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Graphical Abstract

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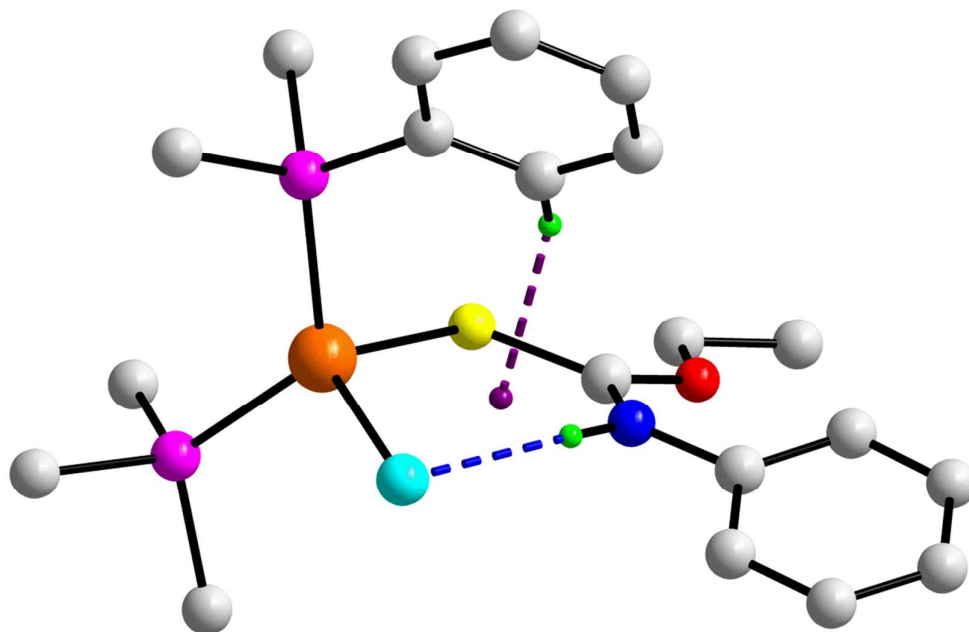
ARTICLE TYPE

Investigations of putative arene-C–H...π(quasi-chelate ring) interactions in copper(I) crystal structures†

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Evidence for C–H...π(CuCl...HNCS) interactions, *i.e.* C–H...π(quasi-chelate ring) where a six-membered quasi-chelate ring is closed by a N–H...Cl hydrogen bond, is presented
10 based on crystal structure analyses of (Ph₃P)₂Cu[ROC(=S)N(H)Ph]Cl. Similar intramolecular interactions are identified in related literature structures. Calculations suggest that the energy of attraction provided by such interactions approximates 3.5 kcal mol⁻¹.

15 Complementing supramolecular synthons based on conventional hydrogen bonding and coordinate bonds, which remain crucial in crystal engineering studies, is a myriad of other intermolecular interactions coming to the fore with the notable example being halogen bonding.[1] Supramolecular association
20 based on π-systems is also well established in all-organic crystal structures and increasingly, chelate rings are being recognised as being capable of forming analogous interactions,[2] reflecting their metalloaromatic nature.[3] Thus, just as arene rings can associate *via* π...π interactions, mixed π(arene)...π(chelate) interactions can
25 occur,[4a] as well as π(chelate)...π(chelate) interactions which are found in up to 40% of certain square planar transition metal complexes and exhibit the same attributes as π...π interactions involving arene rings, such as cooperativity, separation and orientation, *i.e.* parallel and anti-parallel.[4b] As demonstrated by
30 Zarić *et al.* in their systematic evaluations of transition metal acetylacetonate crystal structures, chelate rings may also function as donors and acceptors of C–H...π interactions and impart approximately the same energy of stabilisation as for C–H...π interactions occurring between organic residues.[5] While work
35 continues into this phenomenon,[6] the role of conjugated or resonance-assisted hydrogen bonded systems, where one of the links within the organic ring is a hydrogen bond rather than a formal covalent bond, giving rise to quasi-aromatic rings, is less well understood.[7] Analogous quasi-aromatic rings where one of
40 the constituent atoms is a metal have received considerably less attention and their putative formation forms the focus of the present communication. Herein, the observation and theoretical investigation of intramolecular arene-C–H...π(quasi-chelate rings) interactions in some (Ph₃P)₂Cu[ROC(=S)N(H)Ph]Cl complexes
45 is described, as is the prevalence of analogous interactions in the crystallographic literature.

The new copper(I) complexes were prepared in response to the recently demonstrated anti-cancer potential of platinum[8a] and gold[8b] complexes of thiocarbamides, ROC(=S)N(H)Ar, and the
50 remarkable and selective anti-microbial activity against four Gram-positive bacteria exhibited by phosphanegold(I) derivatives.[8c] The potential of copper(I) complexes as therapeutic agents has been reviewed recently,[9] and so attention was naturally directed to investigating related phosphanecopper(I) derivatives
55 during which the title complexes, (Ph₃P)₂Cu[ROC(=S)N(H)Ph]Cl, R = Me (**1**), Et (**2**) and iPr (**3**), were synthesised and characterised, including by single crystal X-ray crystallography; see ESI for details. Spectroscopy showed the expected characteristics with the only feature worth
60 highlighting is the downfield shift of the ¹H resonance due to the acidic proton as the concentration of the solution was increased, consistent with retention of the N–H…Cl hydrogen bond in solution (see below), see ESI Fig. S1.

The molecular structure of **2** is shown in Fig. 1 and features a
65 tetrahedrally coordinated Cu(I) centre with the environment defined by one chlorido, a thione-S and two phosphane-P atoms; the maximum deviation from regular tetrahedral is found in the P1–Cu–P2 angle of 125.099(19)°. An intramolecular N–H…Cl hydrogen bond is formed closing a (CuCl…HNCS) quasi-chelate
70 ring, see ESI Table S2 for geometric details. The interesting feature of the structure is the relative orientation of one of the phenyl-H atoms which appears to be directed toward the centre of the aforementioned ring. The separations between phenyl-H atom and each of the constituent atoms of the ring are given in
75 the caption of Fig. 1, and from these data it is evident that the phenyl-H atom is not orientated toward any one atom of the ring but rather to the centre of the quasi-chelate ring. The distance between phenyl-H and the centroid of the quasi-ring is 2.31 Å and the angle at is 147°. By analogy with a C–H…π(arene)
80 interaction, this contact can be represented as C–H...π(CuCl…HNCS).

A similar interaction is found in the R = iPr derivative, **3** [phenyl-H...quasi-ring centroid = 2.56 Å and angle at H = 124°; see ESI Fig. S2 for details], but not in the R = Me analogue, **1**,
85 where the shortest H…quasi-ring centroid distance is 3.41 Å. An overlay diagram, ESI Fig. S2c, shows that while the overall molecular structures are similar, the phenyl ring forming the C–H...π(CuCl…HNCS) interaction in **2** and **3** is somewhat splayed in **1**; the dihedral angles between the relevant phenyl ring and the
90 least-squares plane through the non-hydrogen atoms of the quasi-

chelate ring are 36.5(5), 64.02(5) and 55.25(5)° for **1**, **2** and **3**, respectively. It is noted that the quasi-ring in **1** (r.m.s. deviation of the five non-hydrogen atoms = 0.1902 Å) is less planar than the equivalent rings in **2** and **3** (r.m.s. = 0.0997 and 0.0898 Å, respectively). In fact the ring in **1** has a distinct envelope conformation with the Cu atom lying 0.6751(11) Å above the least-squares plane defined by the remaining four non-hydrogen atoms; see ESI Table S3. The other difference between the structures is found in the pattern of Cu–ligand bond lengths (see ESI Table S4) so that in **1**, the Cu–Cl1 bond length is significantly longer, by 0.03 Å, than those in **2** and **3**, and the remaining bond lengths in **1** are concomitantly shorter *cf.* to the equivalent bonds in **2** and **3**. This is not related to the nature of the supramolecular aggregation as C–H...Cl interactions are formed in each of the crystal structures; ESI Figs S3-S5. In **1** and **2** C–H...Cl along with C–H...π(arene) contacts lead to a supramolecular layer and double chain, respectively. In **3**, C–H...Cl, C–H...S and C–H...π(arene) interactions lead to a supramolecular chain. The crystal packing in **1-3** was also evaluated for phenyl embraces (PE), known to be important in stabilising the crystal structures of phenyl-rich molecules.[10] As summarised in the figure captions to ESI Figs S3-S5, the P1-phosphane, *i.e.* not involved in forming the putative C–H...π(CuCl…HNCS) interactions, participates in sextuple PE whereas the P2-phosphane ligand forms parallel quadruple PE interactions in **1**, double PE in **2** but no recognisable pattern is observed in **3**.
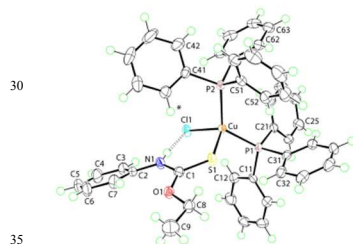

Fig. 1 Molecular structure of **2** showing atom labelling and 70% displacement ellipsoids. The C–H*...Cu, Cl1, S1, N1, C1 and H1n separations are 3.12, 3.41, 2.99, 2.63, 2.88 and 2.48 Å, respectively.

The unusual nature of the C–H...π(CuCl…HNCS) contact prompted a search of the Cambridge Structural Database (CSD version 5.33)[11a] for analogous interactions using CONQUEST.[11b] The initial search comprised seeking a specific arrangement of the Cu, Cl, H, N, C and S atoms as well as the presence of a N–H...Cl hydrogen bond to close the ring: this gave rise to a total of 91 hits. This sub-set was further probed to seek intramolecular C–H...π(CuCl…HNCS) contacts by adding the following restrictions, Fig. 2. The distance, d, from the ring centroid (Cg) to the H atom is ≤ 3.6 Å[6a] and the C–H…Cg angle is in the range $110 \leq \alpha \leq 180°$. Although the quasi-ring was not restricted to be planar, the angle between the normal of the least-squares plane through the six atoms and the C–H vector was restricted to be $\leq 15°$ to ensure the C-bound H atom was approximately plumb to the ring. There were 14 structures,[11] out of a possible 91, that satisfied these criteria; details are summarised in ESI Table S5.

Twelve of the hits contain phosphane ligands, with seven having very similar mononuclear structures with ClP$_2$S donor sets as found for **2** and **3**;[12b-e,h,j-l,o] a simple variation is found in one binuclear example having bridging bidentate phosphanes.[12f] Four

binuclear structures with monodentate phosphane ligands have S[12g,n] or Cl[12i] bridges. The remaining two structures are thione adducts of CuCl.[12a,m] In each case the donor H atom was connected to an aromatic ring. Values of d were in the range 2.28 to 2.92 Å and the α angles varied from 114 to 163°. The planarity of the quasi-chelate ring is not factor in the formation of C–H…π(quasi-chelate ring) interactions as rms deviations of the five non-hydrogen atoms from their least-squares plane vary from a low 0.0297 to 0.3374 Å (ESI Table S5). Nor there is a correlation between the planarity of the quasi-chelate ring and the values of d or α. This is hardly surprising as correlations involving weak interactions are notoriously unreliable.[13]
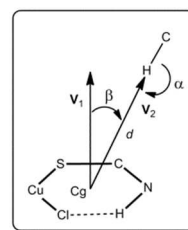

Fig. 2 Search protocols for C–H...π(CuCl…HNCS) interactions: d is the distance between the ring centroid (Cg) of the quasi-chelate ring and the H atom; V_1 is the vector normal to the plane through the ring; α is the C–H…Cg angle; β is the angle between the V_1 and V_2 vectors.

In order to investigate the nature of the C–H...π(CuCl…HNCS) interaction, DFT-D calculations were performed based on the coordinates of one of the literature crystal structures that features an intramolecular contact, *i.e.* **4**,[11o] Fig. 3a. As detailed in the ESI, Gaussian09 was used employing the BP86 functional,[14a,b] including the D3 version of Grimme's dispersion correction,[14c] the second-order perturbation theory[14d] with the def2-TZVP basis set.[14e,f] Initially, the non-covalent interactions were calculated in real space based on the electron density and its reduced gradient using the NCI approach of Yang *et al.*[15] Referring to Figs 3b and c, the surfaces are coloured blue, green and red, correlating with strong attractive, weak attractive and strong non-bonded overlap, respectively. The NCI analysis[15] gives a conical surface pointing to the mass-centre of the ring, representing unambiguously the π-type interaction. An example of T-shaped benzene-dimer can be seen in the Fig. 3b. A similar situation was observed for **4**, in which the green region indicates a weak attractive interaction as commonly presented in π-stacking interactions.
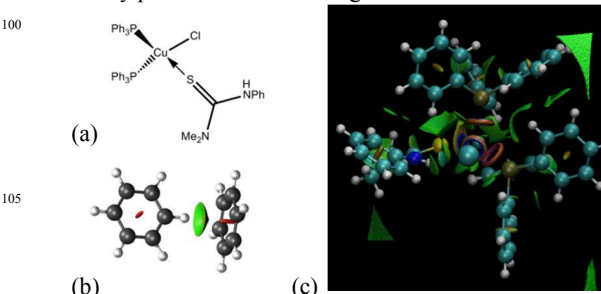

Fig. 3 (a) Chemical structure of **4**, (b) gradient isosurface for a T-shaped benzene-dimer (adapted with permission from Yang *et al., J. Chem. Theor. Comp.* 2011, **7**, 625. Copyright 2014 American Chemical Society), and (c) gradient isosurface for **4**.

Additional calculations were conducted to elucidate the metalloaromaticity of the quasi-chelate ring by calculation of isotropic nucleus-independent chemical shifts (NICS(-1)$_{ISO}$,

NICS(0)$_{ISO}$ and NICS(1)$_{ISO}$) at the centroid of **4**, using the BP86, B3LYP and B3PW91 functionals.[16a,b] The magnetic criterion of aromaticity was not satisfied, with values in the range of -1.32 to 0.32 Å. The model complex **4'**, i.e. without any phenyl rings, and fully optimized at BP86-D/def2-TZVP, lead to a similar conclusion (ESI Fig. S6). Despite the non-aromatic character, these new synthons can form non-covalent interactions in a similar fashion to truly aromatic rings. Support for this is found in the analysis of the molecular orbitals (MO) of both **4** and **4'**. As seen in ESI Fig. S7, three MO's present an alignment between the *p* orbitals of N, C, Cl and S, and the *d* orbital of Cu, forming a quasi-π-system. Further, an estimate of the interaction energy for C–H...π(CuCl…HNCS) was made using the optimal geometries (BP86-D/def2-TZVP) for a model system, C_2H_2…**4'**, removing the basis set superposition error (BSSE) by counterpoise (CP) correction.[16c] Referring to ESI Fig. S8, single point calculations were performed at *r*(H…Ω) distances between 2.2 and 3.0 Å, for three positions in the ring, presenting an average energy at the optimal separation of 3.5 kcal mol^{-1} at MP2 and M062X-D, and 4 to 5 kcal mol^{-1} at B3LYP-D and B3PW91-D. For all calculated positions, the interactions are attractive.

In summary, experimental and theoretical evidence has been presented for attractive (*ca* 3.5 kcal mol^{-1}) intramolecular C–H...π(CuCl…HNCS) interactions which occur in approximately 15% of the copper(I) structures where they may potentially form.

Notes and references

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1   A. Priimagi, G. Cavallo, P. Metrangolo and G. Resnati, *Acc. Chem. Res.*, 2013, **46**, 2686.

2   *The Importance of Pi-Interactions in Crystal Engineering: Frontiers in Crystal Engineering,* ed. E. R. T. Tiekink and J. Zukerman-Schpector, John Wiley and Sons, Singapore, 2012.

3   H. Masui, *Coord. Chem. Rev.*, 2001, **219–221**, 957; F. Feixas, E. Matito, J. Poater and M. Solà, *WIREs Comput. Mol. Sci.*, 2013, **3**, 105.

4   (a) Z. D. Tomić, D. N. Sredojević and S. D. Zarić, *Cryst. Growth Des.*, 2006, **6**, 29; (b) D. N. Sredojević, Z. D. Tomić and S. D. Zarić, *Cryst. Growth Des.*, 2010, **10**, 3901.

5   M. K. Milčić, V. B. Medaković, D. N. Sredojević , N. O. Juranić and S. D. Zarić, *Inorg. Chem.*, 2006, **45**, 4755.

6   (a) E. R. T. Tiekink and J. Zukerman-Schpector, *Chem. Commun.*, 2011, **47**, 6623; (b) V. B. Medaković, G. A. Bogdanović, M. K. Milčić, G. V. Janjić and S. D. Zarić, *J. Inorg. Biochem.*, 2012, **117**, 157; (c) S. K. Singh, M. G. B. Drew and N. Singh, *CrystEngComm*, 2013, **15**, 10255.

7   M. Calvin and K. W. Wilson, *J. Am. Chem. Soc.*, 1945, **67**, 2003; M. Palusiak and T. M. Krygowski, *Chem. Eur. J.*, 2007, **13**, 7996; A. Filarowski and I. Majerz, *J. Phys. Chem. A*, 2008, **112**, 3119; H. Karabiyik, R. Sevincek, H. Petek, M. Aygun, *J. Mol. Model.*, 2011, **17**, 1295; Y. V. Novakovskaya, *Struct. Chem.*, 2012, **23**, 1253; H. Karabıyık, H. Karabıyık and N. O. Îskeleli, *Acta Crystallogr., Sect. B: Struct. Sci.*, 2012, **68**, 71; H. Karabıyık, R. Sevincek and H. Karabıyık, *J. Molec. Struct.*, 2014, **1064**, 135.

8   (a) D. Dolfen, K. Schottler, S.-M. Valiahdi, M.A. Jakupec, B. K. Keppler, E. R. T. Tiekink and F. Mohr, *J. Inorg. Biochem.*, 2008, **102** 2067; (b) C. I. Yeo, K. K. Ooi, A. Md Akim, K. P. Ang, Z. A. Fairuz, S. N. B. A. Halim, S. W. Ng, H.-L. Seng and E. R. T. Tiekink, *J. Inorg. Biochem.*, 2013, **127**, 24; (c) C. I. Yeo, J.-H. Sim, C.-H. Khoo, Z.-J. Goh, K.-P. Ang, Y.-K. Cheah, Z. A. Fairuz, S. N. B. A. Halim, S. W. Ng, H.-L. Seng and E. R. T. Tiekink, *Gold Bull.*, **46** (2013) 145.

9   C. Santini, M. Pellei, V. Gandin, M. Porchia, F. Tisato and C. Marzano, *Chem. Rev.*, 2014, **114** 815.

10 I. Dance and M. Scudder, *Chem. Eur. J.*, 1996, **2**, 481; M. Scudder and I. Dance, *J. Chem. Soc., Dalton Trans.*, 1998, 329.

11 (a) F. H. Allen, *Acta Crystallogr., Sect. B: Struct. Sci.*, 2002, **58**, 380; (b) I. J. Bruno, J. C. Cole, P. R. Edgington, M. Kessler, C. F. Macrae, P. McCabe, J. Pearson and R. Taylor, *Acta Crystallogr., Sect. B: Struct. Sci.*, 2002, **58**, 389.

12 (a) J. T. Lenthall, K. M. Anderson, S. J. Smith and J.W. Steed, *Cryst. Growth Des.*, 2007, **7**, 1858; (b) T. S. Lobana, R. Sharma, A. Castiñeiras and R. J. Butcher, *Z. Anorg. Allg. Chem.*, 2010, **636**, 2698; (c) D. Li, W-J. Shi, T. Wu and S. W. Ng, *Acta Crystallogr., Sect. E: Struct. Rep. Online*, 2004, **60**, m776; (d) T. S. Lobana, P. Kaur, A. Castiñeiras, P. Turner and T. W. Failes, *Struct. Chem.*, 2008, **19**, 727; (e) N. J. M. Sanghamitra, M. K. Adwankar, A. S. Juvekar, V. Khurajjam, C. Wycliff and A. G. Samuelson, *Indian J. Chem., Sect. A: Inorg., Bio-inorg., Phys., Theor. Anal. Chem.*, 2011, **50**, 465; (f) P. Aslanidis, P. J. Cox, S. Divanidis and P. Karagiannidis, *Inorg. Chim. Acta*, 2004, **357**, 4231; (g) S. K. Hadjikakou, P. Aslanidis, P. Karagiannidis, D. Mentzafos and A. Terzis, *Polyhedron*, 1991, **10**, 935; (h) T. S. Lobana, P. K. Bhatia and E. R. T. Tiekink, *J. Chem. Soc., Dalton Trans.*, 1989, 749; (i) T. S. Lobana, R. Sharma, A. Castiñeiras, G. Hundal and R. J. Butcher, *Inorg. Chim. Acta*, 2009, **362**, 3547; (j) T. S. Lobana, S. Khanna, G. Hundal, R. J. Butcher and A. Castiñeiras, *Polyhedron*, 2009, **28**, 3899; (k) N. Gunasekaran, P. Ramesh, M. N. G. Ponnuswamy and R. Karvembu, *Dalton Trans.*, 2011, **40**, 12519; (l) T. S. Lobana, R. Sultana and G. Hundal, *Polyhedron*, 2008, **27**, 1008; (m) M. K. Rauf, Imtiaz-ud-Din, A. Badshah, M. Gielen, M. Ebihara, D. de Vos and S. Ahmed, *J. Inorg. Biochem.*, 2009, **103**, 1135; (n) P. Karagiannidis, S. K. Hadjikakou, P. Aslanidis and A. Hountas, *Inorg. Chim. Acta*, 1990, **178**, 27; (o) R. Singh and S. K. Dikshit, *Polyhedron*, 1995, **14**, 1799.

13 (a) J. D. Dunitz and R. Taylor, *Chem.–Eur. J.*, 1997, **3**, 89; (b) J. Zukerman-Schpector and E. R. T. Tiekink, *CrystEngComm*, 2009, **11**, 2701.

14 (a) A. D. Becke, *Phys. Rev. A*, 1988, **38**, 3098; (b) J. P. Perdew, *Phys. Rev. B*, 1986, **33**, 8822; (c) S. Grimme, J. Antony, S. Ehrlich and H. Krieg, *J. Chem. Phys.*, 2010, **132**, 154104; (d) M. Head-Gordon, J. A. Pople and M. J. Frisch, *Chem. Phys. Lett.*, 1988, **153**, 503; (e) D. Feller, *J. Comp. Chem.*, 1996, **17**, 1571; (f) K. L. Schuchardt, B. T. Didier, T. Elsethagen, L. Sun, V. Gurumoorthi, J. Chase, J. Li, and T. L. Windus, *J. Chem. Inf. Model.*, 2007, **47**, 1045.

15 (a) E. R. Johnson, S. Keinan, P. Mori-Sánchez, J. Contreras-Garcia, A. J. Cohen and W. Yang, *J. Am. Chem. Soc.* 2010, **132**, 6498; (b) J. Contreras-García, E. R. Johnson, S. Keinan, R. Chaudret, J.-P. Piquemal, D. N. Beratan and W. Yang, *J. Chem Theory. Comput.* 2011, **7**, 625.

16 (a) P. R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao and N. J. R. E. Hommes, *J. Am. Chem. Soc.* 1996, **118**, 6317; (b) M. K. Milčić, B. D. Ostojić and S. D. Zarić, *Inorg. Chem.*, 2007, **46**, 7109; (c) S. F. Boys and F. Bernardi *Mol. Phys.*, 1971, **19**, 553.