimental differences between both ion–π interactions. We have also computed the van der Waals radii of several halide anions and we have compared them to the neutral halogen atoms.

1. Introduction

Noncovalent interactions are crucial in many areas of modern chemistry, especially in the field of supramolecular chemistry and molecular recognition.[1] Interactions involving aromatic rings are important binding forces in both chemical and biological systems.[2] Cation–π interactions have been widely studied in the literature including theoretical and experimental methodologies.[3] More recently, interest has been growing in another noncovalent interaction between anion and electron deficient aromatic rings, namely, anion–π interaction.[4] Following the pioneering work describing gas-phase clustering reactions between anions and hexafluorobenzene,[5] and using theoretical methods, Mascal *et al.*,[6] Alkorta *et al.*[7] and our group[8] have almost simultaneously reported the favourable π interaction of anions with electron deficient aromatic rings. There is a great deal of experimental[9–11] and theoretical[12–14] work that evidence that the anion–π interactions play a prominent role in several areas of chemistry, such as molecular recognition[15] and transmembrane anion transport.[16] These interactions are also important in DNA bases like adenine.[17] Moreover, Berryman *et al.* have reported structural criteria for the design of anion receptors based on the interaction of halides with electron-deficient arenes.[18] Recent excellent reviews deal with anion-binding involving π-acidic heteroaromatic rings.[4,19,20]

A recent report claimed that anion–π interactions between neutral aromatic ring and anions are rare, when compared to cation–π interactions.[21] In addition, it is evidenced that in many of the X-ray structures exhibiting anion–π contact, the anion is not located exactly over the center of the ring. Instead, it is displaced with respect to the center of the ring. Conversely, in cation–π interactions observed in crystal structures the cations show more preference for the center of the ring.[21] In this letter we study the directionality of the anion–π interaction by means of high level *ab initio* calculations in complexes of hexafluorobenzene (HFB) and trifluoro-*s*-triazine (TFT) with chloride. For comparison purposes we also study the directionality of the cation–π interaction in the complex of benzene (BEN) with sodium cation. Another focus of uncertainty is the criterion used to define a van der Waals (vdW) contact. That is, should a contact be strictly constrained to distances $\leq \Sigma$vdW radii? Weak interactions may exhibit contacts slightly longer than the ΣvdW radii, for instance the unconventional hydrogen bonds (C–H···O). The cut-off to be used for searching anion–π interactions has not been clearly established. In this letter we shed some light on this topic by considering two different issues. First, the computation of the interaction energy at the minimum and how it changes as the anion moves away along the C_6 (HFB) or C_3 (TFT) axis permits to know if the interaction energy dramatically decreases at distances longer than the ΣvdW radii or, instead, if the interaction energy gradually decreases. Second, the default (tabulated) van der Waals radii for halogens correspond to organic halogen atoms (derived from experimental data of perfluoroalkanes and tetrahalides). The anionic halogen atoms have larger vdW radii as it has been demonstrated in the parametrization (MM3 force field) of transition metal complexes where halogen atoms act as ligands.[22] Therefore the reduced number of hits observed for anion–π complexes can be a consequence of that.

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2. Theoretical methods

The geometry of all the complexes included in this study was optimized at the RI-MP2(full)/aug-cc-pVDZ level of theory within the program TURBOMOLE version 5.10.[23] The RI-MP2 method[24,25] applied to the study of cation–π and anion–π interactions is considerably faster than the MP2 method and the interaction energies and equilibrium distances are almost identical for both methods.[26,27] The binding energies were calculated with correction for the basis set superposition error (BSSE) by using the Boys–Bernardi counterpoise technique.[28] Charge transfer effects have been studied using the Merz–Kollam population method[29] for deriving atomic charges. The calculation of vdW radii has been performed at the MP4/6-311++G(3d,3p) level of theory by means of the Gaussian-03 package.[30] The "atoms-in-molecules" analysis[31] has been performed by means of the AIM2000 version 2.0 program[32] using the MP2/aug-cc-pVDZ wavefunctions. The partition of the interaction energies into the individual electrostatic, polarization, dispersion, and repulsion components has been carried out performing Molecular Interaction Potential with polarization (MIPp),[33] which is an improved generalization of the Molecular Electrostatic Potential (MEP) where three terms contribute to the interaction energy: (i) an electrostatic term identical to the MEP,[34] (ii) a classical dispersion–repulsion term, and (iii) a polarization term derived from perturbation theory.[35] This method has been modified, as previously described,[36] to separate the classical dispersion–repulsion term into a quantum-mechanical computed dispersion term and a classical repulsion term. The MIPp calculations have been performed by means of the MOPETE-98 program.[37]

3. Results and discussion

We have divided this section of the manuscript into three parts. The first and second parts deal with the directionality of ion–π interactions in parallel and orthogonal planes with respect to the molecular plane. The third part is devoted to the results and discussion of the van der Waals radii of anionic halogen atoms.

It should be mentioned that it is difficult to define a criterion which allows classifying a given anion–aromatic contact as an anion–π interaction. A probably very restrictive criterion is to consider a real anion–π interaction only when the anion is exactly over the center of the ring at distances ≤ΣvdW radii. Since most aromatic rings are asymmetrically substituted, the more favourable location is probably not above the center of the ring. Thus, it will be different in each particular case depending on the substitution. A probably unrestrictive criterion but more realistic is to consider an anion–π contact when the anion is located at any place over the ring since the π-system covers the entire ring at distances ≤ΣvdW radii + *d*, where "*d*" has to be defined. We should keep in mind that in hydrogen bonding interactions a wide range of angles and distances are observed and this is the reason for what the hydrogen bonds are classified as strong, moderate and weak, but the name of the interaction does not change. The hydrogen bonds have been rationalized (among others) using the concept of lone pairs of electrons. For instance the HCN crystal contains linear chains of HCN connected by hydrogen bonds. Moreover, hydrogen bonds involving carbonyl groups often have angles near 120°. However not always this is the case. The wide scatter found in the C=O angles in different H-bonded systems is well established.[38] In the next two sections of the manuscript we study the directionality of the anion–π interaction and a comparison with the cation–π interaction is also performed. Before starting the discussion we have repeated the CSD searches, using the same criteria, reported by Hay and Custelcean[21] for anion and cation–π complexes of C_6F_5X (X = any atom) and C_6 arenes, respectively (see Fig. 1). For the search of cation–π complexes we have used Na^+ and we have retrieved a significant number of hits. However, for the search of anion–π complexes of C_6F_5X and Cl^- we have only retrieved 16 structures that correspond to 46 fragments. Therefore we have also included in the search the fluoride anion to increment the number of hits and to obtain a more representative scatter plot (66 contacts). From inspection of the $d_{\text{off-set}}$ *vs.* d_{plane} plots, for the anion–π complexes (Fig. 1, left), a general lack of a preference to reside over a C_6 arene π system can be observed on viewing the placement of the Cl^- and F^- anions located above the C_6 plane. For cation–π complexes (Fig. 1, right), a cloud of contacts is distributed over the entire C_6 surface, but now with a noticeable clustering above the arene π system.

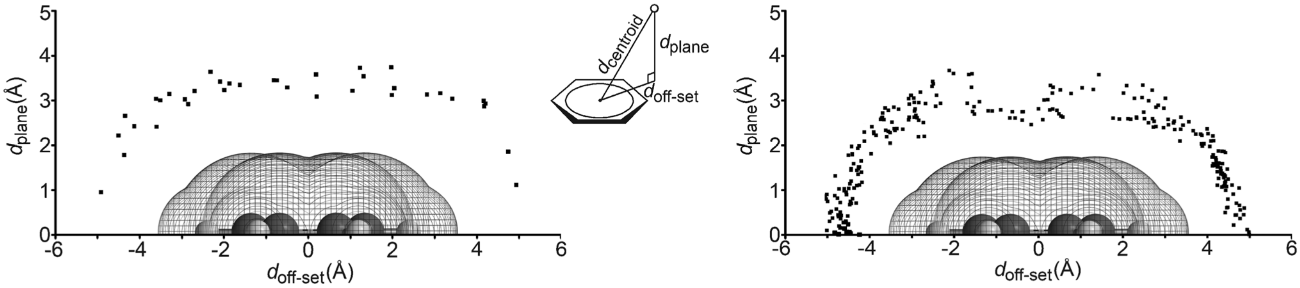

Fig. 1 (left) Distribution of contacts between F^- and Cl^- anions and any C_6F_5X ring (X = any atom) in the CSD: plot of $d_{\text{off-set}}$ *versus* d_{plane} shows the position of Cl^- and F^- anions within ±1 Å of an oblate ellipsoid ($a = b = 4.0$ Å, $c = 3.0$ Å). (right) Distribution of contacts between Na^+ cations and C_6 arenes: plot of $d_{\text{off-set}}$ *versus* d_{plane} shows the position of Na^+ cations within ±1 Å of an oblate ellipsoid ($a = b = 4.0$ Å, $c = 3.0$ Å). The mesh over the benzene molecule is the electron density isosurface rendered at a value of 0.002 e Å^{-3}. (upper-right) Geometric parameters defining the location of an atom in contact with a planar 6-membered ring collected during the search include the distance from the atom to the ring centroid, d_{centroid}, the distance from the atom to the ring plane, d_{plane}. The degree of displacement from the center of the ring, $d_{\text{off-set}}$, is given by $(d_{\text{centroid}}^2 - d_{\text{plane}}^2)^{1/2}$.

3.1 Directionality in parallel planes

In Table 1 we summarize the binding energies with the basis set superposition error (BSSE) correction (E_{BSSE}) and anion-centroid distances (R_e) of $\mathrm{Cl}^{-}\cdots\mathrm{HFB}$ and $\mathrm{Cl}^{-}\cdots\mathrm{TFT}$ complexes at the RI-MP2(full)/aug-cc-pVDZ level of theory. In Fig. 2 we show the different trajectories used to move the anion on the Z = 3.05 Å plane for HFB and Z = 2.94 Å plane for TFT. In the HFB complexes we have studied the effect of moving the Cl^{-} ion in the x axis direction (to one carbon atom) and in the y direction (to the middle of a CC bond). In the TFT ring, in addition to the x and y directions we have studied the movement of the Cl^{-} ion in the xy direction (to one nitrogen atom, see Fig. 2).

It can be observed that for HFB complexes (see Table 1) the interaction energy has a very modest change when the Cl^{-} moves either in the x or in the y direction (less than 1 kcal mol^{-1}). Therefore, the chloride anion can be located at any point over the HFB ring without losing much interaction energy with respect to the minimum. For the TFT ring, the results are similar for the x and y directions where in all points the E_{BSSE} covers at least the 85% of the interaction energy at the minimum. In the xy direction, where the Cl^{-} moves toward the electronegative nitrogen atom, the energy loss is greater (the $\%\mathrm{E}_{\mathrm{BSSE}}$ is 75% over the nitrogen atom, xy_4 point). We have also analyzed the fact that the energies in the Z plane are not reflective of equilibrium distances from the plane of the ring, which is an artifact intrinsic to the movement of the ions in the Z plane. To study this effect, we have relaxed the z coordinate in point x_4, which is the most susceptible to suffer variation. For the $\mathrm{Cl}^{-}\cdots\mathrm{HFB}$ complex, the interaction energy and z coordinate do not change upon relaxation. For the $\mathrm{Cl}^{-}\cdots\mathrm{TFT}$ complex, the interaction energy slightly changes (0.02 kcal mol^{-1} more negative, −14.59 kcal mol^{-1}) and the relaxed z coordinate is found at 2.99 Å, which is a very small variation (0.05 Å). In Table 1 we also summarize the charge of the anion in the complexes. It can be observed that the charge transfer in the $\mathrm{Cl}^{-}\cdots\mathrm{HFB}$ complex at the minimum is 0.17 e. The electron transfer from the anion to the ring is almost the same in all points indicating that charge transfer effects do not depend on the position of the anion in the parallel plane. The same behaviour is observed in the $\mathrm{Cl}^{-}\cdots\mathrm{TFT}$ complexes, where the charge transfer ranges 0.15–0.12 e.

The results for the cation–π complexes are shown in Table 2. In this case the plane used to move the cation in the x and y directions is Z = 2.42 Å. The energetic results for both directions indicate that the energy loss of the cation–π interaction between BEN and Na^{+} is considerably more important than the one computed for the anion–π interaction between HFB and Cl^{-}. For instance, the interaction energy in point x_4 (over one carbon atom) is only 77% of the energy at the minimum and in point y_4 (over the middle of the CC bond) is 81%. This can be used to explain the experimental findings[21] that show more scattering in the location of the ion in anion–π than in cation–π interactions when analyzing the crystal structures retrieved from the Cambridge Structural Database (CSD). As previously performed for anion–π complexes, we have also relaxed the z coordinate in point x_4 in this complex, to examine its effect on the energetic and geometric features at this point. The interaction energy relaxing the z coordinate is

Table 1 Interaction energies with the BSSE correction (E_{BSSE}, kcal mol^{-1}) and their percentage with respect to the interaction energy at the minimum ($\%E_{\mathrm{BSSE}}$), distances (R_e, Å), and charge of the anion (Q, e) at the RI-MP2(full)/aug-cc-pVDZ level of theory for $\mathrm{Cl}^{-}\cdots\mathrm{HFB}$ and $\mathrm{Cl}^{-}\cdots\mathrm{TFT}$ complexes (see Fig. 2 for the nomenclature of points)

Complex	E_{BSSE}	$\%E_{\mathrm{BSSE}}$	R_e	Q (ion)
$\mathrm{Cl}^{-}\cdots\mathrm{HFB}$				
o	−14.05	100	3.05	−0.83
x_1	−14.00	99	3.07	−0.83
x_2	−13.86	98	3.12	−0.83
x_3	−13.59	97	3.22	−0.84
x_4	−13.12	93	3.35	−0.85
y_1	−14.02	100	3.06	−0.83
y_2	−13.90	99	3.11	−0.84
y_3	−13.72	98	3.18	−0.84
y_4	−13.43	95	3.28	−0.85
$\mathrm{Cl}^{-}\cdots\mathrm{TFT}$				
o	−16.55	100	2.94	−0.85
x_1	−16.36	99	2.95	−0.85
x_2	−15.95	96	3.00	−0.86
x_3	−15.38	93	3.09	−0.86
x_4	−14.57	88	3.20	−0.87
y_1	−16.35	99	2.95	−0.85
y_2	−15.85	96	3.00	−0.86
y_3	−15.09	91	3.06	−0.86
y_4	−14.14	85	3.11	−0.86
xy_1	−16.23	98	2.96	−0.85
xy_2	−15.33	93	3.02	−0.87
xy_3	−13.98	84	3.12	−0.87
xy_4	−12.44	75	3.25	−0.88

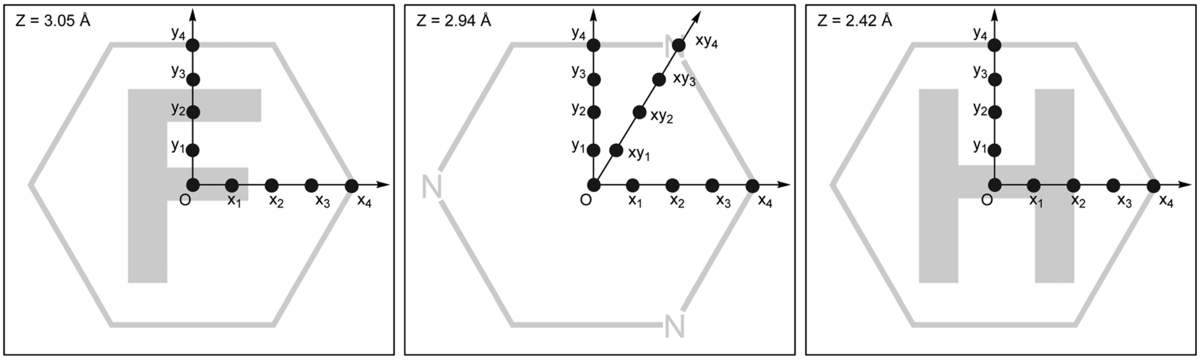

Fig. 2 Schematic representation of the parallel maps in HFB (left), TFT (middle) and BEN (right). The points where the interaction energy with Cl^{-} (left and middle) or Na^{+} (right) ions has been computed are represented as black dots.

Table 2 Interaction energies with the BSSE correction (E_{BSSE}, kcal mol^{-1}) and their percentage with respect to the interaction energy at the minimum (%E_{BSSE}), distances (R_e, Å), and charge of the anion (Q, e) at the RI-MP2(full)/aug-cc-pVDZ level of theory for $Na^+\cdots$BEN complexes (see Fig. 2 for the nomenclature of points)

Point	E_{BSSE}	%E_{BSSE}	R_e	Q (ion)
$Na^+\cdots$BEN				
o	−22.15	100	2.42	0.74
x_1	−21.57	97	2.44	0.74
x_2	−20.12	91	2.52	0.75
x_3	−18.43	83	2.64	0.77
x_4	−17.07	77	2.80	0.79
y_1	−21.71	98	2.44	0.75
y_2	−20.57	93	2.50	0.74
y_3	−19.13	86	2.58	0.76
y_4	−17.85	81	2.71	0.78

−17.94 kcal mol^{-1} and the z coordinate is 2.52 Å, indicating a very small variation with respect to the data summarized in Table 2 for point x_4. Regarding the electron transfer, it is greater in cation–π than in anion–π complexes because the equilibrium distances are considerably shorter compared to anion–π complexes. The electronic transfer from the ring to the cation ranges from 0.26 e at the minimum to 0.21 e at point x_4.

For benzene and hexafluorobenzene complexes we have also analyzed the variation of the different energetic contributions to the total interaction energy in the x and y directions. In Table 3 we summarize the contribution of the electrostatic (E_e), ion-induced polarization (E_p), dispersion (E_d) and repulsion (E_r) terms to the total interaction energy in each point. For the $Cl^-\cdots$HFB the variation of the electrostatic contribution is small. Instead, the variations of E_p and E_r are more significant. Interestingly a compensating effect between both interactions is observed, that is, the E_p contribution increases (more negative) when moving away from the minimum in any direction whilst the E_r becomes more positive. This result is useful to explain the absence of directionality in the anion–π interaction in the Z plane. A totally different scenario is observed for the BEN$\cdots Na^+$ complex. In this case the E_e and E_d contributions decrease in both x and y directions whilst the E_p term remains constant. In addition the repulsion term (E_r) becomes more positive. The overall result is a significant energy loss of the cation–π interaction between BEN and Na^+ in both directions, in agreement with the directionality observed in these complexes.

Table 3 Electrostatic (E_e), polarization (E_p), dispersion (E_d) and repulsion (E_r) contributions to the total interaction energy at several points for $Cl^-\cdots$HFB and $Na^+\cdots$BEN complexes (see Fig. 2 for the nomenclature of points)

Point	E_e	E_p	E_d	E_r
$Cl^-\cdots$HFB				
o	−9.21	−4.65	−7.78	7.58
x_1	−9.22	−4.68	−7.79	7.68
x_2	−9.32	−4.84	−7.69	7.98
x_3	−9.49	−5.06	−7.63	8.59
x_4	−9.69	−5.30	−7.70	9.57
y_1	−9.23	−4.68	−7.84	7.73
y_2	−9.23	−4.73	−7.61	7.67
y_3	−9.38	−4.93	−7.57	8.36
y_4	−9.35	−4.98	−7.23	8.14
$Na^+\cdots$BEN				
o	−12.30	−13.82	−3.04	7.02
x_1	−12.09	−14.06	−2.79	7.37
x_2	−11.38	−13.75	−2.30	7.31
x_3	−10.48	−14.21	−1.88	8.15
x_4	−9.27	−14.20	−1.70	8.09
y_1	−12.17	−14.15	−2.85	7.46
y_2	−11.63	−14.05	−2.44	7.55
y_3	−10.79	−14.57	−2.03	8.55
y_4	−9.85	−14.09	−1.63	7.71

3.2 Directionality in orthogonal planes

In Table 4 we summarize the interaction energies (E_{BSSE}) and anion–centroid distances (R_e) of $Cl^-\cdots$HFB and $Cl^-\cdots$TFT complexes computed in the orthogonal plane $Y = 0$, which is perpendicular to the molecular plane and divides the molecule into two identical halves. In Fig. 3 we show the different trajectories used to move the ion on the $Y = 0$ plane. In the all ion–π complexes we have studied the effect of moving the Cl^- ion in the z axis direction and in the zx direction. The energetic results gathered in Table 4 show that for both anion–π complexes, the effect of moving the anion away along the z axis has a strong influence on the interaction energy. It has been demonstrated that electrostatic and polarization effects dominate the anion–π interaction.[8] Both contributions are very dependent on the distance; therefore the interaction energy obviously decreases as the anion moves away. However, it should be mentioned that in point z_2 (0.7 Å away from the origin) the interaction energy is still the 80% of the E_{BSSE} at the minimum. The results in the xz direction also show an important loss of the interaction energy as the anion moves away from the minimum. In point xz_2 the interaction energy loss is about 20% and in point xz_4 is 55%. The results for the cation–π complexes are shown in Table 5. In this case we have not found differences between the cation–π and the anion–π interactions. When the cation moves away along the z axis the energy loss is significant and it is of the same

Table 4 Interaction energies with the BSSE correction (E_{BSSE}, kcal mol^{-1}) and their percentage with respect to the interaction energy at the minimum (%E_{BSSE}), distances (R_e, Å), and charge of the anion (Q, e) at the RI-MP2(full)/aug-cc-pVDZ level of theory for $Cl^-\cdots$HFB and $Cl^-\cdots$TFT complexes (see Fig. 3 for the nomenclature of points)

Complex	E_{BSSE}	%E_{BSSE}	R_e	Q (ion)
$Cl^-\cdots$HFB				
o	−14.05	100	3.05	−0.83
z_1	−13.40	95	3.40	−0.86
z_2	−11.21	80	3.75	−0.89
z_3	−9.00	64	4.05	−0.91
z_4	−7.17	51	4.40	−0.92
xz_1	−13.09	93	3.45	−0.87
xz_2	−11.13	79	3.76	−0.89
xz_3	−8.43	60	4.23	−0.91
xz_4	−6.36	45	4.66	−0.93
$Cl^-\cdots$TFT				
o	−16.55	100	2.94	−0.85
z_1	−15.69	95	3.30	−0.88
z_2	−13.05	79	3.65	−0.91
z_3	−10.38	63	4.00	−0.92
z_4	−8.14	49	4.35	−0.94
xz_1	−15.08	91	3.35	−0.89
xz_2	−12.92	78	3.65	−0.96
xz_3	−9.56	58	4.10	−0.93
xz_4	−7.08	43	4.52	−0.95

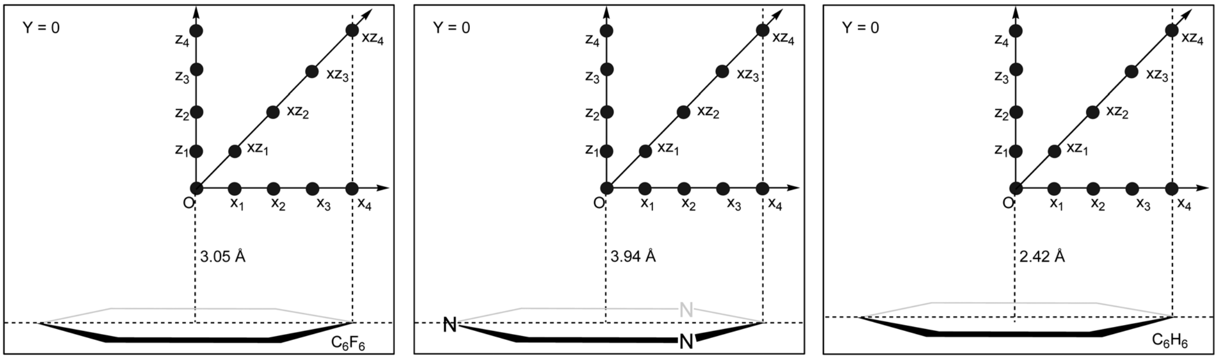

Fig. 3 Schematic representation of the orthogonal maps ($Y = 0$) in HFB (left), TFT (middle) and BEN (right). The points where the interaction energy with Cl^- (left and middle) or Na^+ (right) ions has been computed are represented as black dots.

Table 5 Interaction energies with the BSSE correction (E_{BSSE}, kcal mol^{-1}) and their percentage with respect to the interaction energy at the minimum ($\%E_{BSSE}$), distances (R_e, Å), and charge of the anion (Q, e) at the RI-MP2(full)/aug-cc-pVDZ level of theory for $Na^+\cdots$BEN complexes (see Fig. 3 for the nomenclature of points)

Complex	E_{BSSE}	$\%E_{BSSE}$	R_e	Q (ion)
$Na^+\cdots$BEN				
o	−22.15	100	2.42	0.74
z_1	−20.82	94	2.77	0.75
z_2	−17.38	78	3.12	0.78
z_3	−13.90	63	3.47	0.86
z_4	−10.97	49	3.82	0.89
zx_1	−19.92	90	2.86	0.79
zx_2	−16.19	73	3.29	0.84
zx_3	−13.81	62	3.49	0.86
zx_4	−9.72	44	4.07	0.90

magnitude than for the anion–π interaction. A likely explanation is that both interactions are dominated by the same contributions (electrostatic and polarization). In the *xz* direction the behaviour is also equivalent to the anion–π interaction.

As aforementioned a geometric criterion that allows defining an anion–π contact has not been clearly established yet. The computational results demonstrate that the interaction energy is conserved in an 80% when the anion is moved by 0.7 Å from the minimum along the *z* axis. The same behaviour is observed in the cation–π interaction, when the cation is moved away from the minimum along the *z* axis by 0.7 Å. In addition, in this point the charge transfer has decreased only by 0.06 e. Therefore, we propose as a first approximation to consider an ion–π contact when the distance between the anion and the six carbon atoms of the ring is $\leq \Sigma$vdW radii + d, where $d = 0.7/\cos\alpha$ (α is defined in Fig. 4).

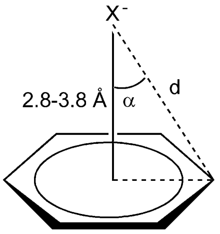

Fig. 4 Definition of α.

We can also estimate that the value of α is ~30° taking into account that the range of distances for anion–π interactions involving halogen atoms is 2.8–3.8 Å measured from the anion to the ring center. Thus, the proposal is to consider the existence of an anion–π contact when the distance is $\leq \Sigma$vdW radii + 0.8 Å from the anion to the carbon atoms of the aromatic ring.

An interesting point is to study at what limit the ion–π interaction no longer exists. This is a difficult issue to address, however a good approximation can be obtained from the AIM analysis. The ion–π interactions have been successfully characterized by the presence of several bonds, ring and cage critical points (CPs) connecting the ion with the ring. Actually, the cage CP has been used as a measure of bond order. In Fig. 5 and 6 we represent the variation of the value of the electron density at the cage CP in anion and cation–π complexes as a function of the distance. It can be observed from the plot that the density at the cage CP decreases rapidly as the ion moves away. The value of the density becomes negligible starting from 5 Å for the anion–π complex and from 4 Å for the cation–π complex.

3.3 van der Waals radii of anionic halogen atoms

It has been demonstrated that the utilization of different van der Waals radii for organic and inorganic halogen atoms

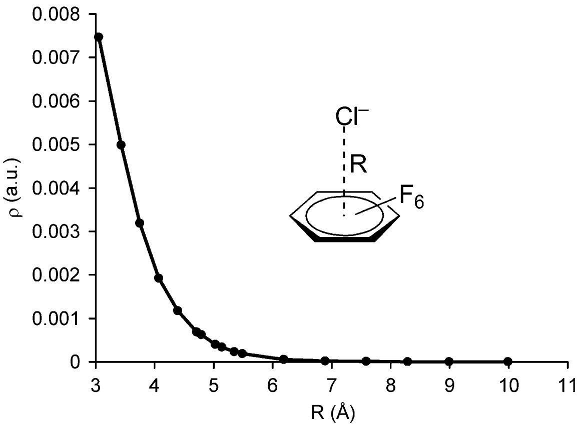

Fig. 5 Plot of the value at the cage CP *versus* the anion-ring centroid distance in $Cl^-\cdots$HFB complex.

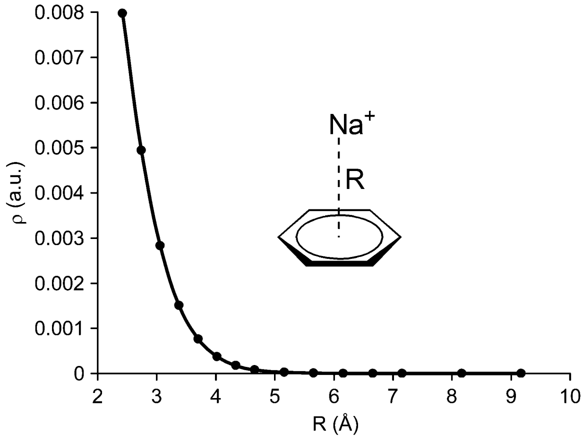

Fig. 6 Plot of the value at the cage CP *versus* the cation-ring centroid distance in $Na^+\cdots$BEN complex.

improves the performance of molecular mechanics calculations of transition metal complexes.[22] The tabulated van der Waals radii[39] for halogen elements that use standard *force fields* give poor geometries in transition metal complexes with halide ligands (ML_nX_m). The source of this error is the inadequacy of the default van der Waals radii. To solve this problem, the utilization of different van der Waals radii for halogen elements depending on their ionic nature is proposed. The default van der Waals radii are adequate for organic halogen atoms and larger radii should be used for inorganic, more anionic, halogen atoms.[22]

In any CSD search of noncovalent interactions as anion–π interactions the existence of a contact is based on the sum of van der Waals radii. Therefore, it is extremely important to use adequate values; otherwise the searches could give erroneous results. In this part of the manuscript we compute the van der Waals radii of organic and inorganic halogen atoms and we compare them with the tabulated data. We have used a methodology that has been proven appropriate for the calculation of van der Waals surface of molecules.[40] It consists of using the helium atom as a probe in geometry optimizations. We have used the MP4/6-311++G(3d,3p) level of theory for the optimization of the two models used (see Fig. 7). These models have been previously used by Ujaque *et al.*[22] to estimate the van der Waals radius (r_w) of chlorine. The model for organic halogen atoms is $H_3C–X\cdots He$ and the model for halides (inorganic halogen atoms) is $Na–X\cdots He$. The results for F, Cl and Br are summarized in Table 6. It can be observed that the resulting optimized distances are longer for inorganic than for organic halogen atoms. The calculation of the helium dimer gives the computed r_w that is 1.57 Å. According to this, the r_w for organic halogen atoms are 1.38 Å for F, 1.72 Å for Cl and 1.98 Å for Br. These values reasonably agree with the tabulated values from Bondi.[39] It should be mentioned that the experimental value for fluorine has been obtained from experimental data of perfluoroalkanes. The experimental value obtained for primary alkane fluorides is 1.40 Å, which is in strong agreement with the estimated value of 1.38 Å. The experimental and tabulated vdW radii values Cl and Br have been obtained from tetrahalides. The experimental value obtained for primary alkane chlorides is 1.73 Å that nicely agrees with the computed value (1.72 Å). In the case of Br, the experimental and computational values differ by 0.13 Å, which is probably within the experimental error. In addition, the experimental vdW radius of Br obtained from the liquid properties of bromobenzene is 1.92 Å which is more similar to the computed value (1.98 Å, see Table 6). The inorganic halogens, more negatively charged than the organic halogen substituents, have significantly larger radii, as expected. Therefore, when a noncovalent contact is defined in any search involving F^-, Cl^- and Br^- anions, this issue has to be taken into account. As a consequence, the aforementioned proposed formula to define an anion–π contact between the anion and the carbon atoms of the ring can be modified if these new r_w values are used. That is $\leq \Sigma$vdW radii + ~0.4 Å, since the ΣvdW radii are longer using the new r_w values than the tabulated ones.

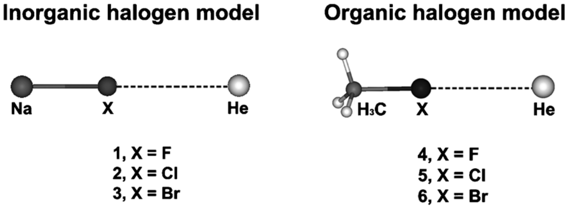

Fig. 7 Complexes **1–6** used to compute the van der Waals radii of organic and inorganic halogen atoms.

Table 6 Equilibrium distances of complexes **1–6** (*d*, Å) and the estimated and tabulated van der Waals radii (r_w, Å) of halogen atoms

Complex	*d*	r_w (tabulated)[a]	r_w (estimated)
$He\cdots He$	3.149	1.40 (He)	1.57 (He)
1, $H_3C–F\cdots He$	2.952	1.47 (F)	1.38 (F)
2, $H_3C–Cl\cdots He$	3.294	1.75 (Cl)	1.72 (Cl)
3, $H_3C–Br\cdots He$	3.554	1.85 (Br)	1.98 (Br)
4, $Na–F\cdots He$	3.286	—	1.71 (F^-)
5, $Na–Cl\cdots He$	3.684	—	2.11 (Cl^-)
6, $Na–Br\cdots He$	3.922	—	2.35 (Br^-)

[a] From ref. 37.

4. Conclusions

The analysis of the results presented in this manuscript offers some interesting conclusions. First, in the anion–π complexes of HFB the displacement of the anion from the minimum in *x* and *y* directions (parallel plane) does not imply a significant interaction energy loss (≤7%), thus supporting a more unrestrictive criterion to consider an anion–π contact, where the anion can be located at any place over the ring. In contrast, in the cation–π complexes of BEN the displacement of the cation in the parallel plane causes a more significant energy loss (≤23%). This helps to explain the dispersion (scattering) observed for the position of the anion over the ring in the crystal structures, which is not observed in the solid state analysis of cation–π interactions. Second, the energy loss when either the anion or the cation moves away from the minimum along the *z* axis is important because the electrostatic and polarization contributions decrease as the distance increases. The energetic and geometric analyses of the complexes allow us to propose a criterion for the cut-off distance in the noncovalent contact definition. The proposal is to consider the existence of an anion–π contact when the distance is ≤ΣvdW radii + 0.8 Å if the standard r_w are used. Third, the tabulated van der Waals radii of halogen atoms are not adequate for anionic halogen atoms. We have obtained new r_w values for F^-, Cl^- and Br^- that can be useful for *force field* parameterization and for their utilization in anion–π searches in the CSD.

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