Synthesis, structure, and reactions of a copper–sulfido cluster comprised of the parent Cu$_2$S unit: {\((\text{NHC})\text{Cu}\)$_2\)(\mu-S)}

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The synthesis of the first Cu$_2$(\mu-S) complex, \((\text{IPr}^*)\text{Cu}_{2}\)(\mu-S) (\text{IPr}^* = 1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene; 1), has been accomplished via three synthetic routes: (1) salt metathesis between (IPr*)CuCl and Na$_2$S; (2) silyl-deprotection reaction between (IPr*)Cu(SSiMe$_3$) and (IPr*)CuF; and (3) acid–base reaction between (IPr*)Cu(SH) and (IPr*)Cu(OBu)$_3$. The X-ray crystal structure of 1 exhibits two two-coordinate copper centers connected by a bent Cu–S–Cu linkage. Application of these synthetic routes to analogous precursors containing the sterically smaller ligand IPr (1,3-bis(2,6-di-isopropylphenyl)imidazol-2-ylidene), in place of IPr*, resulted in the formation of a transient product proposed as \((\text{IPr})\text{Cu})_2\)(\mu-S) (2), which decomposes quickly in solution. The instability of 2 probably results from the insufficient steric protection provided by IPr ligands to the unsaturated Cu$_2$(\mu-S) core; in contrast, 1 is stable both in solution and solid state for weeks. The nucleophilic sulfido ligand in 1 reacts with haloalkyl electrophiles (benzyl halides and dibromoalkanes) with formation of C–S bonds, affording \((\text{IPr})\text{Cu}(\text{SCH}_2\text{Ph})\) and cyclic thioethers, respectively.

Introduction

Copper–sulfido clusters have attracted considerable interest due to their compositional and structural diversity, interesting chemical properties, and role in biochemical processes. The wide variety of stoichiometries and structures found for these clusters arises from the fact that both the copper and sulfur centers can possess a range of coordination numbers. Among copper(II)–sulfido clusters, for example, copper centers are found in two, three, and/or four-coordinate geometries, with coordination numbers for the sulfido ligands ranging from three to nine. The size range of these clusters is correspondingly broad, with examples to date spanning Cu$_4$(\mu$_4$-S)L$_m$ to Cu$_{136}$S$_{56}$L$_{19}$ (L = ancillary ligand).

Implicit in this compositional richness is that it is challenging to design synthetic routes to clusters of specific nuclearity and structure. One synthetic target of interest, for example, are clusters that model the active site of nitrous oxide reductase (N$_2$OR), which catalyzes the reduction of nitrous oxide to nitrogen and water. The histidine-ligated tetracopper cluster at this site (Chart 1) is known in two forms, one of which contains a single sulfido ligand (Cu$_4$(\mu$_4$-S), denoted Cu$_4^z$) and the other two sulfido ligands in the resting 2Cu$_1^0$Cu$_2^1$ redox state (Cu$_2$(\mu$_2$-S)L$_2$, denoted Cu$_2^z$). A few model clusters of the form Cu$_2$(\mu$_2$-S)(\mu-L)$_n$ (L = phosphine, amidinate) have been synthesized that qualitatively replicate the geometry of the Cu$_4$(\mu$_4$-S) core of Cu$_2$ and Cu$_2$. Explicit compositional models for the Cu$_2$(\mu$_2$-S) linkage in Cu$_2$ are also rare: there is a single example of a copper–sulfido complex that consists of the parent Cu$_2$(\mu$_2$-S) unit, [{Cu(2,2’-dipyridylsulfide)}$_2$(\mu$_2$-S)]$^{2-}$, and three clusters...
that contain two singly bridging sulfido ligands, of the type Cu$_2$(µ$_2$-S)$_2$L$_m$ (Chart 1). None of the clusters shown in Chart 1 are available in high synthetic yield (4–37%).

A general challenge to preparing these and other low-nuclearity copper–sulfido clusters is inhibiting condensation of their unsaturated Cu-S units into higher-nuclearity clusters. Nevertheless, such clusters are of general interest because they should allow study of properties and reactions of Cu$_n$S units in the absence of potentially complicating collective effects and multiple reaction sites.

The lack of general synthetic routes to low-nuclearity copper–sulfido clusters motivated us to consider whether bulky N-heterocyclic carbene (NHC) ligands would provide the steric shielding necessary to suppress condensation to higher-nuclearity structures, given that NHC ligands are well-known for the ability to stabilize low-coordinate metal complexes. Recently, we provided support for this hypothesis with a report of the synthesis and characterization of the copper(I) cluster [(IPr)Cu$_3$(µ$_2$-S)]$^+$ (IPr = 1,3-bis(2,6-di-isopropylphenyl)imidazol-2-ylidene). This cluster, together with two clusters of form Cu$_n$(µ$_n$-S)[$\mu$-L], reported recently by Mankad, are the smallest Cu$_n$(µ$_n$-S) clusters known to date. In [(IPr)Cu$_3$(µ$_2$-S)]$^+$, the steric protection provided by the IPr ligand is such that the copper centers are present in their lowest possible coordination number of two, and the cluster is stable without the bridging ancillary ligands found in all other examples of Cu$_n$(µ$_n$-S)L$_m$ clusters. In view of this finding, we investigated whether NHC ligands would allow synthesis and stabilization of the parent Cu$_2$(µ$_2$-S) cluster, of which there is one example for Cu$^{11}$ (Chart 1) and none for Cu$^{15}$. Herein, we describe three synthetic routes devised to provide [(NHC)Cu$^+$]$_2$(µ$_2$-S) compounds (Chart 2). The NHC ligands employed are IPr and IPr* (1, NHC = IPr*; 1,3-bis(2,6-(diphenylmethyl)-4-methylphenyl)imidazol-2-ylidene), and 2, NHC = IPr; these differ substantially from each other in steric bulk, in order to allow the relationship between stability of the complex and steric shielding to be assessed. It is found that all three synthetic routes provide these compounds as at least initial products, albeit in differing yields. Compound 1 is stable in the solid state and solution but 2 has only transient stability in solution, indicating that ancillary ligands with substantial steric bulk are necessary to stabilize these unsaturated clusters. Despite the steric protection provided by the IPr* ligands of 1, it is found that this complex reacts with organic electrophiles via formal transfer of the sulfido ligand.

**Results and discussion**

**Synthetic approaches to [(NHC)Cu$^+$]$_2$(µ$_2$-S) compounds**

The synthesis of the [(NHC)Cu$^+$]$_2$(µ$_2$-S) compounds 1 and 2 was attempted using three routes, shown in Scheme 1. Route (1) is a salt metathesis reaction between (NHC)CuCl and Na$_2$S. Routes (2) and (3) involve the reaction between a compound of the form (NHC)Cu(SR), in which the sulfido ligand of the ultimate product bears a protecting group, and a (NHC)CuX compound for which X is a suitable deprotecting moiety. In route (2) the protecting group is SiMe$_3$, where the reaction between (NHC)Cu(SiMe$_3$)$_3$ and (NHC)CuF could lead to formation of [(NHC)Cu$_2$(µ$_2$-S)]$^+$ via elimination of FSiMe$_3$. This general approach has been applied in the synthesis of [(IPr)Cu$_2$(µ$_2$-S)]Hg from the reaction between (IPr)Cu(SiMe$_3$)$_3$ and Hg(OAc)$_2$, of Cu$_2$m$_2$L$_m$ (L = phosphine) clusters via reactions between Cu(OAc) and S(SiMe$_3$)$_3$, in the presence of L$_1$ and by us to the synthesis of the cluster [(IPr)Cu$_3$(µ$_2$-S)][BF$_4$]$_2$ in which the reaction between [(IPr)Cu$_2$(µ$_2$-S)][BF$_4$]$_2$ and (IPr)CuF cleanly provides the product in 85% yield. In route (3) the protecting group is a proton, which could be removed in an acid–base reaction between (NHC)Cu(SH) and (NHC)Cu(ÔBu) with formation of the desired product and t-butanol. A potential advantage to route (1) is that it uses readily available (NHC)CuCl complexes as starting materials, whereas the precursors in routes (2) and (3) must first be prepared from (NHC)CuCl. On the other hand, routes (2) and (3) could be used, in principle, to prepare mixed-ligand (NHC)Cu(µ$_2$-S)Cu(NHC$^+$) complexes, unlike route (1). The application of these approaches to the synthesis of 1 and 2 are described and compared below.

**Synthesis and characterization of 1**

Compound 1 can be prepared via routes (1), (2), and (3) (Scheme 1), although the purity of the crude product and final yields vary considerably. For route (1), the reaction between excess Na$_2$S (2.5 equivalents) and (IPr*)CuCl$^{11}$ in THF at 50 °C for 2 h resulted in complete consumption of the copper starting material and formation of a light-yellow product subsequently identified as 1 in 67% isolated yield. The reaction is much slower at room temperature, with only ~50% conversion of (IPr*)CuCl to 1 being observed after 12 hours. Compound 1 is stable both in solution and the solid state under N$_2$ atmosphere at room temperature for weeks.

The composition and structure of 1 were established by $^1$H- and $^{13}$C-NMR spectroscopy, elemental analysis, and X-ray
S bond lengths and Cu numbering, but closely resemble those of the tricopper(I) 
cluster \([\{\text{IPr}\} \text{Cu}_3(\mu_3-S)]^+\) (113.02(3)°) and contrasts with the linear structure 
observed for \([\{\text{Cu}(2\text{-dps})_2\}_2(\mu_3-S)]^+\). The synthesis of 1 via route (2) involves the reaction between 
\([\text{IPr}^*\text{Cu}(\text{SSiMe}_3)]\) (3) and \([\text{IPr}^*\text{Cu}F\)] (4) (Scheme 2). Complexes 3 
and 4 have not previously been reported. A logical approach to the synthesis of 3 would seem to be the reaction between \([\text{IPr}^*\text{CuCl}\) and \(\text{S(SiMe}_3)\_2\), given that the analogous reaction between 
\([\text{IPr}^*\text{CuCl}\) and \(\text{S(SiMe}_3)\_2\) at room temperature for 1 hour 
provides the compound \([\text{IPr}^*\text{Cu}(\text{SSiMe}_3)]\) in 87% yield.† However, \([\text{IPr}^*\text{CuCl}\) is observed not to react with \(\text{S(SiMe}_3)\_2\) under identical conditions after several days. Instead, the new 
complex \([\text{IPr}^*\text{Cu}(\text{O'Bu})\)] (5) was found to be a suitable precursor for both 3 and 4. Compound 5 was prepared in 69% yield from the reaction between \([\text{IPr}^*\text{CuCl}\) and \(\text{KO'Bu}\) in THF (Scheme 2). Compound 3 is then cleanly prepared, in 90% isolated yield, 
from the reaction between 5 and one equivalent of \(\text{S(SiMe}_3)\_2\) in 
THF for 1 hour. Compound 4 was prepared by analogy to \([\text{IPr}^*\text{CuCl}\) 
and \(\text{NEt}_3\cdot3\text{HF}\) (91% yield). The compositions of 3, 4, and 5 were established by multinuclear 
NMR spectroscopy and elemental analysis (see ESI†).

Surprisingly, the reaction between an equimolar mixture of 3 
and 4 in THF for 1 hour yielded multiple products, as shown by the 
\(^1H\)-NMR spectrum of the isolated crude product (see ESI†). The crude product contains 1 (~28%, based on resonance 
integration), unreacted 3 (but not 4), and one other set of \(\text{IPr}^*\) 
signals that are not those of the free ligand, indicating it is 
another \(\text{IPr}^*\)-containing compound. Attempts to separate these 
compounds by recrystallization of the crude product proved 
fruitless, and the identity of the secondary product remains 
unknown. Given the complexities of route (2) compared to route 
(1) for the preparation of 1, it was not further investigated. The failure of route (2) stands in marked contrast to the success of 
this general approach in cleanly providing the related cluster 
\([\{\text{IPr}^*\text{Cu}_3(\mu_3-S)]^+\). In contrast to route (2), the acid–base deprotection strategy 
employed in route (3) cleanly provides 1 (Scheme 3). The terminal thioloate complex \([\text{IPr}^*\text{Cu}(\text{SSiMe}_3)]\) (6) was prepared in 86% 
isolated yield from the salt metathesis reaction between \([\text{IPr}^*\)
CuCl and KSH in methanol/THF (Scheme 3), and characterized by $^1$H and $^{13}$C-NMR spectroscopy, elemental analysis, and X-ray crystallography (see ESI†). Compound 6 is a rare example (together with 7, vide infra) of a terminal hydrosulfido complex of copper. The reaction between 6 and 5 cleanly provides 1 in 84% isolated yield (Scheme 3). The overall yield of CuCl via route (3) is 64%, which is slightly lower than that for route (1) (67% yield). Route (1) is preferred for the synthesis of 1 because it requires fewer steps, but route (3) might be useful for the preparation of mixed-ligand (NHC)Cu($\mu$-$\text{S}$)Cu(NHC′) complexes.

Attempted synthesis of 2

The synthesis of 2 (Chart 1) was attempted via the same three routes explored for the synthesis of 1 (Scheme 1) to determine whether the less bulky IPr ligand can support the Cu$_2$($\mu$-$\text{S}$) core. For each route, compounds of the form (IPr)CuX (X = Cl, SSiMe$_3$, F, O′Bu, SH (7)) were employed as starting materials; these are exactly analogous to the (IPr)CuX starting materials used for 1. The starting materials have been previously reported except for (IPr)Cu(SSiMe$_3$) and (IPr)CuF (route (2)) generated via the reaction between (IPr)CuCl and Na$_2$S (route (1)) contained X almost exclusively, together with a small amount of unreacted (IPr) CuCl (see ESI†). In contrast, the reaction between equimolar quantities of (IPr)Cu(SSiMe$_3$) and (IPr)CuF (route (2)) generated X, a new set of IPr signals that are not attributable to the starting materials or free IPr, and a new singlet resonance centered at 0.19 ppm, which is attributed to a Me$_3$Si-containing species that is neither 7 nor FSiMe$_3$. The nature of these additional species is unclear. The mixture produced from the reaction between equimolar quantities of (IPr)Cu(O′Bu) and 8 (route (3)) generated X and 2-BuOH, with the integration of the IPr and 2-Bu resonances being in a 2 : 1 ratio. This latter observation suggests that X contains two IPr ligands, and that X is compound 2.

At longer reaction times, the $^1$H-NMR spectra of the three reaction mixtures showed that product X formed via routes (1) and route (3) is relatively clean, whereas route (2) produced multiple products; this parallels the observations for the synthesis of 1 by these routes. The reaction between (IPr)CuCl and Na$_2$S (route (1)) contained X almost exclusively, together with a small amount of unreacted (IPr) CuCl (see ESI†). In contrast, the reaction between equimolar quantities of (IPr)Cu(SSiMe$_3$) and (IPr)CuF (route (2)) generated X, a new set of IPr signals that are not attributable to the starting materials or free IPr, and a new singlet resonance centered at 0.19 ppm, which is attributed to a Me$_3$Si-containing species that is neither 7 nor FSiMe$_3$. The nature of these additional species is unclear. The mixture produced from the reaction between equimolar quantities of (IPr)Cu(O′Bu) and 8 (route (3)) generated X and 2-BuOH, with the integration of the IPr and 2-Bu resonances being in a 2 : 1 ratio. This latter observation suggests that X contains two IPr ligands, and that X is compound 2.

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Scheme 5 Reaction of 1 with benzyl halides.

{([IPr*]Cu)₂(μ-S)}↓ (μ=S) → (IPr*)CuX + ([IPr*]Cu(SCH₂Ph) → (IPr*)CuX, X=BrCl

Quantitative yield

{([IPr*]Cu)₂(μ-S)}↓ → ([IPr*]Cu(SCH₂Ph))↓

Scheme 6 Reaction of 1 with 1, n-dibromoalkanes.

For route (3), decomposition of 2 provides free IPr and several other unidentified IPr-containing decomposition products. Due to its instability, attempts to isolate and characterize 2 and the accompanying products were unsuccessful.

The instability of 2 in solution is in stark contrast to 1, which is stable for weeks at room temperature in solution and the solid state under nitrogen atmosphere. Given the electronic similarity of the IPr and IPr* ligands, we surmise that the substantial steric bulk of the IPr* ligands of 1 plays a key role in shielding the Cu₂(μ=S) core. To probe this further, the structure of 2 in the gas phase was calculated using density functional theory (see ESIF). The calculated structure of 2 resembles that determined by X-ray crystallography for 1: it displays unremarkable Cu–C and Cu–S bond lengths and a smaller Cu–S–Cu bond angle (111° vs. 120° for 1), reflecting the decreased steric demands of the IPr ligand. These metrical parameters do not point to pronounced electronic differences between 1 and 2 that would account for the instability of the latter. The space-filling models of 1 and 2, shown in Fig. 2, suggest that the stability of 1 instead results from the substantial encapsulation of the Cu₃S core by the IPr* ligands, whereas the IPr ligands of 2 leave the sulfido ligand exposed.

Reactions of 1 with haloalkanes

The instability of 2 suggests that the bridging sulfido ligand of this class of compounds might be a reactive center. A DFT calculation of the frontier orbitals of 1 (see ESIF) shows that the HOMO and HOMO−1 possess substantial sulfur p orbital character, suggesting that the sulfido ligand might be reactive toward electrophiles. In this vein, previously reported dicopper(i) bridging-thiolato complexes of the form [[(IPr)Cu]₂(μ₂-Sₚ)]⁺ (R = CH₄Ph, PhBu, SiMe₃) have the appearance of the initial product that would result from formal attachment by R' to the sulfido ligand of 1. To investigate these possibilities, the reactions of 1 with haloalkanes were studied.

The reactions between 1 and benzyl halides (BnBr and BnCl) were studied by ¹H-NMR spectroscopy. Monitoring of an approximately equimolar mixture of 1 and BnBr in C₄D₆ at room temperature showed that BnBr was consumed in ~1 h, with the quantitative formation of a 1 : 1 molar ratio of (IPr*)CuBr and the new compound ([IPr*]Cu(SbN)) 8 (Scheme 5). The identity of 8 was established by independent synthesis from the reaction between 5 and BnSH (see ESII). The analogous reaction between 1 and 1.2 equivalent of BnCl forms ([IPr*]CuCl) and 8 but is much slower than the BnBr reaction, requiring ~3 days to reach completion at room temperature. At higher temperature (50 °C) the reaction is complete in ~12 h (see ESII).

These clean reactions suggested that 1 might be competent to transfer the sulfido ligand to appropriate substrates. This was explored by reacting 1 with dibromo alkanes (Scheme 6). Treatment of 1 with 1.4 equivalents of 1,3-dibromopropane in C₄D₆ at room temperature resulted in the immediate consumption of 1 and concurrent formation of ([IPr*]CuBr and a reaction intermediate, proposed as ([IPr*]Cu[Si(CH₃)₃Br]) 9 on the basis of its ¹H-NMR signals (δ 3.37 (t, SiCH₃), 2.85 (t, BrCH₂), 1.82 (quin, CH₃CH₂CH₂); see ESIF†). Over the course of 7 h, 9 was gradually consumed, with the concomitant formation of the cyclic thioether thietane (identified by GC-MS and ¹H-NMR spectroscopy) and ([IPr*]CuBr in near quantitative yields. The reactions of 1 with 1,4-dibromobutane or 1,5-dibromopentane proceeded much faster at room temperature. Both reactions were complete within 1 h, with the formation of ([IPr*]CuBr and tetrahydrothiophene or tetrahydrothiopyran in quantitative yields (see ESII). These reactions probably involve the same pathway proposed for the reaction of 1 with 1,3-dibromopropane, although in neither case could reaction intermediates analogous to 9 be observed in the ¹H-NMR spectrum recorded ~5 min after the mixing of reactants in C₄D₆.

The mild conditions for these reactions contrast with those required for the synthesis of the same cyclic thioethers from 1, n-dibromoalkanes and Na₅S. A thorough study of solvents and conditions for the latter reactions showed that optimal product yields (65–95%) are obtained in DMSO solvent at 150 °C, and that lower yields (30–75%) were obtained at lower temperatures or with use of other common solvents (C₆H₆, THF, ETOH, DMF), even with extended heating. While the synthesis of these particular thioethers from 1 is not of practical importance, the mild conditions suggest that 1 might be useful to affect sulfido transfer to more complex organic molecules that present halalkyl substituents. Preliminary evidence indicates that this mode of reactivity is not general to low-nuclearity copper–sulfido clusters: the related cluster [[(IPr)Cu]₃(μ₂-S)] shows no reactivity towards either BnBr or 1,4-dibromobutane at room temperature over five hours.

Conclusions

The compound ([IPr*]Cu)₂(μ-S) 1 is only the second example of a copper–sulfido cluster comprised of a single Cu₃(μ-S) core and the first with the Cu¹ oxidation state. Of the three synthetic routes tested (Scheme 1), the salt metathesis reaction between ([IPr*]CuCl and Na₅S (route 1)) is preferred due to its simplicity and good yield. The acid–base reaction between ([IPr*]CuSH and ([IPr*]Cu(OBu) (route 3)) provides 1 in comparable yield but requires more steps; however, it may be suitable for preparing mixed-ligand (NHC)Cu(μ₂-S)Cu(NHC) compounds. The synthetic routes that produce 1 appear also to generate 2 transiently, but it decomposes too quickly to allow isolation. The stability of 1 evidently depends upon encapsulation of the Cu₃(μ-S) core by the bulky IPr* ligands. The comparative steric...
openness of 2 is evidenced by the capacity of the sulfido ligand to accommodate another \([\text{IPr}]\text{Cu}^+\) unit, in the cluster \([-\text{IPrCu}^+_{2(\mu-S)}\])

\(^{2}\text{x}\). Despite the steric protection afforded by the \(\text{IPr}^*\) ligands of 1, it reacts with haloalkanes with resulting formation of C–S bonds.

The demonstration that the \(\text{Cu}_2(\mu-S)\) reactive core can be stabilized by ligands of suitable steric bulk suggests that other clusters of this class can be prepared with comparably sized NHC by the routes described here, and possibly with other bulky supporting ligands.

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