

Naming Interactions from the Electrophilic Site

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1. INTRODUCTION

In the last few decades, chemical crystallography in general and crystal engineering in particular allowed for a deeper and more subtle understanding of noncovalent interactions, their nature, and their roles. New findings and concepts emerged, and new terms have been proposed to convey them. The supramolecular synthon¹ is a prototypal example, the success of the term being a consequence of the usefulness of the communicated concept. Several other examples could be given.²

Various terms appeared in the literature to designate specific classes, and subclasses, of noncovalent interactions, and in this Perspective we propose a general terminology for all interactions wherein it is possible to identify an element, or moiety, working as the electrophile. This general terminology has been developed by extending the application of a criterion used in the recent definition recommended by IUPAC for the halogen bond.³ The same criterion underlies the definition recommended by IUPAC for the hydrogen bond.⁴ Some terms already used in the literature are in keeping with our proposed extension, and they will be discussed or mentioned before formulating our proposal in order to contextualize it. To substantiate our generalization, a comparatively greater attention will be given to cases where the application of the proposed terminology may be less straightforward (e.g., when fewer precedents from the literature endorse it). When applicable, the proposed convention may offer the advantage of affording a single and unambiguous term for any given interaction. The resulting classification of interactions mimics the classification of elements in the Periodic Table. Throughout this manuscript, the word bond is used as a synonym of interaction as "There is a chemical bond between two atoms or groups of atoms in the case that the forces acting between them are such as to lead to the formation of an aggregate with sufficient stability to make it convenient for the chemist to consider it as an independent 'molecular species'".⁵

2. TOWARD A SYSTEMATIC AND COHERENT TERMINOLOGY

2.1. The Need for an Unambiguous Naming. Hydrogen atoms from a molecule or a molecular fragment Y–H in which Y is more electronegative than H, (e.g., Y = O, N) occasionally form short Y–H···X–R contacts with halogen atoms (X = F, Cl, Br, I; R = C, metal).⁶ In these interactions hydrogen atoms are the positive sites and enter preferentially the region of higher electron density on the electrostatic potential surface of the halogen.⁷ Consistent with the recent definition of hydrogen bond⁴ and previous definitions, these interactions have to be named hydrogen bonds. While their occurrence was recognized by A. Hantzsch as early as in 1915,⁸ they began to be named hydrogen bonds only 40 years later.⁹ The use of this terminology then continued,⁵ but it has been proposed that these interactions can also be named halogen bonds as halogen atoms are involved.¹⁰ A bond obviously involves at least two atoms, but confusion may arise if it is agreed an interaction can be named referring interchangeably to any of them. In the above considered case, hydrogen bond⁴ and halogen bond³ have orthogonal geometric requirement,¹¹ a given interaction adopts either of the two geometries, and the name denoting it has to be unambiguous on this issue. If an interaction can be named referring interchangeably to any of the involved atoms, one of the names delivers wrong geometric information, while if interactions are named referring to the electrophilic ending, as proposed here, no contradiction is possible.¹²

2.2. Hydrogen Bond and Halogen Bond. The term hydrogen bond⁴ is applicable to a quite wide diversity of systems, from HF₂[−] to C–H···π systems. A distinctive requirement for a noncovalent interaction formed by a Y–H fragment to be named hydrogen bond is that Y is more

Received: January 30, 2014

Revised: April 10, 2014

Published: April 15, 2014

electronegative than H, namely, that H functions as electrophilic site.

Halogen atoms have long been considered neutral spheres in dihalogens and negative spheres in halocarbons (as the electronegativity of halogens is higher than carbon). But in the last few decades, it became apparent that the distribution of the electron density in covalently bound halogen atoms is anisotropic¹³ and an amphoteric character results (Figure 1).

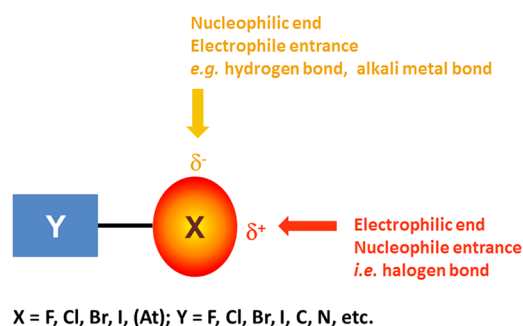


Figure 1. Schematic representation of the anisotropic distribution of the electron density around covalently bound halogen atoms and the pattern of the resulting interactions.

Specifically, dihalogens and organohalogen derivatives show a belt perpendicular to the covalent bond where the electrostatic potential is most negative. Electrophiles enter this region, and if the electrophile is a hydrogen atom, a hydrogen bond is formed. A cap of lower electron density where the electrostatic potential is frequently positive (the so-named σ -hole) is present on the elongation of the covalent bond formed by the halogen. Lone pair possessing atoms, π -systems, and anions can all enter this positive region, and the resulting interactions are halogen bonds.³ Also the term halogen bond is applicable to a quite wide diversity of systems, spanning I_3^- and the dihalogen...benzene adducts, and the essential requirement for an attractive interaction to be named halogen bond is that the halogen atom is the electrophile (Figure 1).

2.3. From Halogen Bond to Chalcogen Bond. Covalently bound sulfur had been observed, more than 40 years ago, to form directional short contacts with both electrophiles and nucleophiles,¹⁴ the former entering preferentially lateral to the covalent bonds, the latter on the elongations of the covalent bonds. The mindset developed in relation to the halogen bond studies favored the rationalization of the attractive interactions that the elements of the Group 16 form with nucleophiles as the result of an overlooked anisotropic distribution of the electron density around sulfur and other Group 16 elements.¹⁵ It has been recognized that, similar to halogen atoms, the electrostatic potential surface in covalently bound chalcogens is most negative lateral to their bonds and electrophiles preferentially enter this region. Conversely, the electrostatic potential is most positive on the elongation of the covalent bonds, and nucleophiles preferentially enter here (Figure 2). The distribution of the electron density of selenium and tellurium is more anisotropic than that of sulfur, and the more polarizable the chalcogen atom is, the stronger the interactions with nucleophiles are. The name chalcogen bond¹⁵ has been employed to designate the interactions wherein elements of the Group 16 function as the electrophilic site.

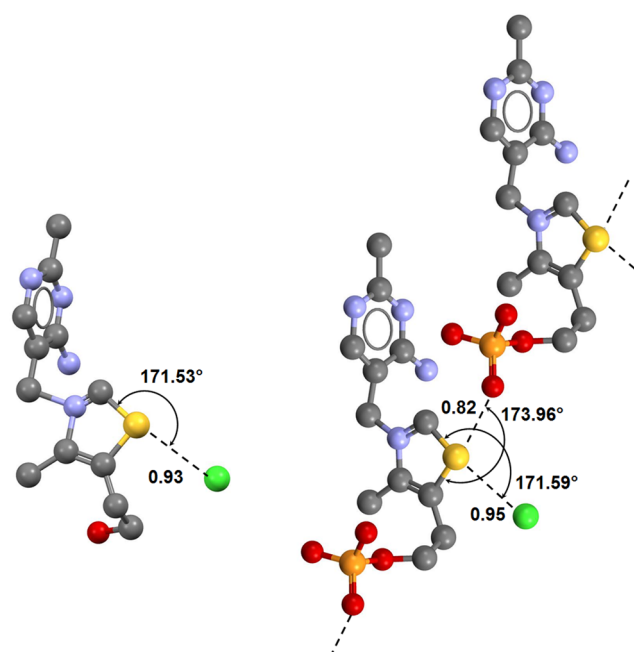


Figure 2. Short and directional chalcogen bonds formed in the solid by the sulfur atom of two derivatives of thiamin, a vitamin of the B complex, on the elongation of one (THIMHC, ref 15k, left) or both (MEMKEU, ref 15l, right) its covalent bonds. Hydrogen atoms have been omitted, chalcogen bonds are dotted lines, and digits are C-S...nucleophile angle (deg) and normalized length of the chalcogen bonds with respect to the sum of van der Waals radius of S and Pauling ionic radius of the entering anion. Color codes: gray, carbon; blue, nitrogen; red, oxygen; green, chlorine; orange, phosphorus; yellow, sulfur.

2.4. From Chalcogen Bond to Pnictogen (Pnicogen) and Tetrrel Bonds. The mindset developed in relation to halogen bond studies allowed the understanding that the anisotropic distribution of the electron density in bound atoms is a quite general phenomenon. Areas of lower electron density, with an often positive electrostatic potential, are present at the surface of many elements along with areas of higher electron density, where the electrostatic potential is negative. The resulting amphoteric behavior is a common event for an element, rather than an exception.

Recent theoretical and experimental studies identified the structural features that increase the electrophilic character of elements of Groups 15 and 14 and allow this character to result in the formation of attractive interactions. Phosphorus, arsenic, and antimony derivatives bearing strong electron withdrawing residue(s) at the Group 15 element attractively interact with electron donor partners thanks to the presence of area(s) with a positive electrostatic potential opposite to the bond(s) to the electron withdrawing residue(s).¹⁶

Group 14 elements show a similar behavior (Figure 3).¹⁷ For instance, SiF_4 and tetramethylethylenediamine give a 1:1 solid adduct,¹⁸ and its structure can be explained via the entrance of the nitrogen lone pairs in the positive σ -holes on silicon. Experimental results show that also germanium and tin attractively interact with lone pair possessing atoms and anions¹⁹ and, similar to halogens, chalcogens, and pnictogens, the more polarizable the Group 14 element is, the more favorable the interaction energies are. Nevertheless, indications suggest that also carbon atoms may attractively interact with nucleophiles opposite to a highly electronegative substituent,

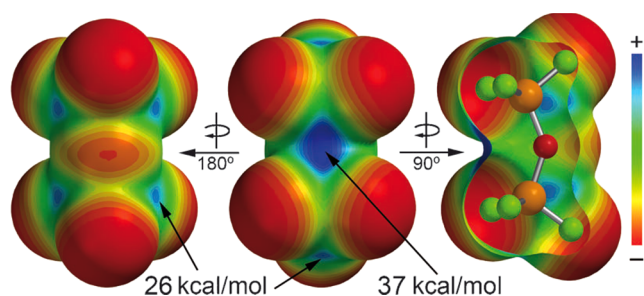


Figure 3. Molecular electrostatic potential surface (MEPS) for $F_3Si-O-SiF_3$. There are four equivalent σ -holes at one side of the molecule (left) and two σ -holes at both ends of the molecule (middle). The most positive part of the MEPS (37 kcal mol^{-1}) is found opposite to the four equivalent σ -holes as a consequence of the superposition of two σ -holes along the bisectrix of the Si-O-Si angle (right) (reprinted with permission from ref 19; copyright 2013 Wiley).

namely, where a positive electrostatic potential is present on their surface.²⁰

With intentional analogy with halogen and chalcogen bonds, the names pnictogen (or pnicogen) bond and tetrel bond^{16–20} have been proposed for the interactions where elements of Group 15 and 14 are the electrophile. These terms, while quite recently proposed, seem to have received a fair acceptance by the scientific community.²¹

2.5. Referring to the Electrophilic Atom. We have discussed above some cases from the literature where interactions are named by referring to the name of the Group of the Periodic Table the element at the electrophilic site belongs to. Numerous cases are reported also where interactions are named by referring specifically to the element at the electrophilic site. The oldest cases date back several decades ago. Focusing on the electrophilic ending in order to name interactions seems to have time-honored precedents.

“The lithium bond” was the title of a paper by Kollmann et al. where, in 1970, calculations predicted that lithium can accept electron density from a suitable electron-rich partner to form an interaction “analogous to hydrogen bonding”.²² Decisive evidence of the lithium bond was reported by Pimentel et al. five years later²³ as a part of studies aimed at proving that some elements give interactions similar to hydrogen bond. More recently $Na^+ \cdots \pi$ interactions have been named the sodium bond.²⁴ The binding of halide anions to beryllium in $BeCl_2$ (to form the $BeCl_2X^-$ adducts, $X = Cl, Br, I$) has been designated as the beryllium bond.²⁵ The attractive interaction between nucleophiles and the positive region on aliphatic carbon atoms bearing an electron-withdrawing residue has been named the carbon bond.^{19,20,26} The terms fluorine bond,²⁷ chlorine bond,²⁸ bromine bond,²⁹ and iodine bond³⁰ have been used to designate the specific sets of interactions formed when the respective halogen atoms attractively interacts with an electron rich partner. Other literature cases of interactions named by referring to the element working as the electrophile are listed in Figure 4 that itemizes attractive interactions formed by the electrophilic element after a hierarchical and periodic scheme.

A nomenclature of interactions based on the name of the Group the electrophilic element belongs to may present advantages with respect to a nomenclature based on the name of the involved electrophilic element. First, a proliferation of terms is avoided; second, the understanding of a variety of interactions is enabled within a periodic frame. In other words,

the Group-based terminology gives the possibility to understand the features of the interaction $Y-X \cdots Z$ ($Y =$ any group, $X =$ electrophilic element, $Z =$ nucleophile) by considering not only the trends observed on changing Y while X and Z remain the same, or on changing Z while Y and X remain the same, but also by considering the trends observed on varying X while Y and Z remain unchanged.

3. NAMING INTERACTIONS FROM THE ELECTROPHILE

Consistency is a value in any field of science, and the terminology used for noncovalent interactions has to be as consistent as possible. The hydrogen bond makes an inescapable precedent when the issue of interactions naming is addressed and a hydrogen bond identifies only those interactions where the hydrogen atom is the positive site.⁴ Similarly, a halogen bond identifies only those interactions where halogen atoms are the positive sites, and several interactions have been designated by focusing on the element which functions as the electrophile. In this Perspective we propose to generalize this “polar approach”, namely, *it is proposed to name noncovalent interactions by referring, whenever convenient or possible, to the name of the Group of the Periodic Table the electrophilic atom belongs to.*³¹

The proposed generalization aims at giving a criterion to assign a single and unambiguous name to all interactions wherein one of the interacting sites functions as the electrophile (and the other as the nucleophile). We discuss below how this can be the case for most of the attractive interactions given by elements of Groups 1, 2, 13–17. An unambiguous identification of the electrophilic and nucleophilic endings is also possible in many interactions given by elements of the d- and f-blocks, for instance, when the respective cations have water or a podand, crown ether, or cryptand in their first coordination sphere. But in other interactions involving d- and f-block elements such an identification is not possible. This is the case, for instance, in metallophilic interactions, typically exemplified by gold–gold bonds, or when back-donation occurs, as in the bonds between some π -conjugated ligands and transition metals. These are typical interactions where our proposed convention should not be applied to. It is out of the scope of this paper to suggest, or to discuss, the application of our proposed terminology to the bonds formed by elements of the d- and f-blocks. An opinion and a consensus on this possible application, the limits it should be given and the advantages it may offer, might emerge in the future after a thorough discussion in the scientific community.

According to the IUPAC definition, “An electrophile (or electrophilic reagent) is a reagent that forms a bond to its reaction partner (the nucleophile) by accepting both bonding electrons from that reaction partner”.³² This is clearly the case for a halogen atom in a halogen bond³ and a hydrogen atom in a hydrogen bond,⁴ but it is not the case for interactions involving the hydrogen atom of a hydride. Halogen atoms can form attractive interactions also by donating electron density from one of their free lone pairs to their partner which, according to the proposed convention, gives the name to the interaction since working as the electrophile. As discussed in paragraph 2.1, donation of electron density can occur from halogen to hydrogen, and the resulting attractive interactions have to be named hydrogen bonds. Similarly, alkali³³ and alkaline earth³⁴ metal cations form short contacts with halogen atoms by entering their negative belt, namely, by functioning as the electrophilic ending of the interaction, which might thus be

Group 1	Group 2	Group 13	Group 14	Group 15	Group 16	Group 17	Group 18
Hydrogen bond (a)							
Alkali metal bond	Alkaline earth metal bond	Icosagen bond	Tetrel bond (p)	Pnictogen bond (u)	Chalcogen bond (w)	Halogen bond (dd)	
Li Lithium (b)	Be Beryllium (g)	B Boron (l)	C Carbon (q)	N Nitrogen (v)	O Oxygen (z)	F Fluorine (ee)	
Na Sodium (c)	Mg Magnesium (h)	Al Aluminium (m)	Si Silicon (r)	P Phosphorus (x)	S Sulfur (aa)	Cl Chlorine (ff)	
K Potassium (d)	Ca Calcium (i)	Ga Gallium (n)	Ge Germanium (s)	As Arsenic (x)	Se Selenium (bb)	Br Bromine (gg)	
Rb Rubidium (e)	Sr Strontium (j)	In Indium (o)	Sn Tin (t)	Sb Antimony (y)	Te Tellurium (cc)	I Iodine (hh)	
Cs Caesium (f)	Ba Barium (k)	Tl Thallium (n)	Pb Lead	Bi Bismuth	Po Polonium	At Astatine	
Fr Francium	Ra Radium		Fl Flerovium		Lv Livermorium		

(a) E. Arunan, G. R. Desiraju, R. A. Klein, J. Sadlej, S. Scheiner, I. Alkorta, D. C. Clary, R. H. Crabtree, J. J. Dannenberg, P. Hobza, H. G. Kjaergaard, A. C. Legon, B. Mennucci, D. J. Nesbitt, *Pure Appl. Chem.* **2011**, *83*, 1637–1641; *Pure Appl. Chem.* **2011**, *83*, 1619–1636. (b) Y. Feng, L. Liu, J.-T. Wang, X.-S. Li, Q.-X. Guo, *Chem. Comm.* **2004**, 88–89. (c) R. D. Rogers, C. B. Bauer, *Comprehensive Supramolecular Chemistry*, J. L. Atwood, J. E. D. Davies, D. D. Macnicol, F. Vogtle, Eds., Pergamon, Oxford, 1996, vol. 1, pgg. 315–356 and refs cited therein. (d) T. Watanabe, A. Ohtsuka, N. Murase, P. Barth, K. Gersonde, *Magn. Reson. Med.* **1996**, *35*, 697–705. (e) J. J. Mooij, A. A. K. Klaassen, E. de Boer, H. M. L. Degens, T. E. M. van den Hark, J. H. Noordik, *J. Am. Chem. Soc.* **1976**, *98*, 680–685. (f) R. Assmus, V. Bohmer, J. M. Harrowfield, M. I. Ogden, W. R. Richmond, B. W. Skelton, A. H. White, *J. Chem. Soc., Dalton Trans.* **1993**, 2427–2433. (g) Yáñez, M.; Móa, O.; Alkorta, I.; Elguero, J. *Chem. Eur. J.* **2013**, *19*, 11637–11643. (h) P. R. Markies, T. Nomoto, O. S. Akkerman, F. Bickelhaupt, W. J. J. Smeets, A. L. Spek, *J. Am. Chem. Soc.* **1988**, *110*, 4845–4846. (i) J. P. Räsänen, E. Pohjala, H. Nikander, T. A. Pakkanen, *J. Phys. Chem. A* **1997**, *101*, 5196–5204. (j) L. N. Appelhans, M. Kosa, A. V. Radha, P. Simoncic, A. Navrotsky, M. Parinello, A. K. Cheatham, *J. Am. Chem. Soc.* **2009**, *131*, 15375–15386. (k) C. J. Baylies, L. P. Harding, J. C. Jeffery, R. Moon, C. R. Rice, T. Riis-Johannessen, *New J. Chem.* **2007**, *31*, 1527–1531. (l) W. T. Klooster, T. F. Koetzle, P. E. M. Siegbahn, T. B. Richardson, R. H. Crabtree, *J. Am. Chem. Soc.* **1999**, *121*, 6337–6343. (m) J. L. Atwood, D. C. Hencir, R. D. Rogers, J. A. K. Howard, *J. Am. Chem. Soc.* **1981**, *103*, 6787–6788. (n) F. Thomas, T. Bauer, S. Schulz, M. Nieger, Z. *Anorg. Allg. Chem.* **2003**, *629*, 2018–2027. (o) K. M. Coward, A. C. Jones, A. Steiner, J. F. Bickley, L. M. Smith, M. E. Pemble, *J. Chem. Soc., Dalton Trans.* **2001**, 41–45. (p) A. Bauz, T. J. Mooibroek, A. Frontera, *Angew. Chem. Int. Ed.* **2013**, *52*, DOI: 10.1002/anie.201306501. (q) D. Mani, E. Arunan, *Phys. Chem. Chem. Phys.* **2013**, *15*, 14377–14383. (r) P. Politzer, J. S. Murray, P. Lane, M. C. Concha, *Int. J. Quantum Chem.* **2009**, *109*, 3773–3780. (s) K. Iwanaga, J. Kobayashi, T. Kawashima, N. Takagi, S. Nagase, *Organometallics* **2006**, *25*, 3388–3393. (t) H. Schumann, Y. Aksu, S. Schutte, B. C. Wassermann, S. H. Muhle, *J. Organomet. Chem.* **2006**, *691*, 1703–1712. (u) S. Scheiner, *Acc. Chem. Res.* **2013**, *46*, 280–288. (v) J. S. Murray, P. Lane, P. Politzer, *Int. J. Quantum Chem.* **2007**, *107*, 2286–2292. (x) S. Zahn, R. Frank, E. Hey-Hawkins, B. Kirchner, *Chem.–Eur. J.* **2011**, *17*, 6034–6038. (y) A. Bauzá, D. Quiñero, P. M. Deyá, A. Frontera, *CrystEngComm* **2013**, *15*, 3137–3144. (w) T. Clark, J. S. Murray, P. Lane, P. Politzer, *J. Mol. Model.* **2008**, *14*, 689–697. (z) J. S. Murray, P. Lane, T. Clark, P. Politzer, *J. Mol. Model.* **2007**, *13*, 1033–1038. (aa) K. Kanoh, Y. Matsuo, K. Adachi, H. Imagawa, M. Nishizawa, Y. Shizuri, *J. Antibiot.* **2005**, *58*, 289–292. (bb) B. M. Goldstein, F. Takusagawa, H. M. Berman, P. C. Srivastava, R. K. Robins, *J. Am. Chem. Soc.* **1983**, *105*, 7416–7422. (cc) B. J. Farran, L. Torres-Castellanos, A. Alvarez-Larena, J. F. Piniella, M. V. Capparelli, *J. Organomet. Chem.* **2002**, *54*, 91–99. (dd) G. R. Desiraju, P. S. Ho, L. Kloo, A. C. Legon, R. Marquardt, P. Metrangolo, P. Politzer, G. Resnati, K. Rissanen, *Pure Appl. Chem.* **2013**, *35*, 1711–1713. (ee) C. Laurence, J. Graton, J.-F. Gal, *J. Chem. Educ.* **2011**, *88*, 1651–1657. (ff) B. Raghavendra, E. Arunan, *J. Phys. Chem. A* **2007**, *111*, 9699–9706. (gg) S. V. Rosokha, I. S. Neretin, T. Y. Rosokha, J. Hecht, J. K. Kochi, *Heteroatom Chem.* **2006**, *17*, 449–459. (hh) C. Laurence, J. Graton, M. Berthelot, M. J. El Ghomari, *Chem.–Eur. J.* **2011**, *17*, 10431–10444.

Figure 4. Classification, after the proposed convention, of interactions formed by elements of Groups 1, 2, 13–17 of the Periodic Table. Color code for interactions: carmine, the term is recommended by IUPAC; blue, the term is used in the literature with the meaning proposed here; light blue, other cases. Color code for elements: dark green, the element is the electrophile in interactions named, in the literature, referring to the name of the element itself; green, adducts are reported in the literature wherein the element functions as the electrophile; light green, it is expected, but not yet documented, the element can function as the electrophile in attractive interactions. The assigned color code for the elements is provisional, and a comprehensive search of the literature (which is out of the scope of this Perspective) may ask for a change (from green to dark green, from light green to green or dark green). Papers are reported in the footnotes wherein IUPAC definitions are given (carmine); interactions given by the elements of the Group are named after the proposed convention (blue); the corresponding element functions as the electrophile in attractive interactions which have been designated using the name of the element (dark green); the corresponding element functions as the electrophile in attractive interactions (green).

named alkali metal bond and alkaline earth metal bond, respectively. The same terms might be used to denote any other attractive interaction formed when these metal cations enter atoms or moieties donating electron density. For instance, the $K^+ \cdots \pi$ -system, $Na^+ \cdots \pi$ -system, $Li^+ \cdots O$, and $Na^+ \cdots N$ interactions occurring when the cations are coordinated by a calixarene, water, a crown ether, or a cryptand might be designated alkali metal bonds and the $Mg^{2+} \cdots O$, $Ca^{2+} \cdots O$, and $Ba^{2+} \cdots N$ interactions formed by the same coordinating species might be denoted alkaline earth metal bonds.

According to the IUPAC definition, boron is the electrophile in the adducts formed with Lewis bases (e.g., π -systems, lone pair possessing atoms, and anions),³⁵ and the same holds for

other elements of Group 13 in most of the corresponding adducts.³⁶ Contacts in these complexes are usually as short as standard covalent bonds, but some other features (e.g., the length change of a given contact between solid and gas phases) are unusual for covalent bonds and are the fingerprint of a noncovalent interaction. According to the convention proposed here, these interactions should be named icosagen bond.

It is already a common practice to name some of the interactions formed by elements of Groups 14–16 in keeping with the proposed convention. This is typically the case when Groups 15 and 16 elements share a lone pair with a proton, the resulting interactions being hydrogen bonds. As mentioned above, attractive interactions occurring when the same elements

share a lone pair with an alkali or alkaline earth metal cation might be named alkali metal bond and alkaline earth metal bond, respectively. We have also discussed how elements of Groups 14–16 function, in some interactions, as the electrophile and the terms tetrel bond, pnictogen bond, and chalcogen bond have been proposed for these interactions in analogy to the term halogen bond. Our proposed convention aims at endorsing the use of these terms for the interactions wherein the elements of the respective Groups are the electrophilic sites.

4. PERIODICITY IN ATTRACTIVE INTERACTIONS

The distribution of the electron density in different elements shows systematic changes. These regular variations are at the basis of the organization of the elements in Groups and Periods in the Periodic Table. They are also responsible for the trends shown by some properties when moving from one element to the adjacent ones in a Group or a Period. Electrophilicity and other properties affecting the interactions given by an atom (e.g., Lewis acidity/basicity, polarizability, and hardness/softness in the context of HSAB theory) show specific trends. By linking the name of attractive interactions to the Group of the element at the electrophilic site, interactions are organized after a scheme where periodicities can be easily identified. In other words, the trends in electrophilicity of the elements (and in related properties affecting interactions) are linked to and translated into periodic features of the interactions formed by the elements.

5. CONCLUSIONS

The systematic naming resulting from the convention proposed offers the advantage of affording a single and unambiguous term for any given interaction by generalizing a criterion which is used in the IUPAC definition of halogen bond³ and underlies the IUPAC definition of hydrogen bond.⁴ The proposed terminology allows a hierarchy of interactions to be developed.

In fact, the interactions sets identified by terms referring to the name of the electrophilic element are subsets of the interactions sets identified by terms referring to the name of the Group the electrophilic element belongs to. For instance, the chlorine bond, bromine bond, and iodine bond are subsets of the halogen bond; the lithium bond and the calcium bond are subsets of the alkali metal bond, and the alkaline earth metal bond, respectively, the carbon bond is a subset of the tetrel bond.

Generality and specificity are valuable features for a scientific concept as the former enables its wide applicability and the latter for predicting specific phenomena. Unfortunately these two features tend to be mutually exclusive, and a scientific concept typically increases its effectiveness when it succeeds in conveniently balancing them. The same is true also for the terminology used to enunciate a concept, and we have structured the convention proposed in this Perspective in order to secure both a wide applicability (i.e., generality) and a robust descriptive power (i.e., specificity). On one side, the identified term conveys specific information on the polar character of the interaction, the associated geometric features, the changes in some interaction properties if the electrophilic atom is changed, etc. On the other side, the proposed generalization encompasses the majority of the attractive interactions formed by the elements of Groups 1, 2, 13–17, and it may be fruitfully used for other interactions having a polar character which enables an unambiguous identification of

the electrophilic, namely, positive, and the nucleophilic, namely, negative, endings.³⁷

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors are grateful to the IUPAC for supporting Project No. 2009-032-1-100 “Categorizing Halogen Bonding and Other Noncovalent Interactions Involving Halogen Atoms”.

REFERENCES

- (1) Desiraju, G. R. *Angew. Chem., Int. Ed.* **1995**, *34*, 2311–2327.
- (2) Aakeröy, C. B.; Chopade, P. D.; Desper, J. *Cryst. Growth Des.* **2011**, *11*, 5333–5336. Aakeröy, C. B.; Champness, N. R.; Janiak, C. *CrystEngComm* **2010**, *12*, 22–43.
- (3) Desiraju, G. R.; Ho, P. S.; Kloo, L.; Legon, A. C.; Marquardt, R.; Metrangolo, P.; Politzer, P.; Resnati, G.; Rissanen, K. *Pure Appl. Chem.* **2013**, *35*, 1711–1713.
- (4) Arunan, E.; Desiraju, G. R.; Klein, R. A.; Sadlej, J.; Scheiner, S.; Alkorta, I.; Clary, D. C.; Crabtree, R. H.; Dannenberg, J. J.; Hobza, P.; Kjaergaard, H. G.; Legon, A. C.; Mennucci, B.; Nesbitt, D. J. *Pure Appl. Chem.* **2011**, *83*, 1637–1641; *Pure Appl. Chem.* **2011**, *83*, 1619–1636. Jeffrey, G. A.; Saenger, W. *Hydrogen Bonding in Biological Structures*; Springer-Verlag: Berlin, 1991 and references cited therein.
- (5) Burrows, H.; Weir, R.; Stohner, J. *Pure Appl. Chem.* **1994**, *66*, 1089–1098.
- (6) Brammer, L.; Bruton, E. A.; Sherwood, P. *Cryst. Growth Des.* **2001**, *1*, 277–290.
- (7) Metrangolo, P.; Resnati, G. *Chem. Commun.* **2013**, *49*, 183–1785. Aullón, G.; Bellamy, D.; Brammer, V.; Bruton, E. A.; Orpen, A. G. *Chem. Commun.* **1998**, 653–654.
- (8) Hantzsch, A. *Chern. Ber.* **1915**, *48*, 797–816.
- (9) Akamotomo, K.; Margoshes, M.; Rundle, R. E. *J. Am. Chem. Soc.* **1955**, *77*, 6480–6486. von R. Schleyer, P.; West, R. *J. Am. Chem. Soc.* **1959**, *81*, 3164–3165.
- (10) Glaser, R.; Murphy, R. F. *CrystEngComm* **2006**, *8*, 948–951.
- (11) Voth, A. R.; Khuu, P.; Oishi, K.; Ho, P. S. *Nat. Chem.* **2009**, *1*, 74–79.
- (12) This would be the case also on agreeing to name interactions referring to the nucleophilic ending, but this requires the IUPAC definitions of hydrogen bond and halogen bond are reformulated.
- (13) Murray, J. S.; Paulsen, K.; Politzer, P. *Proc. Indian Acad. Sci. Ser. Chim.* **1994**, *106*, 267–275. Brinck, T.; Murray, J. S.; Politzer, P. *Int. J. Quantum Chem.* **1992**, *44* (Suppl. 19), 57–64. Brinck, T.; Murray, J. S.; Politzer, P. *Int. J. Quantum Chem.* **1993**, *48* (Suppl. 20), 73–88.
- (14) Kapecki, J. A.; Baldwin, J. E. *J. Am. Chem. Soc.* **1969**, *91*, 1120–1123. Rosenfield, R. E., Jr.; Parthasarathy, R.; Dunitz, J. D. *J. Am. Chem. Soc.* **1977**, *99*, 4860–4862. Guru Row, T. N.; Parthasarathy, R. *J. Am. Chem. Soc.* **1981**, *103*, 477–479.
- (15) (a) Murray, J. S.; Lane, P.; Clark, T.; Politzer, P. *J. Mol. Model.* **2007**, *13*, 1033–1038. (b) Clark, T.; Murray, J. S.; Lane, P.; Politzer, P. *J. Mol. Model.* **2008**, *14*, 689–697. (c) Politzer, P.; Murray, J. S.; Concha, M. C. *J. Mol. Model.* **2008**, *14*, 659–665. (d) Murray, J. S.; Lane, P.; Politzer, P. *Int. J. Quantum Chem.* **2008**, *108*, 2770–2781.
- (16) Wang, W.; Ji, B.; Zhang, Y. *J. Phys. Chem. A* **2009**, *113*, 8132–8135. (f) Shishkin, O. V.; Omelchenko, I. V.; Kalyuzhny, A. L.; Paponov, B. V. *Struct. Chem.* **2010**, *21*, 1005–1011. (g) Metrangolo, P.; Resnati, G. *Nat. Chem.* **2012**, *4*, 437–438. (h) Li, Q.-Z.; Li, R.; Guo, P.; Li, H.; Li, W.-Z.; Cheng, J.-B. *Comput. Theor. Chem.* **2012**, *980*, 56–61. (i) Politzer, P.; Riley, K. E.; Bulat, F. A.; Murray, J. S. *Comput. Theor. Chem.* **2012**, *998*, 2–8. (j) Bauzá, A.; Quiñero, D.; Deyà, P. M.; Frontera, A. *CrystEngComm* **2013**, *15*, 3137–3144.

(k) Watanabe, A.; Tasaki, S.; Wada, Y.; Nakamachi, H. *Chem. Pharm. Bull.* **1979**, *27*, 2751–2759. (l) Hu, N.-H.; Liu, W.; Aoki, K. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 1043–1052.

(16) Murray, J. S.; Lane, P.; Politzer, P. *Int. J. Quantum Chem.* **2007**, *107*, 2286–2292. Politzer, P.; Murray, J. S.; Lane, P. *Int. J. Quantum Chem.* **2007**, *107*, 3046–3052. Zahn, S.; Frank, R.; Hey-Hawkins, E.; Kirchner, B. *Chem.–Eur. J.* **2011**, *17*, 6034–6038. Li, Q.-Z.; Li, R.; Liu, X.-F.; Li, W.-Z.; Cheng, J.-B. *ChemPhysChem* **2012**, *13*, 1205–1212. Adhikari, U.; Scheiner, S. *Chem. Phys. Lett.* **2012**, *532*, 31–35. Scheiner, S. *Acc. Chem. Res.* **2013**, *46*, 280–288.

(17) Politzer, P.; Murray, J. S.; Lane, P.; Concha, M. C. *Int. J. Quantum Chem.* **2009**, *109*, 3773–3780. Murray, J. S.; Lane, P.; Politzer, P. *J. Mol. Model.* **2009**, *15*, 723–729. Politzer, P.; Murray, J. S. *ChemPhysChem* **2013**, *14*, 278–294. Bundhun, A.; Ramasami, P.; Murray, J. S.; Politzer, P. *J. Mol. Model.* **2013**, *19*, 2739–2746.

(18) Cheng, F.; Hector, A. L.; Levason, W.; Reid, G.; Webster, M.; Zhang, W. *Chem. Commun.* **2009**, 1334–1336.

(19) Bauz, A.; Mooibroek, T. J.; Frontera, A. *Angew. Chem., Int. Ed.* **2013**, *52*, 12317–12321.

(20) Mani, D.; Arunan, E. *Phys. Chem. Chem. Phys.* **2013**, *15*, 14377–14383. Thomas, S. P.; Pavan, M. S.; Guru Row, T. N. *Chem. Commun.* **2014**, *50*, 49–51.

(21) Kemsley, J. *Chem. Eng. News* **2014**, 92 (6 January), 25–26.

(22) Kollman, P. A.; Liebman, J. F.; Allen, L. C. *J. Am. Chem. Soc.* **1970**, *92*, 1142–1150.

(23) Ault, B. S.; Pimentel, G. C. *J. Phys. Chem.* **1975**, *79*, 621–626.

(24) Li, Z.; Zhang, X.; Li, H.; Zhu, Y.; Yang, X. *Chem. Phys. Lett.* **2011**, *510*, 273–277.

(25) Yáñez, M.; Móa, O.; Alkorta, I.; Elguero, J. *Chem. Phys. Lett.* **2013**, *590*, 22–26. Yáñez, M.; Móa, O.; Alkorta, I.; Elguero, J. *Chem.–Eur. J.* **2013**, *19*, 11637–11643.

(26) This interaction may be particularly impacting as it may be responsible for some important but poorly understood phenomena such as the hydrophobic interactions, or it may play a role in polymorphism of agrochemicals and drugs.

(27) Laurence, C.; Graton, J.; Gal, J.-F. *J. Chem. Educ.* **2011**, *88*, 1651–1657. Chopra, D.; Guru Row, T. N. *CrystEngComm* **2011**, *13*, 2175–2186.

(28) Raghavendra, B.; Arunan, E. *J. Phys. Chem. A* **2007**, *111*, 9699–9706.

(29) Rosokha, S. V.; Neretin, I. S.; Rosokha, T. Y.; Hecht, J.; Kochi, J. K. *Heteroatom Chem.* **2006**, *17*, 449–459.

(30) Imakubo, T.; Tajima, N.; Tamura, M.; Kato, R.; Nishio, Y.; Kajita, K. *Synth. Met.* **2003**, *181*, 133–134. Laurence, C.; Graton, J.; Berthelot, M.; El Ghomari, M. *J. Chem.–Eur. J.* **2011**, *17*, 10431–10444.

(31) The hydrogen bond stands on its own due to its unique features and the specificities of the hydrogen atom.

(32) Burrows, H.; Weir, R.; Stohner, J. *Pure Appl. Chem.* **1994**, *66*, 1077.

(33) A CSD search (version 5.34, November 2012 plus one update, ConQuest version 1.15) for $Y \cdots X-C$ interactions with $Y = Li^+, Na^+, K^+, Rb^+, Cs^+$ gave 140 hits and 296 counts when $X = Cl, Br, I$; 3947 hits and 18 008 counts when $X = O$; 875 hits and 3622 counts when $X = S$. Only structures with $Y \cdots C > 3.0 \text{ \AA}$ were considered. The median value of the $Y \cdots X-C$ angle is 103.08° when $X = Cl, Br, I$, 116.57° when $X = O$, and 111.34° when $X = S$. This lateral entrance of cations confirm they function as electrophiles.

(34) A CSD search analogous to alkali cations was performed. Only structures with no disorder, no error, and no powder structures were considered. The median values of the $Met^{2+} \cdots O-C$ angle in short contacts are 121.00° , 120.85° , 120.25° , and 119.45° when $Met = Mg, Ca, Sr$, and Ba , respectively. $Met = Mg$ gave 32 hits with 55 counts; $Met = Ca$ gave 112 hits with 262 counts; $Met = Sr$ gave 48 hits with 73 counts; $Met = Ba$ gave 77 hits with 146 counts.

(35) Typical examples of interactions with lone pair possessing atoms are the useful adducts that BH_3 and BF_3 form with nitrogen, oxygen, and sulphur derivatives: Klooster, W. T.; Koetzle, T. F.; Siegbahn, P. E. M.; Richardson, T. B.; Crabtree, R. H. *J. Am. Chem. Soc.* **1999**, *121*,

6337–6343. Colquhoun, H. M.; Jones, G.; Maud, J. M.; Stoddart, J. F.; Williams, D. J. *J. Chem. Soc., Dalton Trans.* **1984**, 6366. CEZJIA: Topel, K.; Hensen, K.; Bats, J. W. *Acta Crystallogr., Sect. C: Cryst. Struct. Commun.* **1984**, *40*, 828–830. DECJAX, DECJEB, DECJIF: Phillips, J. A.; Halfen, J. A.; Wrass, J. P.; Knutson, C. C.; Cramer, C. J. *Inorg. Chem.* **2006**, *45*, 722–731. The adducts that 1,8-bis-borylnaphthalene derivatives form with hydride and fluoride anions are interesting examples of attractive interactions between trivalent boron and anions. AGIPAI: Dorsey, C. L.; Jewula, P.; Hudnall, T. W.; Hoefelmeyer, J. D.; Taylor, T. J.; Honesty, N. R.; Chiu, C. W.; Schulte, M.; Gabbai, F. J. *Chem. Soc., Dalton Trans.* **2008**, 4442–4450. EZAOU: Sole, S.; Gabbai, F. P. *Chem. Commun.* **2004**, 1284–1285.

(36) We are listing below Refcodes, and the corresponding references, of some structures reported in the CSD where the observed contacts formed by aluminium, gallium, indium, and thallium are consistent with an electrophilic behaviour of these elements. BATLEN: Atwood, J. L.; Hrcir, D. C.; Rogers, R. D.; Howard, J. A. K. *J. Am. Chem. Soc.* **1981**, *103*, 6787–6788. EMEPUH, EMEQAO, EMEQES, EMEQIW, EMEQUI, EMERAP: Thomas, F.; Bauer, T.; Schulz, S.; Nieger, M. *Z. Anorg. Allg. Chem.* **2003**, *629*, 2018–2027. GUHZUE, GUJBAO, GUJBES: Coward, K. M.; Jones, A. C.; Steiner, A.; Bickley, J. F.; Smith, L. M.; Pemble, M. E. *J. Chem. Soc., Dalton Trans.* **2001**, 4145. BOCYEX: Barber, M.; Liptak, D.; Oliver, J. P. *Organometallics* **1982**, *1*, 1307–1311. Peters, J. C.; Harkins, S. B.; Brown, S. D.; Day, M. W. *Inorg. Chem.* **2001**, *40*, 5083–5091.

(37) “Molecular species” which seriously challenge the convention proposed in this Perspective can be found, but this is a common situation for most of, probably all, the concepts related to the chemical bond and the terms used to designate them. This is a direct consequence of the tremendous diversity of the bonds present in the millions of “molecular species” prepared and studied by chemists. For instance, the proposed generalization aims at giving a criterion to assign an unambiguous name to most of the attractive interactions given by elements of Groups 1, 2, 13–17, but in some species it is not easy to distinguish unambiguously the covalent bonds formed by an atom from the interaction it is involved in. Phenyllithium gives a tetrahydropyrene solvate. Langer, J.; Köhler, M.; Fischer, R.; Dündar, F.; Görls, H.; Westerhausen, M. *Organometallics* **2012**, *31*, 6172–6182 wherein the C–Li bond is remarkably longer than the Li–O bond (224.5 pm versus 197.9 pm). A similar situation is observed in the ethyl ether solvate. Hope, H.; Power, P. P. *J. Am. Chem. Soc.* **1982**, *105*, 5320–5324 and several other analogous systems, e.g., ENAWOF. Vestergren, M.; Eriksson, J.; Hilmersson, G.; Hakansson, M. *J. Organomet. Chem.* **2003**, *682*, 172–179 Even more remarkable, two or three lithium atoms are bound to a single benzene carbon in these solvates. The robustness of the proposed generalization is confirmed by the fact that whatever “bond” is considered the “interaction”, lithium is the electrophilic ending, and the interaction is realistically designated a lithium bond.