A COMPARATIVE VIEW ON THE POTENTIAL ACTING ON AN ELECTRON IN A MOLECULE AND THE ELECTROSTATIC POTENTIAL THROUGH THE TYPICAL HALOGEN BONDS

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ABSTRACT

This work considers the features of the electrostatic potential (ESP), and the potential acting on an electron in a molecule (PAEM) for the series of isolated dihalide molecules and for their molecular complexes. The joint analysis of these functions enriches the vision of atomic predispositions to the halogen bond formation and reveals details for their characterization. The account for the exchange-correlation interaction in PAEM retains the specific anisotropy of the electrostatic potential, which is commonly used for the halogen bonding explanation within σ-hole concept. Along the halogen bonds, the curvatures of PAEM and ESP functions are opposite. Being jointly mapped on the closed isosurfaces of the reduced density gradient, placed between bound atoms, they are significantly differed from the side facing the halogen atom and from the side looking at the electron donor atom.

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Introduction

The predominating explanation of the halogen-stabilized, chalcogen-, pnictogen- and tetrel- bonds as electrostatically driven molecular interactions is based on the consideration of features of the electrostatic potential of molecules prior interaction. This approach is widely represented in the literature, see1,2,12. The local regions of increased electrostatic potential values, the σ-holes13, which are formed on the extension of the covalent bonds, originate from the anisotropy of the electron density and electrostatic potential of bounded atoms. The latter explains the nature of different types of directional non-covalent interaction14. Similarly, π-hole conception has also been introduced15,16.

The electrostatic potential (ESP) is a scalar function

\[ \varphi_{\text{ESP}}(\mathbf{r}_1) = \sum_a Z_a \delta(|\mathbf{r}_1 - \mathbf{R}_a|) - \int \frac{\rho(\mathbf{r}_2)}{|\mathbf{r}_1 - \mathbf{r}_2|} d\mathbf{r}_2 \]  

generated by the nuclear and electronic parts of the charge density (the atomic units are used)17. Here \( Z_a \) and \( \mathbf{R}_a \) are the atomic number and position of atom \( a \), respectively, and \( \rho(\mathbf{r}_2) \) is the one-electron density. The electrostatic potential at point \( \mathbf{r}_1 \), \( \varphi_{\text{ESP}}(\mathbf{r}_1) \), measures the potential energy \( V_{\text{ESP}}(\mathbf{r}_1) = \varepsilon \varphi_{\text{ESP}}(\mathbf{r}_1) \) that an unit charge \( \varepsilon=\pm1 \) gets when it is moved from infinity to point \( \mathbf{r}_1 \). Test charge is considered as external to a given molecule and all molecular geometric and electronic relaxations are ignored. The electrostatic potential influences the crystal packing peculiarities18,19, as well as the features
of the reactivity\textsuperscript{20,21} and intermolecular interactions, especially in crystal engineering\textsuperscript{22} and pharmaceutical industry\textsuperscript{23}, etc. Also, the electrostatic potential at nuclear position defines the core-electron binding energy\textsuperscript{24,25}, while the gradient of electrostatic field at nuclei does appear in the nuclear quadruple resonance and Mossbauer spectroscopy\textsuperscript{26}, etc.

Gradient of $\varphi_{\text{ESP}}(\mathbf{r}_1)$ defines the electrostatic field $\mathbf{E}(\mathbf{r}_1) = -\nabla \varphi_{\text{ESP}}(\mathbf{r}_1)$; it determines the force acting on arbitrary charge $q$ at $\mathbf{r}_1$:

$$\mathbf{F}(\mathbf{r}_1) = -q \cdot \nabla \varphi_{\text{ESP}}(\mathbf{r}_1) = -\nabla \varphi_{\text{ESP}}(\mathbf{r}_1)$$

This force is tangentially directed to the electrostatic field lines at each point $\mathbf{r}_1$. The ESP in molecules and solids can be measured by electron diffraction\textsuperscript{27-29}, however, this approach still is waiting for appropriate experimental and theoretical development to be the accurate and informative enough.

Very recently the Potential Acting on an Electron in a Molecule, PAEM\textsuperscript{30-34}

$$\varphi_{\text{PAEM}}(\mathbf{r}_1) = -\varphi_{\text{ESP}}(\mathbf{r}_1) + V_{\text{XC}}(\mathbf{r}_1)/\rho(\mathbf{r}_1)$$

has attracted the attention of workers. PAEM is negative everywhere and consists of one-electron electrostatic component, $\varphi_{\text{ESP}}(\mathbf{r}_1)$, and two-electron contribution from the quantum exchange-correlation potential

$$V_{\text{XC}}(\mathbf{r}_1) = -\int \frac{\rho_{\text{XC}}(\mathbf{r}_1, \mathbf{r}_2)}{|\mathbf{r}_1 - \mathbf{r}_2|} \text{d}\mathbf{r}_1 \quad (4)$$

where $\rho_{\text{XC}}(\mathbf{r}_1, \mathbf{r}_2)$ is exchange-correlation density of electrons\textsuperscript{35}. The latter originates from two-electron spinless density

$$\rho_2(\mathbf{r}_1, \mathbf{r}_2) = N(N - 1) \cdot \int_{i=3}^{\infty} \cdots \int_{i=N}^{\infty} \psi^*(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N) \psi(\mathbf{r}_1, \mathbf{r}_2, ..., \mathbf{r}_N) \text{d}\mathbf{r}_3 \cdots \text{d}\mathbf{r}_N \quad (5)$$

($\psi$ is many-electron wave function, $\mathbf{r}_i$ enumerates the electrons, $i=1, ..., N$) and can be presented as

$$\rho_2(\mathbf{r}_1, \mathbf{r}_2) = \rho(\mathbf{r}_1)\rho(\mathbf{r}_2) - \rho_{\text{XC}}(\mathbf{r}_1, \mathbf{r}_2) \quad (6)$$

The first term is the Coulombic part of the two-electron density describing independent distributions of electrons $\mathbf{r}_1$ and $\mathbf{r}_2$; note that $\rho(\mathbf{r}_1) = \int \rho_{\text{XC}}(\mathbf{r}_1, \mathbf{r}_2) \text{d}\mathbf{r}_2$. PAEM (3) characterizes the averaged local energy of interaction of any one (indistinguishable) electron belonging to a given molecule (or a crystal) and the rest of the electrons of the system and all the nuclei\textsuperscript{30,33}. Sign minus in front of $\varphi_{\text{ESP}}(\mathbf{r}_1)$ accounts for the negative charge of electron under consideration. Note that the selfinteraction of the chosen electron with itself, which is presented in the last term in (6), is canceled by corresponding contribution in the electronic part of $\varphi_{\text{ESP}}(\mathbf{r}_1)$.

Potential acting on an electron in a molecule, as any scalar function, allows the standard QTAIM analysis\textsuperscript{37,38}, which in this case has a clear physical interpretation. For example, the total force acting on one electron in a molecule is defined as

$$\mathbf{F}_{\text{PAEM}}(\mathbf{r}_1) = -\nabla \varphi_{\text{PAEM}}(\mathbf{r}_1) = \nabla \varphi_{\text{ESP}}(\mathbf{r}_1) - \nabla [V_{\text{XC}}(\mathbf{r}_1)/\rho(\mathbf{r}_1)]. \quad (7)$$

This force describes the interaction of any one electron of a given molecule (or a crystal) with the averaged distribution of the remaining electrons of the system and all the nuclei and is tangential to the $\mathbf{E}(\mathbf{r}_1)$ field lines. From here on in this paper we shall omit the subscript at $\mathbf{r}$.

In contrast to the electrostatic potential, $\varphi_{\text{ESP}}$, the potential acting on an electron in a molecule, $\varphi_{\text{PAEM}}$, has not yet been applied for exploring the non-covalent molecular interactions, which are commonly assumed as electrostatic-driven ones. Besides, $\varphi_{\text{PAEM}}$ seems to be a suitable tool to study the nature of interactions in the \textit{bonded} systems: it is able to provide the additional information about the specific features of molecular organization in systems, where all the bonds are already formed.

This work aims to find out how the electronic exchange, which is reflected in the PAEM, affects the anisotropy of the bound halogen atoms and to stress the importance of the joint
application of $\varphi_{\text{ESP}}$ and $\varphi_{\text{PAEM}}$. We are also looking for manifestation in $\varphi_{\text{PAEM}}$ of atomic predisposition to participate in the typical halogen bonds and are trying to establish the features of the potential acting on an electron in a molecule for the systems in which the halogen bonds do exist.

Methods

The wave functions of molecular complexes with halogen bonds $\text{B...ClF, Cl}_{2}, \text{BrCl, Br}_{2}, \text{ICI}$, where $\text{B}$ equals $\text{NH}_{3}, \text{H}_{2}\text{O}, \text{H}_{2}\text{S}, \text{CO}$, and hydrogen bonds in $\text{N}$-oxide of picolinic acid and acetamide dimer were calculated by the Kohn-Sham method$^{38}$ in the B3LYP/6-311G(d, p) approximation using the computer code Firefly 8.0$^{39}$ at the fixed nuclear configuration. Geometry optimizations were carried out and the equilibrium structures of all molecular systems were confirmed by harmonic IR frequency analysis.

The calculated wave functions were used to compute the electron density, $\rho(r)$, and to perform the QTAIM analysis of molecules under consideration. The $\varphi_{\text{ESP}}$ and $\varphi_{\text{PAEM}}$ were calculated using Multiwfn software, ver. 3.3.9$^{40}$. The exchange-correlation density was evaluated in terms of Müller approximation$^{41}$: it allows taking into account a pseudo-HF exchange coming from the Kohn-Sham determinant. The electron delocalization indices$^{42,43}$, $\delta(\text{B, Hal})$ and the reduced density gradient$^{44,45}$ (RDG) were computed as well. The quantitative analysis of molecular surface$^{46}$, the distributions of ESP and PAEM on the isosurfaces of both the electron density and RDG were computed by using Multiwfn. Visualisation was made by using MoleCoolQt and Mollso programs$^{48,49}$.

Discussion

The features of ESP and PAEM on the electron density isosurfaces

As is well known$^{50,51}$, the electrostatic potential function mapped on the isosurface of the electron density, $\rho(r)$, around an isolated molecule, locates the $\pi$- and $\sigma$-holes$^{52,53}$, indicating the regions with higher probability of interactions with distanced electron-donor fragments. For convenience of comparison, we will use the $-\varphi_{\text{ESP}}$ function, which shows the ESP of system acting on the electron at $r$.

For isolated dihalide molecules $\text{ICI, BrCl, Cl}_{2}, \text{ClF}$, both $-\varphi_{\text{ESP}}$ and $\varphi_{\text{PAEM}}$ functions reveal pronounced regions of $\sigma$-holes and toroidal belts indicating the charge density depletion and accumulation, correspondingly. On the van der Waals surface of the fluorine atom in FCl molecule, the $\sigma$-hole is almost invisible (Figure 1). Nevertheless, the extremes of $-\varphi_{\text{ESP}}$ and $\varphi_{\text{PAEM}}$ for the fluorine atom are observable, see Table 1.

For the halogen atoms in the series $\text{Hal} = \text{I, Br, Cl, F}$, the values $-\varphi_{\text{ESP}}(\text{Hal})$ increase, becoming positive for the F atom. Keeping in mind that we consider the interaction of the electrostatic potential with an electron, the classic repulsive conditions for an electron within the $\sigma$-hole of fluorine take place. At that, this repulsion is visibly lower than that for an electron on the belt corresponding to location of the electron lone pairs around fluorine atoms. On the contrary, the negative values of $\varphi_{\text{PAEM}}(\text{Hal})$ decrease from iodine to fluorine. It indicates that actually the fluorine holds its own electrons in the $\sigma$-hole better than other halogens due to the exchange interaction and electrostatic attraction. For the fluorine this attraction on the $\sigma$-hole is even locally stronger than on the belt. Note that for all halogens, with the exception of fluorine, inequality $\varphi_{\text{PAEM}}(\text{Hal}) > \varphi_{\text{PAEM}}{^\text{belt}}(\text{Hal})$ is valid, but only for fluorine atom $\varphi_{\text{PAEM}}{^\text{sigma}}(\text{F}) < \varphi_{\text{PAEM}}{^\text{belt}}(\text{F})$. Nevertheless, in the ClF molecule, the F atom stimulates the highest attractive potential $\varphi_{\text{PAEM}}{^\text{sigma}}$ for the chlorine atom, being covalently bound with the latter. The lowest negative value of $\varphi_{\text{PAEM}}$ are observed on the belt around the chlorine atom in the ClF molecule. The analysis of the depth of $\sigma$-holes for the Cl atom in Hal–Cl molecules has shown the following. As the electronegativity of the Hal substituent increases in the I, Br, Cl, F, series, the $-\varphi_{\text{ESP}}(\text{Cl})$ decreases from $-0.017$ to $-0.072$ a. u., and $\varphi_{\text{PAEM}}{^\text{sigma}}(\text{Cl})$ decreases from $-0.278$ to $-0.297$ a. u. In general, the differences $\Delta\varphi_{\text{ESP}}(\text{Cl}) = \Delta\varphi_{\text{PAEM}}{^\text{sigma}}(\text{Cl}) = 

\text{...}
\[ |\psi_{\text{ESP}}(\text{Cl}) - \psi_{\text{ESP}}^{\text{belt}}(\text{Cl})| \] and \[ \Delta \varphi_{\text{PAEM}}(\text{Cl}) = |\psi_{\text{PAEM}}(\text{Cl}) - \psi_{\text{PAEM}}^{\text{belt}}(\text{Cl})| \] vary identically for the chlorine atom (Fig. 1, the 3rd and 4th rows) in the considered series.

Figure 1. Distributions of \(-\varphi_{\text{ESP}}(1\text{st and 3rd rows})\) and \(\varphi_{\text{PAEM}}(2\text{nd and 4th rows})\) mapped on the isosurfaces of the electron density, \(\rho(\vec{r}) = 0.001 \text{ a. u.}\), for ICl, BrCl, Cl\(_2\), ClF molecules.

<table>
<thead>
<tr>
<th>Molecules</th>
<th>(-\varphi_{\text{ESP}}) (a. u.)</th>
<th>(-\varphi_{\text{ESP}}^{\text{belt}}) (a. u.)</th>
<th>(-\varphi_{\text{ESP}}) (a. u.)</th>
<th>(-\varphi_{\text{ESP}}^{\text{belt}}) (a. u.)</th>
<th>(\varphi_{\text{PAEM}}) (a. u.)</th>
<th>(\varphi_{\text{PAEM}}^{\text{belt}}) (a. u.)</th>
<th>(\varphi_{\text{PAEM}}) (a. u.)</th>
<th>(\varphi_{\text{PAEM}}^{\text{belt}}) (a. u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I–Cl</td>
<td>-0.074</td>
<td>0.002</td>
<td>-0.017</td>
<td>0.012</td>
<td>-0.286</td>
<td>-0.345</td>
<td>-0.278</td>
<td>-0.308</td>
</tr>
<tr>
<td>Br–Cl</td>
<td>-0.060</td>
<td>0.003</td>
<td>-0.030</td>
<td>0.009</td>
<td>-0.280</td>
<td>-0.342</td>
<td>-0.283</td>
<td>-0.324</td>
</tr>
<tr>
<td>Cl–Cl</td>
<td>-0.042</td>
<td>0.004</td>
<td>-0.042</td>
<td>0.004</td>
<td>-0.289</td>
<td>-0.343</td>
<td>-0.289</td>
<td>-0.343</td>
</tr>
<tr>
<td>F–Cl</td>
<td>0.010</td>
<td>0.018</td>
<td>-0.072</td>
<td>-0.000</td>
<td>-0.356</td>
<td>-0.342</td>
<td>-0.297</td>
<td>-0.390</td>
</tr>
</tbody>
</table>
Thus, our PAEM results show that for isolated dihalide molecules the account of exchange-correlation interaction does not change the specific manifestation of the anisotropy of electrostatic potential for the halogen atoms. Therefore the halogen bonding interactions may be really classified as dominantly electrostatically driven. At the same time, a joint analysis of the ESP and PAEM functions shed the new light on atomic predispositions to the halogen bonding.

Meanwhile, in stable molecular complexes in which non-covalent interactions are already formed, the anisotropy of the electrostatic potential between the neighboring molecules carries the information about the whole system. In this case, the characteristics of ESP in the region of non-covalent interactions, as a rule, acquire the blurred meaning. Quantitative relationships between the electrostatic potential extremes and the strength of corresponding intermolecular interactions, including examples of complexes with halogen bonds, were already discussed in the literature. We took the opportunity to compare the anisotropy of ESP and PAEM functions in the four representative complexes with strong and very weak halogen bonds: NH$_3$...ClF, NH$_3$...Cl$_2$, OC...ClF, OC...Cl$_2$. To do that, the ESP and PAEM functions were mapped on the isosurfaces of the electron density (Figure 2) corresponding to the contours, slightly exceeding the value of the electron density, $\rho(r_{\text{BCP}})$ at the halogen bond critical points (BCP).

For halogen atoms in complexes the values of ESP and PAEM extremes, that manifest themselves on the isosurfaces of the electron density, are listed in Table S1. These examples demonstrate that both the base features and the polarity of halogen molecules influence the strength of considered halogen bonds. All the images show very similar patterns of ESP and PAEM anisotropy. The traces of $\sigma$-holes that are preserved after the halogen bond formation (Figure 2) have the lower ESP and PAEM negative values in comparison with those on the electron toroidal belts around halogen atoms.

![Figure 2](image-url)

Figure 2. Distributions of $-\phi_{\text{ESP}}$ and $\phi_{\text{PAEM}}$ mapped on the isosurfaces of the electron density around molecules. Top: the halogen bond N...Cl in NH$_3$...ClF complex ($\rho(r)=0.06$ a. u.), bottom: the halogen bond C...Cl in the complex OC...Cl$_2$ ($\rho(r)=0.03$ a. u.)

It is instructive to compare the difference between the potentials values $-\phi_{\text{ESP}}^\sigma$ and $\phi_{\text{PAEM}}^\sigma$ in the epicenter of $\sigma$-hole and the average maxima of $-\phi_{\text{ESP}}^{\text{belt}}$ and $\phi_{\text{PAEM}}^{\text{belt}}$ on the belts of halogens (Figure 3). Let us check how the difference of the ESP on the $\sigma$-hole and on the belt, $\Delta\phi_{\text{ESP}} = |\phi_{\text{ESP}}^\sigma - \phi_{\text{ESP}}^{\text{belt}}|$, and the corresponding difference of PAEM, $\Delta\phi_{\text{PAEM}} = |\phi_{\text{PAEM}}^\sigma - \phi_{\text{PAEM}}^{\text{belt}}|$, are suitable for characterization of the bound halogen atoms. Figure 3 illustrates that the values $\Delta\phi_{\text{ESP}}$ and $\Delta\phi_{\text{PAEM}}$ are qualitatively similar. At the same time, in $\phi_{\text{PAEM}}$ function the increasing of values in transition from the NH$_3$ complexes to the complexes of weak base CO, is more pronounced than in $-\phi_{\text{ESP}}$. For nonpolar molecule Cl$_2$ this difference is always slightly less than for polar ClF molecule in abovementioned complexes.

Thus, the values of $-\phi_{\text{ESP}}$ and $\phi_{\text{PAEM}}$ on the electron density isosurfaces in complexes with halogen bonds illustrate the approximately similar pattern, however the contrast between strong and weak halogen bonds appears slightly brighter in $\phi_{\text{PAEM}}$. 
Figure 3. Comparison of ESP and PAEM extreme values at the epicenters of the σ-holes and average values on the belts of halogens in the complexes with halogen bonds

The features of ESP and PAEM extremes on the closed RDG isosurfaces

One of the modern tools used to detect the non-covalent interactions between atoms is the analysis of reduced density gradient\(^45,46\) (RDG). For abovementioned series of complexes, we have computed the functions \(-\varphi_{ESP}^{RDG}\) and \(\varphi_{PAEM}^{RDG}\) on the different sides of closed RDG isosurfaces, which characterize the typical regions of halogen bonds. We have compared these patterns with commonly used ones, when the mapped function \(\text{sign}(\lambda_2)\rho(r)\), where \(\lambda_2\) is the second largest eigenvalue of electron density Hessian matrix, is mapped on the RDG isosurface. It has been found that for a weak halogen bond, the function \(\text{sign}(\lambda_2)\rho(r)\) looks in the complex just the same, both from the side of the electron donor atom and from the halogen (Figure 4a). In contrast, the significantly lower negative values of \(-\varphi_{ESP}\) and \(\varphi_{PAEM}\) are always observed from the side that faces the halogen, which acts as an acceptor of the electron density. It is remarkable that the differences in \(-\varphi_{ESP}\) and \(\varphi_{PAEM}\) functions, measured on the opposite sides of RDG isosurface, distinguish the electron donor and electron acceptor in the pair of interacted atoms.

Figure 4. Distributions of a) \(\text{sign}(\lambda_2)\rho(r)\), b) \(-\varphi_{ESP}\), c) \(\varphi_{PAEM}\) functions mapped on the isosurface of RDG =0.5 along the weak halogen bond C…Cl in the complex OC…ClF. The upper and bottom images correspond to opposite views of RDG isosurfaces

Let us compare \(-\varphi_{ESP}^{RDG}\) and \(\varphi_{PAEM}^{RDG}\) extremes measured from the different sides of the RDG isosurface: from the electron donor atoms (C, N, O) and from the side of H or Cl atoms. The difference in \(-\varphi_{ESP}^{RDG}\) and \(\varphi_{PAEM}^{RDG}\) extremes on the opposite sides decreases noticeably when we turn from strong to weak non-covalent interactions. The overall growing of \(-\varphi_{ESP}^{RDG}\) and \(\varphi_{PAEM}^{RDG}\) values is similar, see Figure 5. However, for the weak complexes formed by CO molecule, the changes in \(-\varphi_{ESP}^{RDG}\) and \(\varphi_{PAEM}^{RDG}\) values are more expressed than for the relatively strong NH\(_3\) complexes, if we follow from polar ClF to homopolar Cl\(_2\) molecules. We can summarize that both values \(\Delta\varphi_{ESP}^{RDG}=|\varphi_{ESP}^{RDG}(B)-\varphi_{ESP}^{RDG}(H,\text{Hal})|\), and \(\Delta\varphi_{PAEM}^{RDG}=|\varphi_{PAEM}^{RDG}(B)-\varphi_{PAEM}^{RDG}(H,\text{Hal})|\) remain more significant (~0.20 – 0.30 a.u.) for the strong non-covalent interactions and assume quite small values (~0.04 – 0.06 a.u.) for the weak ones (Table S2). Thus, the \(-\varphi_{ESP}\) and \(\varphi_{PAEM}\) potentials mapped on the RDG isosurfaces are
significantly different from the side facing the halogen atom and from the side, looking at the electron donor atom; therefore they are more informative than corresponding maps on the isosurface of the electron density in the halogen bond region in the complexes of bound molecules.

Along the any interatomic line connecting the the bound atoms, the PAEM function is extreme and negative. Thus, the PAEM barriers separate all the nuclei in a molecule or in molecular complex. The lower PAEM barrier, the easier neighboring atoms share electrons, and the more significant covalence of the bond between them.

The behavior of functions \(-\varphi_{\text{ESP}}\) and \(\varphi_{\text{PAEM}}\) along the bond line in the linear complex of carbon monoxide with chlorine molecule \(\text{O} \equiv \text{C} \cdots \text{Cl} \cdots \text{Cl}\) is shown in Fig.6. The triple O≡C bond exhibits significantly lower barriers, \(-\varphi_{\text{ESP}}^{\text{max}} = -1.74\) a. u. and \(\varphi_{\text{PAEM}}^{\text{max}} = -3.09\) a. u., than the single Cl–Cl bond in the chlorine molecule: \(-\varphi_{\text{ESP}}^{\text{max}} = -0.63\) a. u. and \(\varphi_{\text{PAEM}}^{\text{max}} = -1.47\) a. u. The weakest halogen bond C…Cl shows the highest barriers: \(-\varphi_{\text{ESP}}^{\text{max}} = -0.04\) a. u. and \(\varphi_{\text{PAEM}}^{\text{max}} = -0.52\) a. u. It is interesting to note that in O≡C…Cl–Cl complex the exchange-correlation contribution to \(\varphi_{\text{PAEM}}\) lowers the barrier in the triple covalent bond O≡C more than in the single covalent bond Cl–Cl; they are both larger than those for the halogen bond C…Cl (Figure 6). A similar situation is observed for more stable NH₃ complexes: with respect to the \(-\varphi_{\text{ESP}}^{\text{max}}\) barrier, the barrier \(\varphi_{\text{PAEM}}^{\text{max}}\) decreases more strongly for the Cl–F and Cl–Cl.

**Table 2.** The extreme values of ESP and PAEM barriers, the electron density at the BCP and their positions at the distance from the electron donor atom nucleus to atom Hal for halogen bonds in molecular complexes.

<table>
<thead>
<tr>
<th>Complex</th>
<th>Position of (-\varphi_{\text{ESP}}^{\text{max}}) (a. u.)</th>
<th>Position of (\varphi_{\text{PAEM}}^{\text{max}}) (a. u.)</th>
<th>Position of (\rho(r_{\text{BCP}})) (a. u.)</th>
</tr>
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<tbody>
<tr>
<td>NH₃…Br₂</td>
<td>1.862</td>
<td>-0.139</td>
<td>2.074</td>
</tr>
<tr>
<td>NH₃…BrCl</td>
<td>1.834</td>
<td>-0.178</td>
<td>2.023</td>
</tr>
<tr>
<td>NH₃…Cl₂</td>
<td>1.875</td>
<td>-0.138</td>
<td>2.046</td>
</tr>
<tr>
<td>NH₃…ClF</td>
<td>1.850</td>
<td>-0.141</td>
<td>2.031</td>
</tr>
<tr>
<td>NH₃…ICl</td>
<td>1.809</td>
<td>-0.200</td>
<td>2.050</td>
</tr>
<tr>
<td>H₂O…Br₂</td>
<td>1.897</td>
<td>-0.079</td>
<td>2.246</td>
</tr>
<tr>
<td>H₂O…BrCl</td>
<td>1.854</td>
<td>-0.116</td>
<td>2.175</td>
</tr>
<tr>
<td>H₂O…Cl₂</td>
<td>1.916</td>
<td>-0.077</td>
<td>2.215</td>
</tr>
<tr>
<td>H₂O…ClF</td>
<td>1.849</td>
<td>-0.109</td>
<td>2.146</td>
</tr>
<tr>
<td>H₂O…ICl</td>
<td>1.819</td>
<td>-0.148</td>
<td>2.184</td>
</tr>
<tr>
<td>H₃S…Br₂</td>
<td>2.694</td>
<td>-0.102</td>
<td>2.897</td>
</tr>
<tr>
<td>H₃S…BrCl</td>
<td>2.612</td>
<td>-0.133</td>
<td>2.802</td>
</tr>
<tr>
<td>H₃S…Cl₂</td>
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<td>2.889</td>
</tr>
<tr>
<td>H₃S…ClF</td>
<td>2.560</td>
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<td>2.716</td>
</tr>
<tr>
<td>H₃S…ICl</td>
<td>2.611</td>
<td>-0.146</td>
<td>2.847</td>
</tr>
<tr>
<td>OC…Br₂</td>
<td>2.343</td>
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</tr>
<tr>
<td>OC…BrCl</td>
<td>2.248</td>
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<td>OC…Cl₂</td>
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<td>-0.044</td>
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<tr>
<td>OC…ClF</td>
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<td>-0.129</td>
<td>2.421</td>
</tr>
<tr>
<td>OC…ICl</td>
<td>2.144</td>
<td>-0.143</td>
<td>2.490</td>
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</table>
covalent bonds than for the halogen bonds N…Cl. Thus, it can be stated that the height of $\varphi_{\text{PAEM}}^{\text{max}}$ barrier varies symbatically with the (non-covalent) bond order. That observation is supported by quantitative comparison of $\varphi_{\text{PAEM}}^{\text{max}}$ with the Mayer fuzzy bond orders $^{57,58}$ for bonds in NH$_3$ and CO complexes, see Table S3.

Figure 6. The $-\varphi_{\text{ESP}}$ and $\varphi_{\text{PAEM}}$ functions for bonds in O≡C…Cl–Cl complex (a. u.)

Table 2 clearly illustrates that for the halogen bonds in complexes B…ClF, B…Cl$_2$, B…BrCl, B…Br$_2$, B…ICI, where B = NH$_3$, H$_2$O, H$_2$S, the barriers $-\varphi_{\text{ESP}}^{\text{max}}$ and $\varphi_{\text{PAEM}}^{\text{max}}$ significantly differ in their magnitude.

Negative peaks of $\varphi_{\text{PAEM}}^{\text{max}}$ lies in the range from $-0.900$ till $-0.519$ a. u. In turn, the range of $-\varphi_{\text{ESP}}^{\text{max}}$ is from $-0.200$ till $-0.044$ a. u. The potential accounting for the exchange and correlation of electrons makes the barriers of halogen bonds noticeably lower in comparison with the electrostatic potential. Comparison of $\varphi_{\text{PAEM}}^{\text{max}}$ values with the stretching force constants of the halogen bonds, $k_0$, estimated by Legon $^{59,60}$ et al., shows that the more lower barriers correspond to the more stronger halogen bonds (Figure S1 in Suppl. Materials). In complexes of the strong electron donor, NH$_3$, for relatively stronger halogen bonds, the $-\varphi_{\text{ESP}}^{\text{max}}$ and $\varphi_{\text{PAEM}}^{\text{max}}$ barriers are lower than in complexes with the weakest electron donor CO. Moreover, the weakening of the halogen bonds is accompanied by the increasing of barriers $\varphi_{\text{PAEM}}^{\text{max}}$.

Also we note that the change of $\varphi_{\text{PAEM}}^{\text{max}}$ can be compared with changes in the corresponding electron delocalization indices, which are immediately linked with the exchange-correlation density of electrons $^{42-44}$. For the considered series of halogen bonds defined by electron donors B: NH$_3$, CO, H$_2$S, H$_2$O, the following equations of $\varphi_{\text{PAEM}}^{\text{max}}$ vs $\delta$(B, Hal) have been found:

$$\varphi_{\text{PAEM}}^{\text{max}} = -0.30 - 1.05 \cdot \delta$(B, Hal),
$$

were B = H$_2$S; correlation coefficient r=0.98

$$\varphi_{\text{PAEM}}^{\text{max}} = -0.40 - 1.07 \cdot \delta$(B, Hal),
$$

B = NH$_3$; CO; r=0.98

$$\varphi_{\text{PAEM}}^{\text{max}} = -0.43 - 1.23 \cdot \delta$(B, Hal),
$$

B = H$_2$O; r=0.93

They have the high correlation coefficients and rather close slope angles (Figure 7) in the rows defined by the mentioned electron-donor molecules B.

Figure 7. The relationships between $\varphi_{\text{PAEM}}^{\text{max}}$ and electron delocalization indices $\delta$(B, Hal) for halogen bonds defined by electron donors: NH$_3$ and CO (a), H$_2$S (b), H$_2$O (c)
Asymmetry of ESP and PAEM barriers

The shape of $-\varphi_{ESP}$ and $\varphi_{PAEM}$ barriers show pronounced asymmetry along the halogen bonds. On the side of the electron donor atoms (N or C) (Figure 8 a,b), the $-\varphi_{ESP}$ function increases more steeply than it falls off on the side of the halogen atom in ClF or Cl$_2$ molecules, which are acceptors of electrons.

This observation can be interpreted as a manifestation of a more rigid repulsion of electrons by the inner electrostatic field of the system in the region between the electron-donor atom and the halogen bond center. The lower stiffness of the $-\varphi_{ESP}$ function from the side that faces halogen is explained as follows. In this region, the halogen nucleus is less shielded by electrons, and this assures the more effective attraction of an electron placed close to the center of the halogen bond to the halogen nucleus. The curvature of $\varphi_{PAEM}$ barrier is the opposite. The more sloping branch is observed from the side of electron lone pairs that face the electron-donor atoms (N, C) (Figure 8); and $\varphi_{PAEM}$ has steeper drop from the side of the $\sigma$-hole (Cl). In other words, the exchange and correlation influence the curvature of $\varphi_{PAEM}$ barrier along the halogen bonds: the exchange-correlation component of $\varphi_{PAEM}$ function not only substantially reduces the barrier itself, but also flattens it from the side of the electron-donor atom and makes it more rigid on the side of the electron-acceptor atom.

![Figure 8. Asymmetry of $\varphi_{PAEM}$ (blue) and $-\varphi_{ESP}$ (red) barriers a) for N…Cl and Cl–F bonds in H$_3$N…Cl–F complexes; b) for C…Cl and Cl–Cl bonds in O≡C…Cl–Cl complex. Atomic units are used](image-url)

Considering the polar and nonpolar bonds in complexes of Cl$_2$ and ClF molecules involved in halogen bonds with ammonia (Figure 8), we observe quite noticeable spacing between the Cl–F polar bond peak positions in $-\varphi_{ESP}$ and $\varphi_{PAEM}$; at the same time, this interval is almost imperceptible for the nonpolar bond Cl–Cl.

It is very instructive to compare the relative location of $-\varphi_{ESP}^{\text{max}}$ and $\varphi_{PAEM}^{\text{max}}$ extremes on the N…Cl–Cl and N…Cl–F halogen bond lines. For all these bonds, the positions of $-\varphi_{ESP}^{\text{max}}$ are always closer to the electron donor atom, while the positions of $\varphi_{PAEM}^{\text{max}}$ are located closer to the halogen atom. In addition, on the interatomic lines of all the halogen bonds, the location of $\varphi_{PAEM}^{\text{max}}$ is between $-\varphi_{ESP}^{\text{max}}$ and the BCP position of the electron density (see Table 2). Thus, the relative positions of $-\varphi_{ESP}^{\text{max}}$ and
The max extremes, namely, their order along interatomic line, can serve as a useful criterion for the halogen bond identification. The maximum of $\phi_{\text{PAEM}}^{\text{max}}$ is located closer to atom acting as the halogen bond donor; the maximum of $-\phi_{\text{ESP}}^{\text{max}}$, on the contrary, is closer to the halogen bond acceptor.

**Conclusions**

In this work, we carefully compared the behavior of the two functions, the electrostatic potential, $\phi_{\text{ESP}}$, and the potential acting on an electron in a molecule, $\phi_{\text{PAEM}}$, with attention to their applicability for the halogen bond characterization. Considering the series of isolated dihalide molecules, we have found that the account for the Kohn-Sham exchange interaction in $\phi_{\text{PAEM}}$ does not distort the specific manifestation of the anisotropy of the electrostatic potential mapped on the around-molecule isosurface of the electron density, which is commonly used for explanation the halogen bonding in the form of $\sigma$-hole concept. The negative extremes on the $\sigma$-holes in PAEM decrease from iodine to fluorine. The $\sigma$-hole of fluorine holds electrons better than for the other halogens due to the combine d action of the exchange and electrostatic effects. It is interesting, that only for the fluorine this attraction on the $\sigma$-hole is stronger than that on its belt.

Distributions of $-\phi_{\text{ESP}}$ and $\phi_{\text{PAEM}}$ mapped on the isosurfaces of the electron density around the bound molecules in complexes show very similar patterns, which, nevertheless, reflect the anisotropy of these functions for the halogen atoms. Considering $-\phi_{\text{ESP}}$ and $\phi_{\text{PAEM}}$ on the different sides of the RDG closed isosurfaces, we have noted that the significantly lower negative values are observed from the side of halogen, which acts as an acceptor of the electron density. For the halogen bonds in complexes B...ClF, B...Cl2, B...BrCl, B...Br2, B...ICl, where B = NH3, H2O, H2S, CO, the account for the exchange and correlation of electrons significantly reduces the PAEM barriers, $\phi_{\text{PAEM}}^{\text{max}}$, in comparison with the $-\phi_{\text{ESP}}^{\text{max}}$. The values of $\phi_{\text{PAEM}}^{\text{max}}$ correlate with the electron delocalization indices; corresponding equations have been found. We have also revealed that the opposite curvatures of $-\phi_{\text{ESP}}$ and $\phi_{\text{PAEM}}$ distributions are observed along the halogen bonds. From the side of the electron donor atoms, the $-\phi_{\text{ESP}}$ function increases more steeply than it drops from the side of the halogen atoms, which are acceptors of electrons. The location of $\phi_{\text{PAEM}}^{\text{max}}$ is closer to the atom acting as a halogen bond donor; the position of $-\phi_{\text{ESP}}^{\text{max}}$, on the contrary, is closer to a halogen bond acceptor. Thus, the relative positions of $-\phi_{\text{ESP}}$ and $\phi_{\text{PAEM}}$ can serve as a criterion for the halogen-bond donor identification in the pair of atoms.

Thus, the $\phi_{\text{PAEM}}$ function is a useful tool for characterization the features of halogen bonds, for the quantitative comparison of their strength and for identification, what atom in the bound pair is the electron acceptor. The joint analysis of the ESP and PAEM functions enriches the vision of atomic predispositions to the halogen bond formation as well as the others non-covalent interactions.

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**Keywords:** electrostatic potential, potential acting on an electron in a molecule, non-covalent interactions, reduced density gradient, halogen bond

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Additional Supporting Information may be found in the online version of this article.
References and Notes

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A COMPARATIVE VIEW ON THE POTENTIAL ACTING ON AN ELECTRON IN A MOLECULE AND THE ELECTROSTATIC POTENTIAL THROUGH THE TYPICAL HALOGEN BONDS

The joint analysis of the potential acting on an electron in a molecule (PAEM) and the electrostatic potential (ESP) expands the tools for halogen bond studying within the σ-hole concept. The curvatures of PAEM and ESP distribution along the halogen bond are opposite. For a typical halogen bond, PAEM mapped on the isosurface of the reduced density gradient from the side of halogen is differed from one on the side of the electron donor atom.

GRAPHICAL ABSTRACT FIGURE ((Please provide a square image to be produced at 50 mm wide by 50 mm high. Please avoid graphs and other figures with fine detail due to the relatively small size of this image.))