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Accepted 12th June 2015

DOI: 10.1039/c5sc01578b

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## A hexanuclear gold carbonyl cluster†‡

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The hexanuclear gold carbonyl cluster [PPh<sub>4</sub>]<sub>2</sub>[Au<sub>6</sub>(CF<sub>3</sub>)<sub>6</sub>Br<sub>2</sub>(CO)<sub>2</sub>] (**4**) has been obtained by spontaneous self-assembly of the following independent units: CF<sub>3</sub>AuCO (**1**) and [PPh<sub>4</sub>][Br(AuCF<sub>3</sub>)<sub>2</sub>] (**3**). The cyclo-Au<sub>6</sub> aggregate **4**, in which the components are held together by unassisted, fairly strong aurophilic interactions (Au⋯Au ~310 pm), exhibits a cyclohexane-like arrangement with chair conformation. These aurophilic interactions also result in significant ν(CO) lowering: from 2194 cm<sup>-1</sup> in the separate component **1** to 2171 cm<sup>-1</sup> in the mixed aggregate **4**. Procedures to prepare the single-bridged dinuclear component **3** as well as the mononuclear derivative [PPh<sub>4</sub>][CF<sub>3</sub>AuBr] (**2**) are also reported.

## Introduction

There is much current interest in the study of gold carbonyls, mainly because of both the intriguing nature of the [Au]–CO bond and their involvement in gold-catalyzed transformations of CO, including its low-temperature oxidation by molecular oxygen as well as water-gas shift reaction.<sup>3</sup> Direct unambiguous information on the active species in the latter processes is still lacking.<sup>4</sup> IR spectroscopy is a powerful tool helping to assign the oxidation state of the active sites on the catalyst surface as well as to evaluate the influence of the chemical environment.<sup>4,5</sup> Well-established gold carbonyls for appropriate comparison are therefore valuable species, although they still remain scarce.<sup>6</sup> Aside from the following dinuclear derivatives: Cl<sub>3</sub>Au(μ-Cl)AuCO,<sup>7</sup> (tBu<sup>F</sup>O)<sub>3</sub>Al(μ-Cl)AuCO and [Cl(AuCO)<sub>2</sub>][Al(OtBu<sup>F</sup>)<sub>4</sub>],<sup>8</sup> the handful of currently isolated gold carbonyls are all mononuclear, either neutral XAuCO (X = Cl,<sup>9</sup> CF<sub>3</sub>,<sup>10</sup> OSO<sub>2</sub>F,<sup>11</sup> HB(pz\*)<sub>3</sub>,<sup>12</sup>) or cationic LAuCO<sup>+</sup> species (L = CO,<sup>11,13</sup> SIDipp,<sup>14,15</sup> IDipp,<sup>15</sup> PMes<sub>3</sub>,<sup>14,16</sup> DPCh<sup>17</sup>). Additionally, some oligomers of unknown nuclearity have been suggested to form in frozen concentrated solutions of ClAuCO in CH<sub>2</sub>Cl<sub>2</sub>.<sup>18</sup>

To the best of our knowledge, discrete polynuclear gold carbonyl compounds featuring both the Au–CO and Au⋯Au

interactions are still lacking. Such species, if experimentally available, might illustrate two key interactions occurring on the catalyst surface: (1) CO coordination to an exposed gold center, and (2) cohesive bonding interaction of this active site with the bulk catalyst support. Here we report on a discrete hexanuclear gold carbonyl cluster formed by spontaneous self-assembly of independent Au<sub>1</sub> and Au<sub>2</sub> units, which are held together by *unassisted* aurophilic interactions alone.<sup>§19–21</sup> It is further shown that such aurophilic interactions have a distinct effect on the vibrational properties of the highly sensitive [Au]–CO unit, which can therefore act as a fine probe of the molecular environment.

## Results and discussion

The gold carbonyl compound CF<sub>3</sub>AuCO (**1**) has already proven to be a useful synthon of the 'AuCF<sub>3</sub>' fragment toward neutral ligands.<sup>10</sup> We have found now that the 1:1 reaction of compound **1** with [PPh<sub>4</sub>]Br proceeds in a similar way giving rise to CO replacement (Scheme 1) with formation of the mononuclear anionic derivative [PPh<sub>4</sub>][CF<sub>3</sub>AuBr] (**2**). This air- and moisture-stable compound shows a typical linear arrangement (Fig. 1).

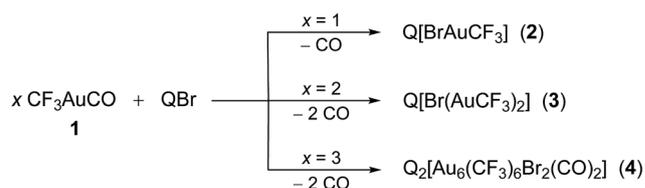
The coordination of bromide results in significant lengthening of the Au–C distance (211.9(4) pm) with respect to that observed in both the neutral parent species **1** (204.7(14) pm)<sup>10</sup>

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† Dedicated to Prof. Dr Pablo Espinet on the occasion of his 65th birthday. Abbreviations are defined prior to the Acknowledgements section. As defined in ref. 1, "clusters are molecular units which may contain small or large numbers of similar atoms where there are several short internuclear distances between atom pairs." This definition is fully compatible with that originally given by F. A. Cotton (ref. 2).

‡ Electronic supplementary information (ESI) available: Experimental procedures, comments on the X-ray structure determinations and 3D Hirschfeld surfaces for the ions constituting the crystal of **4**. CCDC 1049919–1049921. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/c5sc01578b



Scheme 1 Synthetic procedures affording the trifluoromethyl-gold derivatives 2–4. In all cases Q<sup>+</sup> = [PPh<sub>4</sub>]<sup>+</sup>.



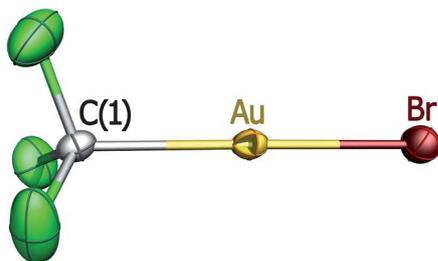


Fig. 1 Displacement-ellipsoid diagram (50% probability) of the mononuclear  $[\text{CF}_3\text{AuBr}]^-$  anion as found in single crystals of **2**. Selected bond lengths (pm) and angles ( $^\circ$ ) with estimated standard deviations: Au–Br 240.5(1), Au–C(1) 211.9(5), av. C(1)–F 132.1(7); C(1)–Au–Br 177.64(15), av. Au–C(1)–F 110.7(4), av. F–C(1)–F' 108.2(5).

and the homoleptic anionic derivative  $[\text{NBu}_4][\text{Au}(\text{CF}_3)_2]$  (203.3(2) pm).<sup>10a</sup> The Au–Br distance (240.5(1) pm) is, in turn, comparable to that found in the homoleptic complex halide  $[\text{NBu}_4][\text{AuBr}_2]$  (237.6(3) pm).<sup>22</sup> In the crystal lattice of compound **2**, the anions are separated by the cations resulting in large intermetallic separations (>0.7 nm).

The 2 : 1 reaction of compound **1** with  $[\text{PPh}_4]\text{Br}$  gives rise (Scheme 1) to the dinuclear species  $[\text{PPh}_4][\text{Br}(\text{AuCF}_3)_2]$  (**3**) containing single-bridging bromide. In the crystal, the dinuclear anions are self-assembled in pairs (Fig. 2) showing significant intermolecular auriphilic interactions (av. Au...Au'  $\sim$ 326 pm), which apparently counteract Coulomb repulsion between the constituent anions in the dimer. The intramolecular intermetallic separation within each dinuclear  $[\text{Br}(\text{AuCF}_3)_2]^-$  anion is, in turn, too long to denote any bonding interaction: av. Au...Au'  $\sim$ 368 pm. Similar structural patterns have been found in certain halonium  $[\text{X}(\text{AuPR}_3)_2]^+$  salts.<sup>23</sup> Recent theoretical studies on the model halonium monocations  $[\text{X}(\text{AuPH}_3)_2]^+$  (X = F, Cl, Br, I) at the  $X\alpha$  level conclude that they should also undergo self-assembly against Coulomb repulsion to form tetranuclear  $[\text{X}(\text{AuPH}_3)_2]_2^{2+}$  clusters, whereby the intermolecular interaction energy for each Au...Au pair was estimated to be 85.0 kJ mol<sup>-1</sup> on average.<sup>24</sup> It has also been suggested that such type of associations might be counterion-mediated.<sup>25</sup> With regard to this possibility, it is interesting to note that no pairwise association was, in fact, observed in several other  $[\text{X}(\text{AuL})_2]^+$  salts,<sup>26</sup> including the recently reported chloronium gold carbonyl derivative  $[\text{Cl}(\text{AuCO})_2][\text{Al}(\text{O}t\text{Bu})_4]^-$ .<sup>8</sup>

The av. Au–C distance in compound **3** (194(2) pm) is significantly shorter than in the mononuclear derivative **2** (211.9(5) pm), whereas the av. Au–Br distance in the single-bridging system of compound **3** (244.2(3) pm) is just slightly longer than that found in the terminal Au–Br bond of **2** (240.5(1) pm). The geometry of the Au–Br–Au unit in the anionic compound **3** is very similar to that found in the cationic derivative  $[\text{Br}(\text{AuPPh}_3)_2][\text{SbF}_6]$ , which is also associated in pairs in the solid state.<sup>23</sup> The relationship between these cationic  $[\text{X}(\text{AuPR}_3)_2]^+$  and anionic  $[\text{Br}(\text{AuCF}_3)_2]^-$  species illustrates the already pointed functional similarity between the corresponding cationic 'AuPR<sub>3</sub><sup>+</sup>' and neutral 'AuCF<sub>3</sub>' fragments, regardless of their different global charge.<sup>10a</sup>

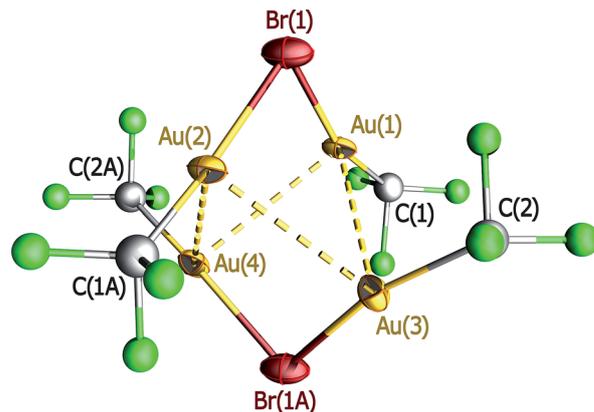


Fig. 2 Structure drawing of one of the two crystallographically independent pairs of dinuclear  $[\text{Br}(\text{AuCF}_3)_2]^-$  anions in disordered state as found in crystals of  $\mathbf{3} \cdot \text{CH}_2\text{Cl}_2$ . Displacement ellipsoids (50% probability) are given only for the heavy atoms. Selected bond lengths (pm) and angles ( $^\circ$ ) with estimated standard deviations: av. Au–Br 244.2(3), av. Au–C 194(2), av. C–F 138(2), av. intramolecular Au...Au' 367.6(2), av. intermolecular Au...Au' 325.9(2); av. Au–Br–Au' 97.6(1), av. C–Au–Br 168.6(7), av. Au–C–F 118(2), av. F–C–F' 99(2).

We considered whether the strong electrophilic 'AuCF<sub>3</sub>' neutral fragment would enable to build a trinuclear  $[(\mu_3\text{-Br})(\text{AuCF}_3)_3]^-$  derivative. To this aim, compound **1** was reacted with  $[\text{PPh}_4]\text{Br}$  in 3 : 1 ratio. However, instead of the targeted trinuclear species, a hexanuclear compound with formula  $[\text{PPh}_4]_2[\text{Au}_6(\text{CF}_3)_6\text{Br}_2(\text{CO})_2]$  (**4**) was obtained (Scheme 1). The reaction outcome makes it clear that the residual nucleophilicity of bridging bromide,  $\mu_2\text{-Br}$ , in component **3** is not sufficient to expel the extremely labile CO ligand in component **1**. Attempts to force the release of CO resulted in extensive decomposition.

The precise nature of compound **4** was established by X-ray diffraction methods. The crystal lattice is formed by large cations and anions with little polarizing effect on each other and showing no sign of significant extra covalent interactions between them.<sup>¶27–32</sup> The anion (Fig. 3) is, in fact, an aggregate of the following components: the anion of compound **3** and the neutral precursor species **1**. The components are held together solely by auriphilic interactions of similar strength: Au...Au  $\sim$ 310 pm. The six gold(i) atoms exhibit a cyclohexane-like arrangement with chair conformation, *cyclo*-Au<sub>6</sub>, of which just a single precedent is known.<sup>33</sup> Upon aggregation, the Au–Br–Au angle in component **3** closes from 97.6(1) to 90.28(3) $^\circ$ , probably to favor the auriphilic interaction with component **1**. All these interactions are broken in solution, since the <sup>19</sup>F NMR signals of aggregate **4** dissolved in CH<sub>2</sub>Cl<sub>2</sub> correspond to the separate components **1** + **3** in the appropriate 1 : 1 ratio (see Experimental in ESI<sup>†</sup>). Solid samples of **4** at room temperature show no sign of luminescent behavior by UV irradiation.

The stereochemistry of hexanuclear gold clusters is largely dominated by a planar arrangement of the six gold centers in the metal core. For instance, the most simple neutral Au<sub>6</sub> and charged (Au<sub>6</sub>)<sup>±</sup> bare clusters<sup>34</sup> as well as different  $[\text{Au}_6(\text{CO})_n]^-$  adsorbates ( $n = 1\text{--}3$ )<sup>35</sup> and even Au<sub>6</sub>H<sub>n</sub> ( $n = 1\text{--}6$ ) binary



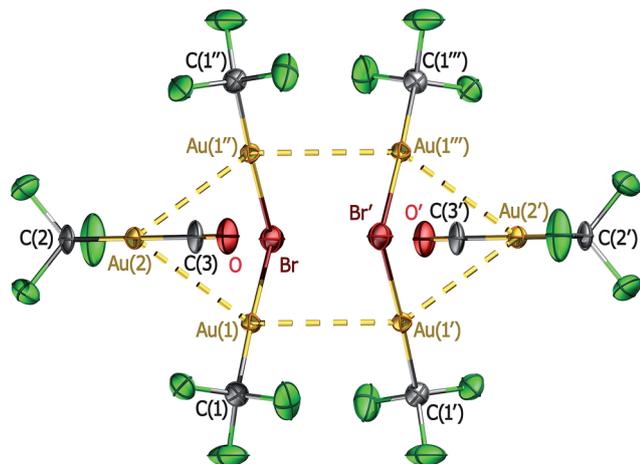


Fig. 3 Displacement-ellipsoid diagram (50% probability) of the hexanuclear  $[\text{Au}_6(\text{CF}_3)_6\text{Br}_2(\text{CO})_2]^{2-}$  anion as found in single crystals of **4**. Selected bond lengths (pm) and angles ( $^\circ$ ) with estimated standard deviations: (a)  $\text{Au}(1)-\text{Br}$  245.30(7),  $\text{Au}-\text{C}(1)$  201.1(6), av.  $\text{C}(1)-\text{F}$  136.5(8),  $\text{Au}(2)-\text{C}(2)$  204.5(9),  $\text{Au}(2)-\text{C}(3)$  201.2(11),  $\text{C}(3)-\text{O}$  108.3(11), av.  $\text{C}(2)-\text{F}$  136(1),  $\text{Au}(1)\cdots\text{Au}(2)$  314.83(3),  $\text{Au}(1)\cdots\text{Au}(1')$  307.24(4);  $\text{Au}(1)-\text{Br}-\text{Au}(1')$  90.28(3),  $\text{C}(1)-\text{Au}(1)-\text{Br}$  177.9(2), av.  $\text{Au}(1)-\text{C}(1)-\text{F}$  115.0(4), av.  $\text{F}-\text{C}(1)-\text{F}$  103.4(5),  $\text{C}(2)-\text{Au}(2)-\text{C}(3)$  175.8(3),  $\text{Au}(2)-\text{C}(3)-\text{O}$  179.2(8), av.  $\text{Au}(2)-\text{C}(2)-\text{F}$  114.6(6), av.  $\text{F}-\text{C}(2)-\text{F}$  103.8(7).

hydrides<sup>36</sup> all have been assigned triangular planar structures following theoretical calculations. Cyclic planar arrangements of the gold centers were experimentally found in the homoleptic neutral compounds  $[\text{Au}_6(\text{SMes})_6]$ ,<sup>37</sup>  $[\text{Au}_6(\text{P}^t\text{Bu}_2)_6]$  and  $[\text{Au}_6(\text{PCy}_2)_6]$ ,<sup>38</sup> as well as in the heteroleptic  $[\text{Au}_6\text{Cl}_4(\text{dppmpm})_2]^{2+}$  cation containing double-bridging tetraphosphine ligands.<sup>39</sup> The precise arrangement of gold centers in hexanuclear gold clusters, however, can be imposed by the presence of heteroatoms and/or additional centers that may exert a template effect. Thus, whereas the six gold(i) atoms in the heterometallic  $[\text{Ag}(\text{AuMes})_6]^+$  cation build a planar hexagonal ring around the central  $\text{Ag}^+$  ion,<sup>40</sup> they were found to nucleate in an octahedral fashion around the hyperaurated C atom in the  $[\text{C}(\text{AuPPh}_3)_6]^{2+}$  cation.<sup>41</sup> Even the nature of the ancillary ligands is known to play a key role on the stereochemistry of hexanuclear gold clusters. As an example, a standard planar metal core was experimentally found in  $[\text{Au}_6(\text{S}_2\text{CR})_6]$  ( $\text{R} = o\text{-tolyl}$ ),<sup>42</sup> whereas a unique chair conformation was observed in  $[\text{Au}_6(\text{S}_2\text{CNR}_2)_6]$  ( $\text{R} = \text{aza-15-crown-5}$ ).<sup>33</sup> The latter arrangement was considered exceptional and it was attributed to the steric effect of the bulky R substituent. Moreover, it has also been noted that “sometimes, the geometry is not imposed by the nature of the bridging ligand(s) but by aurophilicity”.<sup>20e</sup> Compound **4** is a nice example of this particular behavior whereby, in the absence of significant steric constraints, the structure of the metal core is driven by aurophilic interactions. Recently, the effect of both aurophilic interactions and the nature of ancillary ligands on the self-assembly of complex molecular systems, as well as on the rich structural diversity found in the family of Au<sup>i</sup> thio-derivatives, has been studied in detail.<sup>43</sup>

Compound **4** provides a unique opportunity to compare the structural and spectroscopic properties of a gold carbonyl

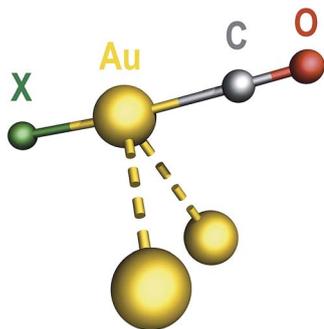
molecule, namely  $\text{CF}_3\text{AuCO}$ , in two different and well defined chemical environments: (a) in isolated pure form (**1**), and (b) adsorbed onto a gold framework (**4**). None of the structural parameters of component **1** are substantially modified in aggregate **4**. However, the  $\nu(\text{CO})$  vibration undergoes a significant frequency decrease upon aggregation. In the separate component **1**, each  $\text{CF}_3\text{AuCO}$  molecule is surrounded by three identical neighbors with trigonal symmetry, resulting in an extended three-dimensional network of *weak* aurophilic interactions ( $\text{Au}\cdots\text{Au}$  345.9(1) pm).<sup>10</sup> In solid samples of component **1**,  $\nu(\text{CO}) = 2194\text{ cm}^{-1}$ , whereas in the *cyclo-Au*<sub>6</sub> aggregate **4** featuring *substantially stronger* aurophilic interactions ( $\text{Au}\cdots\text{Au} \sim 310\text{ pm}$ ) the value drops to  $\nu(\text{CO}) = 2171\text{ cm}^{-1}$ . Recent theoretical calculations on  $\text{CF}_3\text{AuCO}$  and related systems predicted that aurophilic interactions might have an impact on the vibrational properties of the  $[\text{Au}]-\text{CO}$  unit.<sup>14,44</sup> We now provide experimental support for this prediction, as it is found that aurophilic interactions do have a distinct effect on the  $\nu(\text{CO})$  frequency. The experimentally observed trend is, however, opposite to the theoretical predictions: the stronger the interaction, the lower the  $\nu(\text{CO})$  frequency.

It is well known that  $[\text{Au}(\text{L})]^+$  and ‘AuX’ fragments—both having single vacant coordination sites—are isolobal with the simplest Lewis acid, proton  $\text{H}^+$ .<sup>45</sup> This isolobal relationship enables to establish a formal comparison between our  $\text{CF}_3\text{AuCO}$  molecule and the formyl cation  $\text{HCO}^+$ . The  $\nu(\text{CO})$  frequency of this protonated carbonyl is known to lower from  $2184\text{ cm}^{-1}$  in the gas phase<sup>46</sup> to  $2110\text{ cm}^{-1}$  in the condensed phase, namely in superacidic  $\text{HF}(\text{l})/\text{SbF}_5$  medium.<sup>47</sup> Such a large decrease was attributed to interaction of the  $\text{HCO}^+$  cation with  $\text{SbF}_5$  or anionic species derived thereof. This frequency lowering by interaction of  $\text{HCO}^+$  with extremely weak nucleophiles|| is in keeping with our experimental finding with the isolobal  $\text{CF}_3\text{AuCO}$  molecule, where the  $\nu(\text{CO})$  frequency drops from  $2194\text{ cm}^{-1}$  in the separate component **1** to  $2171\text{ cm}^{-1}$  in the *cyclo-Au*<sub>6</sub> aggregate **4** owing to fairly strong aurophilic interactions.

## Conclusions

Compound **4**, formed by spontaneous self-assembly of smaller pre-existing units (Scheme 1), is the first polynuclear gold carbonyl derivative to have been structurally characterized (Fig. 3). A cyclohexane-like arrangement in chair conformation was found for the *cyclo-Au*<sub>6</sub> metal core even in the absence of significant conformational locks. In compound **4**, the neutral gold carbonyl molecule  $\text{CF}_3\text{AuCO}$  appears to be adsorbed onto a gold framework without the need of any kind of assistance. Since aurophilic interactions are the only cohesive forces holding together this supramolecular aggregate, it can be taken as a model for the local environment of gold carbonyl species adsorbed onto gold layers (Scheme 2). Compound **4** is a unique species because of its high nuclearity and also because it enables to check the influence of the strength of aurophilic interactions on the properties of the highly sensitive  $[\text{Au}]-\text{CO}$  unit. We have now experimentally established that aurophilic interactions, although weak in nature, are able to produce significant changes in the  $\nu(\text{CO})$  value of gold carbonyls, as had





Scheme 2 Model for local coordination environment of a [Au]-CO unit of an exposed gold site on a gold surface (X stands for any monodentate substituent).

been theoretically predicted.<sup>14,44</sup> This result should be taken into account when considering the properties of [Au]-CO units on the surface of supported gold catalysts.

## Abbreviations

av.	Average
Cy	Cyclohexyl
DPCb	1,2-Bis(diaminophosphino)-1,2-dicarba- <i>closo</i> -dodecaborane
dpmpm	<i>meso</i> -Bis[(diphenylphosphinomethyl)phenylphosphino]methane
IDipp	1,3-Bis(2,6-diisopropylphenyl)imidazol-2-ylidene
Mes	2,4,6-Trimethylphenyl (mesityl)
Mes'	2,4,6-Tris(isopropyl)phenyl
pz*	3,5-Bis(trifluoromethyl)pyrazolyl
SIDipp	1,3-Bis(2,6-diisopropylphenyl)imidazolin-2-ylidene
<i>t</i> Bu <sup>F</sup>	Perfluoro- <i>tert</i> -butyl

## Acknowledgements

This work was supported by the Spanish MINECO/FEDER (Project CTQ2012-35251), and the Gobierno de Aragón (Grupo Consolidado E21: *Química Inorgánica y de los Compuestos Organometálicos*).

## Notes and references

§ Auophilic interactions are among the most important secondary interactions currently known in chemistry.<sup>19</sup> Although usually weak in nature, they are instrumental in shaping a most stunning variety of clusters, polynuclear compounds and supramolecular frameworks.<sup>20</sup> Auophilic interactions also have a marked influence on the electronic properties of the chemical entity, thus enabling the fine-tuning of the energy levels and hence of the optical properties thereby involved.<sup>21</sup> The effect on other fundamental spectroscopic properties, however, is by far less known.

¶ Three-dimensional Hirschfeld surfaces (HSs) have been calculated for each ion constituting the crystal of **4** (Fig. S3 and S4 in ESI<sup>†</sup>).<sup>27</sup> These HSs are unique to each constituent unit and provide a convenient way for comparison of intermolecular contacts relative to van der Waals radii through a simple red–white–blue colour scheme.<sup>28</sup> It becomes clear that the ions constituting the crystal lattice of **4** are virtually non-interacting. Just a few small, red spots of poor intensity are to be

located in the corresponding HS, which have been specifically analyzed and considered of little (if any) significance as justified in what follows. In particular, the interatomic distances associated with the few, seeming H-bonds are at the long end of the commonly admitted range,<sup>29</sup> and the angles between the atoms involved deviate significantly from linearity (<135°). These geometric parameters jointly indicate extremely poor interactions. The possibility of significant F...CO interactions of both intra- and inter-molecular character was also considered. Such interactions are known to be favored in some salts of superelectrophilic metal carbonyl cations [M(CO)<sub>x</sub>]<sup>q+</sup> with fluorinated [SbF<sub>6</sub>]<sup>n-</sup> anions—*n*, *q* and *x* being integers—and have been thoroughly studied.<sup>30</sup> F...CO contacts at >300 pm, as found in compound **4**, are well within the 10% safety margin of the sum of the corresponding van der Waals radii, *r*<sub>vdw</sub>(F) + *r*<sub>vdw</sub>(C) = 317 pm,<sup>31</sup> and have been previously considered as of just marginal importance.<sup>30,32</sup>

|| Anions such as [SbF<sub>6</sub>]<sup>-</sup> or [Sb<sub>2</sub>F<sub>11</sub>]<sup>-</sup> typically behave as extremely poor nucleophiles. Nevertheless, they are known to interact with sufficiently strong electrophilic centers, as for instance, in (PF<sub>3</sub>)<sub>2</sub>Pt(SbF<sub>6</sub>)<sub>2</sub> and (P<sup>∧</sup>P)Pt(Sb<sub>2</sub>F<sub>11</sub>), where P<sup>∧</sup>P = (CF<sub>3</sub>)<sub>2</sub>PCH<sub>2</sub>CH<sub>2</sub>P(CF<sub>3</sub>)<sub>2</sub>.<sup>48</sup> This is most probably the case of the HCO<sup>+</sup> cation in HF(*l*)/SbF<sub>5</sub> medium.<sup>47</sup>

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