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"Higher Order" Cyanocuprate Structure: Cyanide Is Lithium Bound

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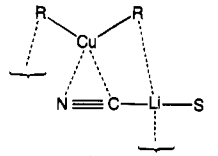
Preparing organocuprates from CuI in the mid 1960's, House, Whitesides,[1a] Posner, and Corey[1b] pioneered the resulting avalanche of applications in organic synthesis. House subsequently introduced CuBr·DMS as a precursor for organocuprates with improved stability and reactivity.[2] In 1981, Lipshutz employed CuCN as the source of Cu(I) and showed that the cuprate reagent prepared from 2 equiv of alkyllithium and 1 equiv of CuCN provided high yields in the alkylation of secondary alkyl chlorides.[3] In spite of the fact that others had previously exploited R_3CuLi_2 compositions for improved yields and enhanced stereoselectivity,[4] "$R_2Cu(CN)Li_2$" was proposed as a fundamentally new type of reagent and named a "higher order" mixed cuprate. Although no definitive spectroscopic or structural evidence was presented then or since, the postulate of a tricoordinate, dianionic copper σ-bound by cyanide[5] continues to decorate the literature.[6] Evidence to the contrary has come from NMR,[7] EXAFS,[8] and theoretical studies.[9] The latter investigations not only underscore the absence of a metal-ligated cyanide, but also present specific, low-energy alternatives for the structure of the reagent. In an attempt to counter this body of work, Lipshutz and James have recently amended the "higher-order" cuprate concept by suggesting the existence of a complex in which the cuprate is π-bonded to cyanide **1**.[10]



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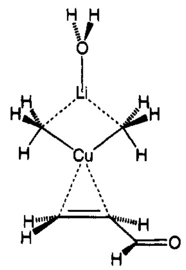

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To examine the updated Lipshutz proposal, a series of calculations employing density-functional theory (DFT) in combination with relativisitic pseudopotentials on copper have been performed. DFT can provide equlibrium geometries, vibrational frequencies, bond dissociation energies, and reaction energies in excellent agreement with experiment.[11] For first row transition metals, the relatively inexpensive B3LYP functional[12] outperforms MP2 and has been suggested to be the method of choice for small transition metal systems.[13] The Gaussian 92/DFT B3LYP implementation[14] was used in the present work as B3LYP/LANL2DZ.[15] For methylcopper the method yields a bond length of 1.927 Å and a zero-point energy corrected dissociation energy of 49.9 kcal/mol. Agreement with results at the triple ζ correlated level is excellent (1.936 Å and 49.0 kcal/mol, respectively[18]). Optimization of the dimethylcuprate anion results in a bond length of 1.988 Å, slightly overestimating the X-ray determined values of 1.936[19a] and 1.941[19b] Å for the uncomplexed anion.

Features of the π-complex of acrolein and lithiated dimethylcuprate **2** include a molecule of water coordinated to the lithium cation as a first solvation sphere surrogate for the ether solvent ordinarily employed in cuprate chemistry. The $Me_2CuLi\cdot(OH_2)$ moiety lies in a plane containing the olefinic carbons and orthogonal to the average plane of the conjugated system. Though copper lies over the center of the C=C bond, the Cu−C bond lengths are slightly asymmetric (r(Cu−CH$_2$) 2.085; r(Cu−CHC) 2.142 Å) as previously calculated at lower levels of theory.[9c,20] The complexation energy is 14.9 kcal/mol relative to the sum of the energies for the isolated, optimized fragments.

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(15) LANL2DZ as incorporated in Gaussian 92 employs the Los Alamos 10-electron effective core potential (ECP-2) plus double ζ (DZ) basis for copper ((8s2p5d)/[3s2p2d] contraction with (341/311/41) splitting)[16] and utilizes the D95V basis[17] for atoms from H to Ne.

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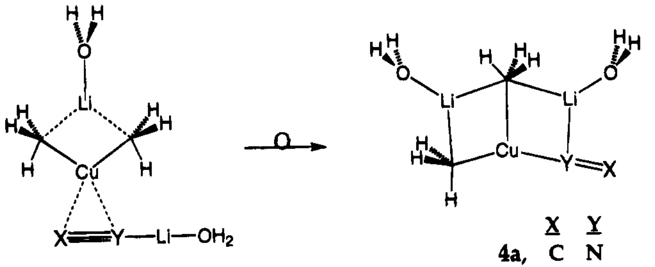
Structure **2** was modified to **3** by replacing acrolein with $CNLiOH_2$ and $NCLiOH_2$ in two separate experiments; the copper positioned directly over the center of the C=N bond in both. Optimization with B3LYP/LANL2DZ causes a no-barrier rearrangment characterized by the loss of π-complexation and by the association of the cyanide bonded lithium cation with one of the cuprate methyl groups. The resulting structures **4a,b** are best described as two dimensional ladders with three rungs. Similar topologies have been observed for lithium amides[21] and lithium phosphanides[22] in the solid state by X-ray crystallography. A particularly apt analogy is the three-rung mixed aggregate of lithium diisopropylamide and lithium chloride (**5**).[23] The second ladder rung is a relatively long Li−Cl bond, as is the corresponding $Cu-CH_3$ bond in **4a** [r(Cu−C) ladder rail 2.071 Å, ladder rung 2.270 Å]. Barrierless reorganization of the π-complexes to **4** can be attributed to electron repulsion occasioned by attempting to bring the lithiated but nevertheless highly ionic cyanide and cuprate aggregates together in intimate association.



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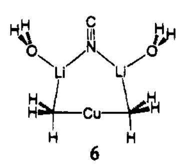
	X	Y
4a,	C	N
b,	N	C



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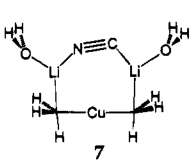

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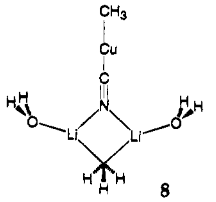

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Coulombic repulsion can be mediated by moving the lithium cations between the anions to give topological isomers **6**−**8**. Not only are the negative centers separated in space relative to **4**, but both anions within the complex benefit by energy-lowering interactions with both cations. The optimized structures are calculated to be 21.7, 20.6, and 20.5 kcal/mol, respectively, more stable than **4a**. The result that the latter *asymmetric* bicyclo[2.2.0] system is a local minimum stands in contrast to the findings for analogous *symmetric* R_2CuXLi_2 bicycles treated at a similar level of theory.[9a,c,20,24] In those cases, the [2.2.0]-structures spontaneously ruptured the central ladder bonds in a smooth downhill process to give monocycles similar to **6**. Constraint of the central connection to average bond distances led to optimized structures from 15−20 kcal/mol above the latter. The even higher energy of **4** relative to **6** suggests that bicycles **4a,b** reside in very shallow energy minima.

Not coincidentally, structure **6** corresponds to the global minimum found previously in the examination of a more complete set of isomers of $Me_2Cu(CN)Li_2{\cdot}(OH_2)$.[9a] The absence of copper-bound cyanide in THF at −78 °C by NMR,[7] EXAFS,[8] and XANES[8b] not only rules out a higher-order cuprate, but also **8**. Boltzmann populations (−78 °C) derived from the DFT energies concur: **6** (87%), **7** (7%), **8** (6%).

A complementary comparison furnishes additional support for the $Li_2(CN)^+$ bridged linear dimethylcuprate **6** as a prime candidate for the solution structure of $Me_2Cu(CN)Li_2$.[9] EXAFS measurements suggest a 0.04 Å increase in the average Cu−C bond length upon passing from the latter to the π-complex formed with methyl *trans*-cinnamate. The corresponding calculated increase in the same direction for **2** and **6** is 0.12 Å. Given the differences in enone structure between experiment and theoretical model, the bond lengthenings are mutually supportive.

In conclusion, the supposition of a π-complex between the metal in dialkylcuprates and the cyanide anion is supported by neither experiment nor theory. Quantitatively, formulation **1** is at least 25 kcal/mol higher in energy than other topologies such as **6**−**8**. Qualitatively, this can be understood as a problem in charge separation. In the absence of other strong influences, a collection of charged particles will arrange itself to minimize repulsion between like charges and maximize interactions between unlike ones. The highly ionic species $Me_2Cu(CN)Li_2 = Me_2CuLi{\cdot}LiCN$ containing three anions and three cations clearly prefers monocyclic **6** with CN nitrogen flanked by a pair of lithium cations. At the level of theory employed here and elsewhere,[9] the Li_2CN bridged dialkylcuprate Gilman structure is the favored arrangment assuming that the six particle aggregate is a discrete species in THF solution. Although the electron repulsion principle applies equally well to monomers or oligomers, indirect support for the assumption of monomers is found in the molecular weight determination for Me_3CuLi_2,[25] the participation of both Me_3CuLi_2 and Me_3Cu_2Li in detectable equilibria,[5b,25] the mediation of copper ligand exchange by Me_3Cu_2Li[26] and the insolubility of $Me_5Cu_3Li_2$,[4b] all in THF. NMR studies on Me(R)Cu(CN)Li_2 in THF, though not definitive, are likewise consistent with monomeric structures.[5c,27]

Finally, the answer to the question "If the cyano ligand is not on copper, then where is it?"[10] is clear. It is on the lithiums.

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[27] A referee suggests that the equally intense methyl doublet in the ^1H and ^{13}C NMR spectra of Me(R)Cu(CN)Li_2 (R = n-Bu) of ref 5c implicates aggregates rather than monomers such as **6**. The same paper, however, reports a methyl singlet for R = t-Bu and an unequal methyl doublet (1:2) for R = Ph. When CN is replaced by SCN, the methyl resonances appear in a ratio of 1:4. A common aggregate structure would not seem compatible with these observations. The small energy differences between **6**, **7**, and **8** (0.0, 1.1 and 1.2 kcal/mol, respectively) suggest that relative populations can be perturbed by changes at both R = Me and CN. The varying Me ratios are thus reasonably interpreted as a shift in the equilibrium partition between **6**−**8** in response to substitution.