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An unexpected transmetalation intermediate: isolation and structural characterization of a solely CH_3 bridged di-copper(I) complex

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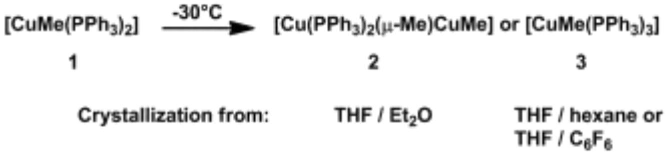
Structural characterizations of unsupported, two metal centres bridging methyl groups are rare. They have been proposed as transmetalation intermediates in cuprate chemistry, but as yet no structural evidence has been presented. We have isolated a di-copper(I) complex with solely a methyl ligand bridging two Cu(I) atoms, representing a new bonding mode of CH_3.

Organocopper(I) reagents are highly important transmetalation agents in catalytic cross-coupling reactions, and homo-organocuprates $[CuR_2]^-$ (R = alkyl, aryl) as their anionic counterparts, so-called Gilman reagents, represent the most frequently used transition metal reagents in C–C bond forming reactions in organic synthesis.[1] Thus, great efforts have been made to elucidate the structures of such organocopper(I) compounds in order to gain a deeper understanding of their reactivity, which is mandatory for the design of efficient catalytic cycles involving transmetalation and for control over regio- and stereoselectivity of the alkylation. The development in this regard is particularly impressive for methyl copper(I), which has originally been described by the group of Gilman in the early 1950s as extremely reactive in solution and potentially explosive, thus no structural data had been reported until recently.[2] However, the formation of its lithium homocuprate Me_2CuLi, usually further stabilized by an additive such as LiX (X = I, CN), gave an easy-to-handle methylating agent,[2a, 3] now widely used in organic synthesis, particularly in 1,4-addition reactions to enones.[4] The adduct $Me_2CuLi \cdot LiX$ tends to self-aggregate in solution, and its structure and reactivity highly depend on the solvent, the specific additive, and the concentration.[1c, 5] Thus, a number of NMR spectroscopic and mass spectrometric studies have been undertaken to understand the solution behaviour of Gilman cuprates and the alkylation reaction mechanisms, which is still an active research field.[5-6]

However, the reactivity of MeCu has also been tamed by coordination of various ligands, such as phosphines[7] or N-heterocyclic carbenes (NHCs),[8] which now allows its use as co-catalyst for acrylonitrile polymerization[9] as well as for E–H bond activation reactions.[10] In analogy to Gilman cuprates, the solution behaviour of phosphine stabilized MeCu is extremely complex, including a wide range of equilibria involving naked CuMe, $\{CuMe\}_n$ oligomers and $[CuMe(PR_3)_n]$ complexes in various stoichiometries. On the basis of *in situ* NMR spectroscopic studies, dimerization of $[CuMe(PCy_3)]$ and subsequent methyl transfer from one Cu atom to another has also been proposed, leading to the presence of a cuprate complex in solution, but no structural evidence was available so far.[7a, 7c, 7d, 9] Herein, we report a dicopper(I) complex bearing a methyl ligand bridging the two copper atoms, which has wider implications for understanding cuprate chemistry and organocopper transmetalation reactions.

$[CuMe(PPh_3)_2]$ (**1**) was synthesized following a literature procedure, which involves reductive alkylation of $[Cu(acac)_2]$ with $Al(OEt)Me_2$ in the presence of an excess PPh_3, giving **1** as a yellow powder.[7a, 7b] Its further purification has been reported by washing the powder with diethyl ether; however, our attempts of purification via recrystallization of **1** led, unexpectedly, to the isolation of single crystals of $[Cu(PPh_3)_2(\mu\text{-}Me)CuMe]$ (**2**) (Scheme 1 and Fig. 1). Specifically, slow diffusion of diethyl ether into a THF solution of **1** at -30 °C gave **2** in 67% yield, while at higher temperature only decomposition of **1** is observed. Changing the conditions of the crystallization by substituting diethyl ether with hexane or C_6F_6 as the antisolvent yields $[CuMe(PPh_3)_3]$[7d] (**3**) instead.



Scheme 1 Conditions for isolation of **2** or **3** from dissolved **1**.

According to the single crystal X-ray diffraction data, **2** exhibits a carbon unit bridging two copper atoms, which raises the question of its identity, i.e. whether indeed a CH_3 group connects two Cu(I) atoms or whether a CH_2 moiety is present, indicating a mixed-valence complex with Cu(I) and Cu(II). Solid state EPR measurements of a cooled sample at -20 °C gave no magnetic answer, arguing against a paramagnetic mixed-valence compound.

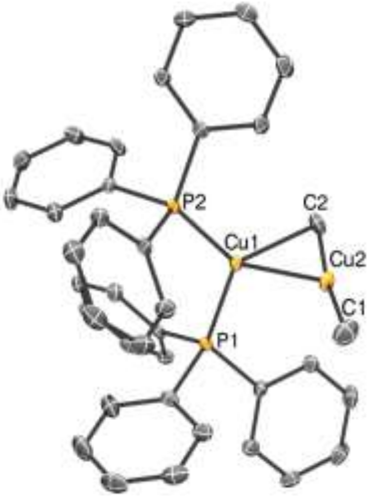


Fig. 1 Molecular structure of [Cu(PPh$_3$)$_2$(μ-Me)CuMe] (**2**) obtained from single crystal X-ray diffraction studies. Thermal ellipsoids drawn at 50 % probability level; H atoms omitted for clarity.

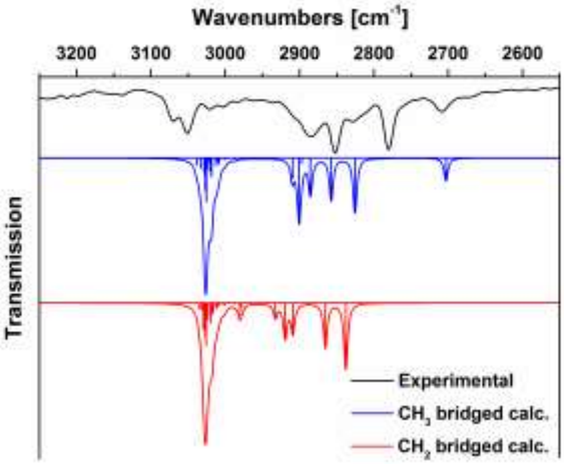


Fig. 2 Comparison of the experimental solid state IR spectrum of **2** (black) with the calculated spectra of [Cu(PPh$_3$)$_2$(μ-CH$_2$)CuMe] (red) and [Cu(PPh$_3$)$_2$(μ-CH$_3$)CuMe] (blue).

Compound **2** is highly sensitive towards moisture, oxygen and temperature, and decomposes at room temperature in solution quickly, albeit more slowly in the solid state. Nevertheless, several attempts were necessary to perform some quick solid-state NMR studies. The $^{13}C\{^1H\}$ CP/MAS solid-state NMR spectrum of crystalline **2** (Fig. S11) gives broad signals centred at +1, -5, -8 and -16 ppm, respectively, which can be attributed to chemically different methyl groups, but may also arise from partial decomposition or $^1J(^{63,65}Cu,^{13}C)$ couplings. However, the $^{31}P\{^1H\}$ CP/MAS solid-state NMR spectrum of a freshly prepared sample was acquired with 16 scans in 3 minutes (Fig. S12).

The spectrum shows two asymmetric quartets for the two inequivalent phosphorus atoms ($\delta_{iso}(^{31}P_A) \approx -2$, $\delta_{iso}(^{31}P_B) \approx -4.6$ ppm) in the crystal structure. The splittings between the lines of these quartets increase to higher field. The observed asymmetric quartets arise from *J* and residual dipolar couplings of the ^{31}P nuclei with the two copper isotopes, ^{63}Cu and ^{65}Cu. A spinsystem simulation without dipolar interaction can be found in the SI (Fig. S13). In addition, the ^1H BR24 Cramps solid-state NMR shows two signals at 0.8 and -0.6 ppm, which can be assigned to the different methyl moieties in **2** (Fig. S14).

The identity of the bridging alkyl moiety in **2** was further determined by ATR-FTIR spectroscopy and comparison with the calculated IR spectra (BP86-D3BJ/def2-tzvp/ZORA) for a hypothetical CH$_2$ bridged and a CH$_3$ bridged complex. The experimental IR spectrum of **2** gives five bands at 2710, 2781, 2830, 2852 and 2885 cm^{-1}, the latter with a shoulder, and several overlapping bands above 3000 cm^{-1} (Fig. 2). IR bands in the region between 2700 and 2900 cm^{-1} are typical for a bridging CH$_3$ group.[11] The calculated IR spectrum of [Cu^I(PPh$_3$)$_2$(μ-CH$_2$)Cu^{II}Me] shows five bands between 2838-2932 cm^{-1}, but the low energy vibration at 2710 cm^{-1} was only reproduced by [Cu^I(PPh$_3$)$_2$(μ-CH$_3$)Cu^{I}Me], giving five bands at 2703, 2825, 2857, 2885, and at 2901 cm^{-1} with a shoulder.

The identity of **2** being resolved as [Cu(PPh$_3$)$_2$(μ-Me)CuMe], its structure can either be understood as coordination of MeCu to [CuMe(PPh$_3$)$_2$], or as binding of $\{Cu(PPh_3)_2\}^+$ to one Cu–Me bond of linear dimethyl cuprate $\{CuMe_2\}^-$. We prefer the latter description due to the non-ideally trigonal planar coordination geometry of Cu2 and the C1–Cu2–C2 angle of 172.1(1)° (Table 1). In accordance with a donor-acceptor interaction between the cuprate and cationic $\{Cu(PPh_3)_2\}^+$, the Cu2–C2 bond (2.011(2) Å) is significantly increased compared to the bond between Cu2 and the terminal C1 (1.924(2) Å), which is within the range of other dimethyl cuprates.[3, 7c, 12] The geometry of the Cu1 atom is distorted tetrahedral, as can be seen from the angles around that metal centre given in Table 1. The Cu1–Cu2 distance of 2.4121(4) Å is very similar to the one found in {[*t*Bu$_2$P(NSiMe$_3$)$_2$-$\kappa^2 N$]Cu}$_2$(μ-CPh$_2$) (2.4165(3) Å), a rare example of a structurally characterized dicopper(I) complex with two copper atoms bridged only by an μ-carbene and not by other ligands.[13] However, **2** is, to the best of our knowledge, the first dicopper(I) complex bridged only by a methyl group.

Table 1 Selected structural parameters of [Cu(PPh$_3$)$_2$(μ-Me)CuMe] (**2**).

Distance (Å)		angle (°)	
Cu1–Cu2	2.4121(4)	C1–Cu2–C2	172.1(1)
Cu1–P1	2.2580(6)	P1–Cu1–P2	122.33(2)
Cu1–P2	2.2618(6)	C2–Cu1–Cu2	52.05(6)
Cu1–C2	2.137(2)	Cu1–C2–Cu2	
Cu2–C2	2.011(2)	C2–Cu2–Cu1	
Cu2–C1	1.924(2)	C1–Cu2–Cu1	

It has to be mentioned at this point that structural proof of di- or bimetallic complexes of the type {M(μ-Me)M} with no other bridging moieties is very rare. We found only one example in which two transition metals are bridged by solely a methyl group, i.e. [PtMe(dmpe)(μ-Me)Cu(PtBu$_3$)].[14] Two other structurally characterized compounds that are similar, MeLi and Me$_2$Mg complexes of {Ni(C$_2$H$_4$)$_2$} reported by Pörschke and co-workers, have been debated to contain additional interactions between the alkali/earth alkali metal and one of the olefin ligands at the nickel(0) center.[15]

The potential existence of monomeric cuprates of the type [L$_2$Cu(μ-Me)CuMe] (L = OMe$_2$, SMe$_2$) has been proposed on the basis of theoretical stability studies.[16] An NBO analysis showed that the calculated structures should gain their stability mainly from the donor-acceptor interaction between one of the Cu-Me bonds and the cationic $\{L_2Cu\}^+$ fragment, although cuprophilic interactions are also present, adding to the stabilization of the 3-center-2-electron-bond.[16] In line with that interpretation, the Mayer bond order in **2** obtained from our DFT calculations is ca. 1/3 for each of the bonds in the Cu1-Cu2-CH_3 triangle, which is mainly formed by HOMO, HOMO-5 and HOMO-11 (Fig. 3 and Fig. S8), the latter two involving cuprophilic interactions.

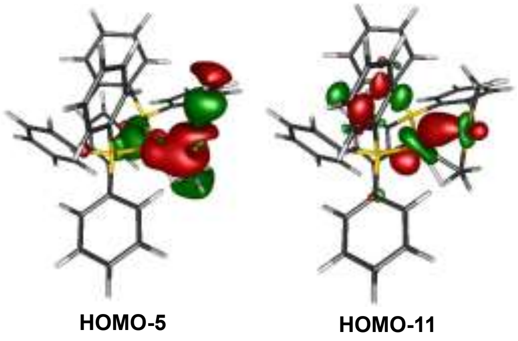
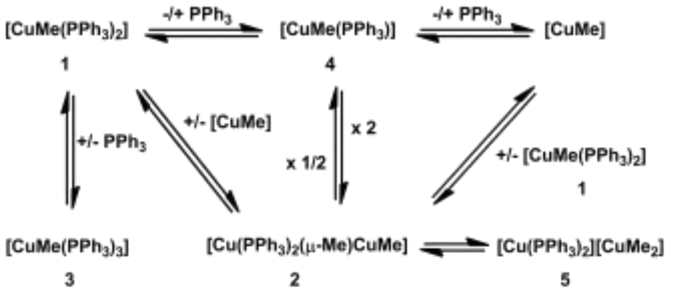


Fig. 3 Bonding orbitals of the Cu-(μ-Me)-Cu triangle motif in **2** obtained from DFT calculations (BP86-D3BJ/def2-tzvp/ZORA) showing the cuprophilic interactions.

The fact that either **2** or $[CuMe(PPh_3)_3]$ (**3**) are obtained from $[CuMe(PPh_3)_2]$ (**1**), depending on the solvent used for crystallisation, suggests an equilibrium between a number of species in solution. This apparently involves, for copper phosphine alkyl compounds, rare ligand redistribution, i.e. phosphine and methyl transfer between the two copper atoms (Scheme 2). In order for **1** to form **3**, phosphine association is necessary, which can only be generated by prior ligand dissociation from other **1**, forming $[CuMe(PPh_3)]$ (**4**). A PCy_3 analogue of **4** has previously been isolated, and formation of $[CuMe(PCy_3)_2]$ upon addition of phosphine has been suggested, which is the inverse reaction to our proposal.[9] Further loss of phosphine could give [CuMe], which promotes formation of isolated $[CuMe(PPh_3)_3]$ (**3**), and allows association to **1** giving the isolated complex **2**. An interesting reaction is dimerization of **4**, involving phosphine transfer from one copper atom to the other. Indeed, we were able to observe this ligand redistribution by dissolving **2** in d_8-toluene solution at -40 °C giving $[CuMe(PPh_3)]$ (**4**), as a ^1H-^{13}C HSQC NMR experiment shows a cross-peak at 0.50/-6.0 ppm, typical for monophosphine copper methyl complexes (Fig. 4).[7c, 8-9, 17]



Scheme 2 Possible equilibrium reactions arising from dissolution of **1** leading to the isolation of **2** and **3**, and to the observation of **4** and **5**.

In contrast, in d_8-THF solution at the same temperature the neutral compound $[Cu(PPh_3)_2(\mu\text{-}Me)CuMe]$ (**2**) dissociates into the ion pair $[Cu(PPh_3)]^+/[CuMe_2]^-$ (**5**) as the main species, giving rise to a ^1H-^{13}C HSQC cross-peak at -0.42/-7.5. However, further unidentified minor CuMe compounds are also present (^1H-^{13}C: -0.98/-15.5, 0.22/-5). The $^{31}P\{^1H\}$ NMR spectrum shows two broad overlapping resonances at -3 and -5 ppm, which are much broader than the one found in d_8-toluene at -4.1 ppm, indicating interconversion between these complexes (Figs. S17 and S22). The proposed equilibrium between **2** and **5** has been confirmed by re-dissolving **5** in d_8-toluene, which gave an ^1H-^{13}C HSQC spectrum identical to an original sample of **2** dissolved in the same solvent (Fig. S19).

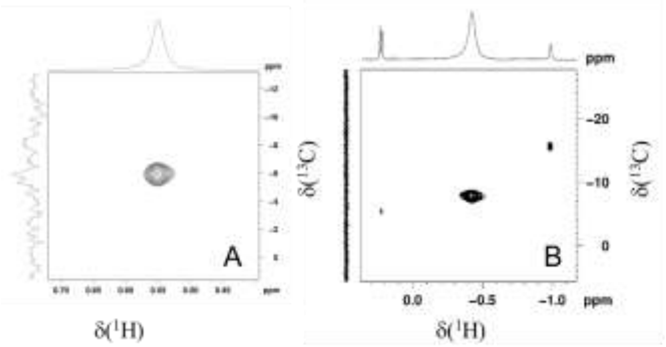


Fig. 4 ^1H-^{13}C HSQC NMR spectra after dissolving **2** in d_8-toluene (left, A) and d_8-THF (right, B) at -40°C. The projections in the f1-direction show the ^{13}C-DEPT135-NMR-spectra, respectively.

The isolation and structural characterization of the intermediate $[Cu(PPh_3)_2(\mu\text{-}Me)CuMe]$ (**2**) provides a nice snapshot of the above described methyl and phosphine ligand redistribution equilibrium. Several implications arise from our findings. The employment of copper alkyl phosphine complexes allows formation of a variety of species, which can potentially participate in the reaction of interest. For instance, both cuprates as well as free phosphine formed from $[CuMe(PCy_3)]$ can initiate anionic acrylonitrile polymerization, indicating that the original compound as such is not involved in the polymerization reaction.[9]

Furthermore, bimetallic intermediates, which are stabilized by weak metallophilic interactions, play an important role in cooperative bimetallic catalysis. Organic group transfer solely supported by labile d^8-d^{10} bonds has been proposed mainly on the basis of kinetic and DFT studies for Sonogashira and Stille cross-coupling reactions co-catalyzed by Cu(I) or Au(I),[18] and the Negishi coupling reaction is also thought to benefit from Pd(II)-Zn(II) bond formation.[19] Very recently, coupling of alkynes mediated by dual gold catalysis has been proposed to involve a di-gold(I) key complex exhibiting d^{10}-d^{10} aurophilic interactions.[20] Despite that aurophilic interactions are much stronger than cuprophilic interactions (15 vs. 4 kcal/mol),[21] our findings suggest that the latter can also foster ligand redistribution and organic group transfer.

A typical reaction of dimethylcuprate is alkylation of α,β-unsaturated ketones, such as 3-methyl-cyclo-2-hexen-1-one, which reacts with Gilman's reagent within 12 hours in almost quantitative yield.[4] In contrast, **2** shows only 50% conversion to give 3-dimethylcyclohexanone at room temperature as well as at -30 °C within 8 hours, partially due to decomposition. The degree of association between $[CuMe_2]^-$ and its counterion was shown to be very important for the reactivity,[1c, 5] and that the alkylation reaction of 4-methyl-cyclo-2-hexen-1-one stops upon adding 15-crown-5.[22] The formation of a π-complex between, e.g., Me_2CuLi, either as a monomer or as a contact ion pair, and the substrate is a crucial step, involving simultaneous coordination of Li^+ to the enone carbonyl oxygen and the cuprate.[6c, 23] In addition, theoretical studies suggest that bending of linear $[CuMe_2]^-$ by a coordination partner is crucial for weakening of the Cu–Me bond and would therefore increase the reactivity.[24] The lower activity of **2** compared to Gilman´s reagent in the methylation of enones can thus be explained with a much weaker interaction in solution between dimethylcuprate and $[Cu(PPh_3)_2]^+$ than with Li^+, which is due to the higher steric demand of the copper phosphine complex and its higher stability in solution as isolated cation.

In conclusion, we have isolated and structurally characterized the first dicopper(I) complex, $[Cu(PPh_3)_2(\mu\text{-}Me)CuMe]$ (**2**), in which two metal centres are solely bridged by a methyl group and experience stabilizing metallophilic interactions. Apart from **2**, only one Pt-Cu complex as an example for transition metal {M(μ-Me)M} compounds without further bridging ligands exists.[14] Complex **2** is a result of phosphine ligand redistribution and represents a transmetalation intermediate on the way from $[CuMe(PPh_3)_2]$ (**1**) to $[Cu(PPh_3)_2]^+[CuMe_2]^-$ (**5**), which we observed in solution. Thus, we were able to show a new bonding mode of CH_3 and provide structural evidence for previously proposed solution equilibria, giving further inside into transmetalation reactions of organocopper compounds.

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Notes and references

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Electronic Supplementary Information (ESI) available: Details of synthesis, NMR spectroscopy, computations and X-ray diffraction, as well as experimental and simulated NMR and IR spectra. See DOI: 10.1039/c000000x/

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