



Showcasing joint research from Instituto de Síntesis Química y Catálisis Homogénea (ISQCH), CSIC-Universidad de Zaragoza, Spain, and the Laboratoire Hétérochimie Fondamentale et Appliquée (LHFA), Université Paul Sabatier-CNRS, Toulouse, France.

Electrophilicity of neutral square-planar organosilver(III) compounds

Trifluoromethyl, CF_3 , is one of the few ligands able to stabilise Ag(III) complexes. In the neutral frame formed with a series of Group 5 monodentate ligands, the Ag(III) centre still shows substantial acidity favouring coordination of an additional ligand.

As featured in:



See Noel Nebra, Babil Menjón *et al.*, *Chem. Commun.*, 2023, **59**, 4166.


 Cite this: *Chem. Commun.*, 2023, 59, 4166

 Received 2nd February 2023,
 Accepted 22nd February 2023

DOI: 10.1039/d3cc00493g

rsc.li/chemcomm

Electrophilicity of neutral square-planar organosilver(III) compounds†

 Daniel Joven-Sancho,^a Luca Demonti,^b Antonio Martin,^a
 Nathalie Saffon-Merceron,^c Noel Nebra,^{*b} Miguel Baya^a and
 Babil Menjón^{ib*}

Neutral Ag(III) complexes stabilised with just monodentate ligands are here unambiguously established. In a series of square-planar (CF₃)₃Ag(L) compounds with hard and soft Group 15 donor ligands, L, the metal center has been found to exhibit substantial acidity favouring apical coordination of an additional ligand under no coordination constraints.

Neutral silver(III) compounds are rare chemical species.¹ Aside from the binary compounds^{2,3} AgF₃ and Ag₂O₃—both exhibiting extended structures[‡]—, all known neutral Ag(III) compounds are stabilised by polydentate ligands (Chart 1). Thus, macrocyclic ligands such as confused porphyrins, carbaporphyrinoids, corroles or carbacorroles are especially suited.⁴ Two additional kinds of molecular compounds have been isolated with bidentate ligands: the dithiolate complex (CF₃)₂Ag(S&S) (S&S = diethyldithiocarbamate) of unknown structure⁵ and the five-coordinate (CF₃)₃Ag(N&N) compounds, where N&N = bpy or phen (Chart 1c).^{6,7} In this work, neutral Ag(III) complexes stabilised with just monodentate ligands are exemplified in the solvento-complex (CF₃)₃Ag(NCMe) (1) and some of its derivatives with Group 15 donor ligands. Evidence for substantial electrophilic character at the metal centre is also given.

The solvento-complex (CF₃)₃Ag(NCMe) has remained intriguing for more than two decades. Previous efforts to prepare it under different experimental conditions^{5,8} gave compounds with significant discrepancies in their ¹⁹F NMR spectroscopic properties (Table S1 in the ESI†). In one case,⁵ the compound

was claimed to have been isolated as a colourless oil in 8.2% estimated yield. This claim, however, is at odds with the observed properties of the gold homologous species (CF₃)₃Au(NCMe), which we isolated as a white solid.⁹ Even more intriguing is the purported failure to replace the MeCN molecule by other ligands.^{5,8} Here, we provide a reliable procedure to prepare the neutral organosilver(III) compound (CF₃)₃Ag(NCMe) (1), which we first isolate as a white solid.

We have found that by treating the anionic chloride complex¹⁰ [(CF₃)₃AgCl][−] with TiClO₄ in MeCN (Scheme 1), the neutral organosilver(III) compound (CF₃)₃Ag(NCMe) (1) is formed quantitatively on a spectroscopic basis (¹⁹F NMR; Fig. S1 in the ESI†). After the appropriate workup, the desired compound is isolated as a deliquescent white solid in moderate yield due to its high solubility in most organic media.

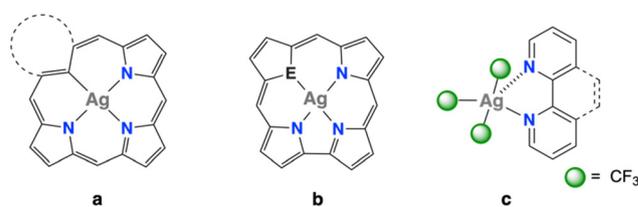


Chart 1 Schematic representation of the neutral Ag(III) complexes stabilised by polydentate ligands: (a) confused porphyrines or carbaporphyrines; (b) corroles (E = N) or carbacorroles (E = CR); (c) bpy or phen. Peripheral substitution may occur at various positions. Confusion may also occur at more than one ring.



Scheme 1 Synthetic procedures to prepare the neutral organosilver(III) compounds 1–5 (dmap = 4-dimethylaminopyridine).

^a Instituto de Síntesis Química y Catálisis Homogénea (ISQCH), CSIC-Universidad de Zaragoza, Zaragoza 50009, Spain. E-mail: b.menjon@csic.es

^b Laboratoire Hétérochimie Fondamentale et Appliquée (LHFA), Université Paul Sabatier, CNRS, 118 Route de Narbonne, Toulouse 31062, France. E-mail: noel.nebra-muniz@univ-tlse3.fr

^c Institut de Chimie de Toulouse ICT-UAR2599, Université de Toulouse UPS, CNRS, 118 route de Narbonne, Toulouse 31062, France

† Electronic supplementary information (ESI) available: Experimental, spectroscopic, computational and X-ray diffraction details (.pdf); atomic coordinates of the optimized structures (.xyz). CCDC 2226904–2226910. For ESI and crystallographic data in CIF or other electronic format see DOI: <https://doi.org/10.1039/d3cc00493g>



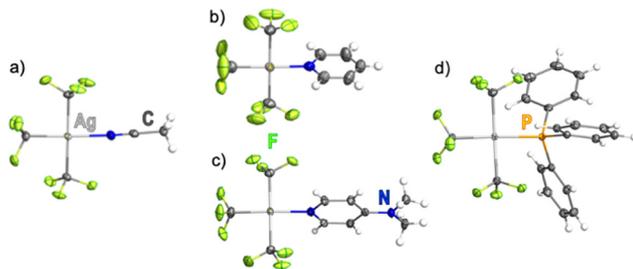


Fig. 1 Displacement-ellipsoid diagram (50% probability) of the *SP*-4 neutral $(\text{CF}_3)_3\text{Ag}(\text{L})$ complexes as found in single crystals of **1** (a), **2** (b), **3** (c), and **4** (d). Crystallographic details and relevant structural parameters are given in the ESI†

Compound **1** has square-planar (*SP*-4) geometry (Fig. 1a; Table S3 in the ESI†) as established by single-crystal X-ray diffraction methods (sc-XRD). The observed Ag–N distance (209.05(16) pm) is significantly shorter than those found for the basal Ag–N bonds in the five-coordinate complexes $(\text{CF}_3)_3\text{Ag}(\text{bpy})$ (214.3(3) pm) and $(\text{CF}_3)_3\text{Ag}(\text{phen})$ (213.9(2) pm).⁶ In addition to the different coordination number (4 vs. 5), the bond shortening observed here can also be attributed to the lack of strain in **1** and to the different hybridisation of the N-donor atom in each case (*sp* vs. *sp*²).

In contrast to previous reports,^{5,8} we found that the MeCN molecule in **1** can be easily replaced by other donors, both soft and hard, as actually expected for a typical labile ligand.¹¹ Thus, a set of neutral $(\text{CF}_3)_3\text{Ag}(\text{L})$ compounds [$\text{L} = \text{py}$ (**2**), *dmap* (**3**), PPh_3 (**4**), AsPh_3 (**5**)] has been prepared by simple exchange processes (Scheme 1). All these new compounds have been isolated and spectroscopically characterised (ESI†). The NMR spectra of the phosphine complex **4** are particularly rich due to the presence of various nuclei with $\frac{1}{2}$ nuclear spin (Fig. S4–S6 in the ESI†). Structural characterisation by sc-XRD (Fig. 1) reveals that these neutral complexes exhibit *SP*-4 structure, as in the parent complex **1**. Except for the phosphine complex **4** (Table S13 in the ESI†), the Ag–C distance *trans* to the neutral L ligand is substantially shorter than in the mutually *trans* Ag–CF₃ due to the different *trans* influence of the CF₃ group and the L ligand.¹² As an example, in the *dmap* complex **3** (Table S11 in the ESI†), the Ag–C bond distance in the CF₃–Ag–L axis (205.2(4) pm) is significantly shorter than the average value in the CF₃–Ag–CF₃ line: 209.3(4) pm.

The most salient feature in this set of compounds is the observed tendency to associate an additional ligand at the apical position. This feature is clearly seen in the arsine complex $(\text{CF}_3)_3\text{Ag}(\text{AsPPh}_3)\cdot\text{OCMe}_2$ (**5-OCMe**₂) and exemplified in the case of the pyridine complex $(\text{CF}_3)_3\text{Ag}(\text{py})$ (**2**), which has also been crystallised as the MeCN and *py* solvates: **2-NCMe** and **2-py** (Fig. 2). In all these cases, the solvent molecule enters the coordination sphere of silver. The additional bond is substantially longer than a standard covalent bond, but much shorter than the sum of the corresponding van der Waals radii.

This kind of interaction is best described making use of the descriptor recently introduced by Álvarez and coworkers, namely the penetration index.¹³ This descriptor, $p(\text{AB})$, provides a measure of

the interpenetration of the electron clouds of the involved atoms A/B and is especially suited for interactions lying between typically covalent and van der Waals bonding interactions, *i.e.* somewhere between the intra- and intermolecular dominions. By using this tool, we obtain $p(\text{AB})$ values ranging from 70% to 76% for the apical interaction in our solvate-complexes $(\text{CF}_3)_3\text{Ag}(\text{L})\cdot\text{L}'$ (Fig. 2). This means that the apical Ag...E interaction is quite similar in all cases, regardless of the different nature of the donor atom (E = N or O) or its precise hybridisation (*sp* or *sp*² in the case of N). Of key importance is also the fact that the Ag...E line virtually coincides with the normal to the best basal plane, the deviation being $< 4^\circ$ in all cases (precise values given in the ESI†). Thus, the position of the apical donor atom E matches both metrical and angular criteria to indicate a genuine Ag...E interaction.

We also performed theoretical calculations on various $(\text{CF}_3)_3\text{Ag}(\text{L})/\text{L}'$ systems in the gas phase ($\text{L}' = \text{NCMe}$, Me_2CO) in order to evaluate the influence of the crystal lattice on establishing the apical interaction. The referred systems were modelled under no symmetry or environmental restraints. We found that in these isolated systems, the additional ligand L' also enters the metal coordination sphere (Fig. S9 and S10 in the ESI†) as the result of a stabilising (exothermic) interaction (Table S16 in the ESI†). In the calculated energy minima, the L' ligand is also located at the apical site near the basal plane normal. The calculated Ag... L' distance in the **2-NCMe** molecule (276.0 pm) shows excellent agreement with that experimentally observed in the crystal (278.4(3) pm). The agreement is less satisfactory in the case of **5-OCMe**₂ (Ag... $\text{L}' = 276.0$ (theor.) vs. 265.3(1) (exptl.) pm), but still reasonable. Following our calculations, it becomes clear, that the neutral $(\text{CF}_3)_3\text{Ag}(\text{L})$ complexes exhibit a significant tendency to associate an additional ligand at the apical site. The resulting interaction is not just a solid-state effect, but evidences an intrinsic electrophilic character of the silver(III) centre (Chart 2). The loose apical interaction has little effect on the geometry of the basal unit. This is in contrast with the anionic halide systems $[(\text{CF}_3)_2\text{AgX}_2]^-$ previously observed, where the association of an additional X[−] anion resulted in marked structural changes.¹⁴ Regardless of the extent of distortion observed in each system, it can be concluded that the electrophilic character of the Ag(III) centre seems to be a general feature in *SP*-4 complexes. It would therefore be advisable to take it into account when trying to

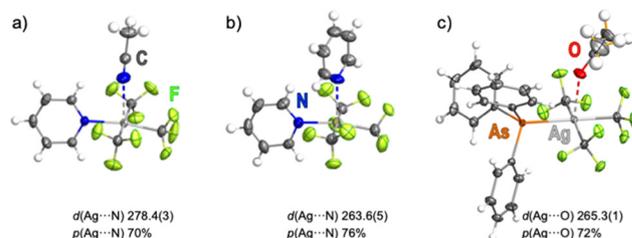


Fig. 2 Displacement-ellipsoid diagram (50% probability) of the solvates $(\text{CF}_3)_3\text{Ag}(\text{L})\cdot\text{L}'$ as found in single crystals of **2-NCMe** (a), **2-py** (b), and **5-OCMe**₂ (c). The Ag... L' distance is indicated in each case together with the corresponding penetration index, $p(\text{AB})$.¹³ Crystallographic details and relevant structural parameters are given in the ESI†



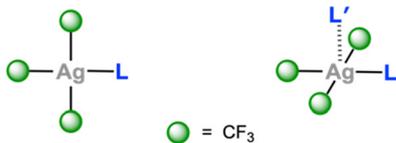


Chart 2 Graphic illustration of the tendency to associate an additional ligand at the apical site observed in the neutral $(\text{CF}_3)_3\text{Ag}(\text{L})$ complexes, whereby the electrophilic character of the $\text{Ag}(\text{III})$ centre is clearly evidenced.

trace reliable reaction mechanisms, as this might lead to a better understanding of the chemical processes.

Compound 2-py bears an interesting relationship with $(\text{CF}_3)_3\text{Ag}(\text{bpy})$,⁶ since the two pyridine rings are detached in the former, whereas they are linked in the latter. A detailed comparison of their structures is therefore in order. In both cases, the basal Ag–N distance is indistinguishable within the experimental error: 213.1(5) vs. 214.3(3) pm. These values are just marginally longer than in the non-solvated *SP-4* complex 2: 210.0(6) pm (Table S5 in the ESI[†]). By contrast, the apical Ag–N distance is substantially longer where the two rings are disconnected, 263.6(5) vs. 245.4(3) pm. This shortening can be assigned to the geometric constraint imposed by the chelating bpy ligand and involves an increment in the penetration index $p(\text{AB})$ from 76% in 2-py (Fig. 2b) to 86% in $(\text{CF}_3)_3\text{Ag}(\text{bpy})$. We can now attribute the apical interaction to a common effect, namely the electrophilicity of the $\text{Ag}(\text{III})$ centre (Chart 2). The apical interaction is incipient in 2-py and tighter in $(\text{CF}_3)_3\text{Ag}(\text{bpy})$.

In this work, we first isolate the solvento-complex $(\text{CF}_3)_3\text{Ag}(\text{NCMe})$ (**1**), which has obvious synthetic potential. It provides a convenient entry to a series of $(\text{CF}_3)_3\text{Ag}(\text{L})$ complexes including the first documented compound with $\text{Ag}(\text{III})$ –As bond (**5**: $\text{L} = \text{AsPh}_3$). These neutral, square-planar $\text{Ag}(\text{III})$ complexes show a conspicuous tendency to uptake an additional ligand at the apical position (Fig. 2). Our calculations demonstrate that this feature is not just a solid-state effect, but rather has its origin in an intrinsic electrophilic character of the $\text{Ag}(\text{III})$ centre (Chart 2).

This work was supported by the Spanish MICIU/FEDER (Project PID2021-122869NB-I00), the CNRS, the Université Paul Sabatier, the Agence Nationale de la Recherche (ANR-JCJC-20-CE07-0023), and the Gobierno de Aragón (Grupo E17_20R). BIFI (Instituto de Biocomputación y Física de Sistemas Complejos) and CESGA (Centro de Supercomputación de Galicia) are acknowledged for allocation of computational resources.

D. J.-S. thanks the Spanish MICIU for a grant (BES-2016-078732). L. D. is thankful to the French MESR for PhD funding.

Conflicts of interest

There are no conflicts to declare.

Notes and references

‡ The structures of AgF_3 (80477-ICSD)² and Ag_2O_3 (59193-ICSD)³ are isomorphous with their corresponding gold homologues.

§ The penetration index, $p(\text{AB})$, of two given atoms A and B is defined as follows: $p(\text{AB}) = 100 \cdot [\nu(\text{A}) + \nu(\text{B}) - d(\text{AB})] \cdot [\nu(\text{A}) + \nu(\text{B}) - r(\text{A}) - r(\text{B})]^{-1}$, where $d(\text{AB})$ is the actual distance between the involved atoms, and $r(\text{A})/\nu(\text{A})$ and $r(\text{B})/\nu(\text{B})$ are their respective covalent/van der Waals radii.¹³

- (a) M. Malischewski, in *Comprehensive Organometallic Chemistry IV*, ed. P. L. Holland, Elsevier, 2021, vol. 1, ch. 5, pp. 109–134; (b) A. Higelin and S. Riedel, in *Modern Synthesis Processes and Reactivity of Fluorinated Compounds*, ed. H. Groult, F. Leroux and A. Tressaud, Elsevier, Amsterdam, 2017, vol. 3, ch. 19, pp. 561–586; (c) S. Riedel, in *Comprehensive Inorganic Chemistry II*, eds. E. V. Antipov, A. M. Abakumov and A. V. Shevelkov, Elsevier, Amsterdam, 2013, vol. 2, ch. 8, pp. 187–221; (d) S. Riedel and M. Kaupp, *Coord. Chem. Rev.*, 2009, **253**, 606.
- B. Žemva, K. Lutar, A. Jesih, W. J. Casteel, Jr., A. P. Wilkinson, D. E. Cox, R. B. von Dreele, H. Borrmann and N. Bartlett, *J. Am. Chem. Soc.*, 1991, **113**, 4192.
- (a) B. Standke and M. Jansen, *Z. Anorg. Allg. Chem.*, 1986, **535**, 39; (b) B. Standke and M. Jansen, *Angew. Chem., Int. Ed. Engl.*, 1985, **24**, 118.
- (a) M. Toganoh and H. Furuta, *Chem. Rev.*, 2022, **122**, 8313; (b) S. Ganguly and A. Ghosh, *Acc. Chem. Res.*, 2019, **52**, 2003; (c) T. D. Lash, *Chem. Rev.*, 2017, **117**, 2313; (d) B. Szyszko and L. Latos-Grażyński, *Chem. Soc. Rev.*, 2015, **44**, 3588; (e) T. D. Lash, *Chem. – Asian J.*, 2014, **9**, 682; (f) C. Brückner, *J. Chem. Educ.*, 2004, **81**, 1665.
- D. Naumann, W. Tyrre, F. Trinius, W. Wessel and T. Roy, *J. Fluorine Chem.*, 2000, **101**, 131.
- L. Demonti, N. Saffon-Merceron, N. Mézailles and N. Nebra, *Chem. – Eur. J.*, 2021, **27**, 15396.
- Z. Lu, S. Liu, Y. Lan, X. Leng and Q. Shen, *Organometallics*, 2021, **40**, 1713.
- R. Eujen, B. Hoge and D. J. Brauer, *Inorg. Chem.*, 1997, **36**, 1464.
- A. Pérez-Bitrián, M. Baya, J. M. Casas, L. R. Falvello, A. Martín and B. Menjón, *Chem. – Eur. J.*, 2017, **23**, 14918.
- D. Joven-Sancho, M. Baya, L. R. Falvello, A. Martín, J. Orduna and B. Menjón, *Chem. – Eur. J.*, 2021, **27**, 12796.
- (a) S. F. Rach and F. E. Kühn, *Chem. Rev.*, 2009, **109**, 2061; (b) B. N. Storhoff and H. C. Lewis, Jr., *Coord. Chem. Rev.*, 1977, **23**, 1.
- (a) A. G. Algarra, V. V. Grushin and S. A. Macgregor, *Organometallics*, 2012, **31**, 1467; (b) P. Sgarbossa, A. Scarso, G. Strukul and R. A. Michelin, *Organometallics*, 2012, **31**, 1257; (c) T. G. Appleton, H. C. Clark and L. E. Manzer, *Coord. Chem. Rev.*, 1973, **10**, 335.
- D. M. Gil, J. Echeverría and S. Alvarez, *Inorg. Chem.*, 2022, **61**, 9082.
- D. Joven-Sancho, M. Baya, A. Martín, J. Orduna and B. Menjón, *Angew. Chem., Int. Ed.*, 2021, **60**, 26545.

