

Effect of HMPA on the Composition of Organocyanocuprates. First Observation of a ${}^2J_{{}^{13}\text{C}-{}^{13}\text{CN}}$ Coupling Constant in a Vinylcyanocuprate

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Abstract: Variable temperature ${}^1\text{H}$ - and ${}^{13}\text{C}$ -NMR spectroscopic analysis of THF and THF–HMPA solutions of stannylcyanocuprates, as well as their addition products to 1-alkynyl ethers have been conducted. When prepared in the presence of HMPA, the reagents and addition products formed exist as mixtures in which some free lithium cyanide is present and the remaining cyanide is otherwise complexed. When stannylcyanocuprates were prepared in THF solutions no LiCN was detected. Heteronuclear NMR of the intermediates formed in the low-temperature reaction of a ${}^{13}\text{C}$ -labeled acetylenic ether with a THF–HMPA solution of stannylcyanocuprate $(\text{Bu}_3\text{Sn})_2\text{Cu}({}^{13}\text{CN})\text{Li}_2$ reveals a ${}^{13}\text{CN}-{}^{13}\text{C}$ -vinyl carbon coupling consistent with a vinylcuprate intermediate containing cyanide and a vinyl group bound to a common center. Coupling between a metal bound ${}^{119}\text{Sn}$ and ${}^{13}\text{C}$ -vinyl carbon was observed in the intermediate suggesting these two atoms are bound to a common center. The lack of ${}^{119}\text{Sn}-{}^{13}\text{CN}$ coupling in the intermediate suggested ${}^{119}\text{Sn}$ and ${}^{13}\text{CN}$ were bound to different atoms. Requirements are met in both higher order and lower order cuprate structures. When “ $\text{Me}_2\text{Cu}({}^{13}\text{CN})\text{Li}_2$ ” is prepared in THF, no free LiCN is observed and neither is it generated on addition of HMPA. When $\text{Me}_2\text{Cu}({}^{13}\text{CN})\text{Li}_2$ is prepared in HMPA-containing solutions it exists with the corresponding cyanide-free species and LiCN.

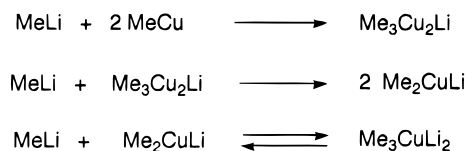
Introduction

Since the 1952 report by Gilman *et al.*² of the *in situ* preparation of Me_2CuLi (1), organocuprates have become favorite reagents for many transformations. House,³ and later others,⁴ demonstrated that cuprates, prepared from CuI, underwent reactions not readily effected by organometallics based on lithium or magnesium. While the versatile chemistry of cuprates has grown⁵ knowledge of the nature of the species has lagged.

In 1977 Ashby reported⁶ that several methylcopper species were formed from mixing $\text{MeLi}-\text{MeCu}$ in different stoichiometric ratios. Thus, in Me_2O and THF, species with the stoichiometry of $\text{Me}_3\text{Cu}_2\text{Li}$ and Me_2CuLi were found to exist when the $\text{MeLi}-\text{MeCu}$ ratio was 1:2 and 1:1, respectively. When the ratio $\text{MeLi}-\text{MeCu}$ was 2:1, evidence for an equilibrium mixture of species with the stoichiometries of Me_3CuLi_2 , Me_2CuLi , and MeLi was found (Scheme 1).

The presence of Me_3CuLi_2 was considered to be responsible for the higher stereoselectivity⁷ and reactivity⁸ observed in mixtures of MeLi and Me_2CuLi compared with those in MeLi or Me_2CuLi .⁹

Scheme 1



In 1981 Lipshutz *et al.* proposed¹⁰ the formation of “higher order mixed cyanocuprates” (H.O. cuprates) by the addition of 2 equiv of an organolithium reagent (MeLi) to 1 equiv of copper cyanide (CuCN). These H.O. cyanocuprates $[\text{Me}_2\text{Cu}(\text{CN})\text{Li}_2]$ were assumed to be dianionic salts with three ligands, one the cyano group, bound to copper; hence, they are formally $\text{Cu}(\text{I})$ dianionic salts.¹¹

It has been claimed that higher order cuprates are more reactive and give higher yields in displacements and epoxide openings than the lower order Gilman-like cuprates.¹² Higher order cuprates are claimed to be more stable than lower order cuprates. Their higher stability has been attributed¹³ to back-bonding from the filled d-orbital on copper into the empty π^* -orbital on the nitrile ligand.

Whether or not the cyanide ligand is bonded to copper in H.O. cuprates has been a topic of recent controversy.^{14–16} An alternative formulation for these reagents was proposed by Bertz¹⁵ in which the cyano group is not covalently bound to copper but is present as lithium cyanide coordinated to a Gilman-

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(2) Gilman, H.; Jones, R. G.; Woods, L. A. *J. Org. Chem.* **1952**, *17*, 1630.

(3) House, H. O.; Respass, W. L.; Whitesides, G. M. *J. Org. Chem.* **1966**, *31*, 3138.

(4) (a) House, H. O.; Umen, M. J. *J. Org. Chem.* **1973**, *38*, 3893. (b) Whitesides, G. M.; Fischer, W. F.; San Filippo, J.; Bashe, R. W.; House, H. O. *J. Am. Chem. Soc.* **1969**, *91*, 4871. (c) Corey, E. J.; Posner, G. H. *J. Am. Chem. Soc.* **1967**, *89*, 3911.

(5) (a) Posner, G. H. *Org. React.* **1972**, *19*, 1–113. (b) Lipshutz, B. H.; Sengupta, S. *Org. React.* **1992**, *41*, 135–631.

(6) Ashby, E. C.; Watkins, J. J. *J. Am. Chem. Soc.* **1977**, *99*, 5312.

(7) Macdonald, T. L.; Still, W. C. *J. Am. Chem. Soc.* **1975**, *97*, 5280.

(8) House, H. O.; Chu, C. Y. *J. Org. Chem.* **1976**, *41*, 3083.

(9) Ashby, E. C.; Lin, J. J. *J. Org. Chem.* **1977**, *42*, 2805.

(10) Lipshutz, B. H.; Wilhelm, R. S.; Floyd, D. M. *J. Am. Chem. Soc.* **1981**, *103*, 7672.

(11) Lipshutz, B. H.; Wilhelm, R. S.; Kozlowski, J. A. *Tetrahedron* **1984**, *40*, 5005.

(12) Lipshutz, B. H. *Synthesis* **1987**, *4*, 325.

(13) Lipshutz, B. H.; Kozlowski, J. A.; Wilhelm, R. S. *J. Org. Chem.* **1983**, *48*, 546.

(14) Lipshutz, B. H.; Sharma, S.; Ellsworth, E. L. *J. Am. Chem. Soc.* **1990**, *112*, 4032.

(15) Bertz, S. H. *J. Am. Chem. Soc.* **1990**, *112*, 4031.

(16) Bertz, S. H. *J. Am. Chem. Soc.* **1991**, *113*, 5470.

like species ($\text{Me}_2\text{CuLi}\cdot\text{LiCN}$). This formulation was based on the fact that no significant differences were observed between the ^{13}C -NMR chemical shifts for C-1 of methyl- and ethylcuprates, prepared from 2 equiv of the organolithium reagent and CuI or CuCN. Lipshutz reported¹⁴ that although the ^{13}C -NMR resonances for C-1 in cuprates prepared from CuCN [$\text{Me}_2\text{Cu}(\text{CN})\text{Li}_2$] and CuI ($\text{Me}_2\text{CuLi}\cdot\text{LiI}$) are coincident when the species are examined in THF solutions, they are observed at significantly different locations when examined in DMS and Et_2O solutions.

Support for the Bertz formulation was the observation¹⁶ that for THF solutions containing 2 equiv of MeLi or EtLi and 1 equiv of Cu^{13}CN no 2J ^{13}C - ^{13}CN couplings were observed between C-1 (in Me and Et groups) and ^{13}CN at -78 and -100 °C with or without HMPA. Nevertheless, 2J ^{13}C - ^{13}CN coupling constants (20.8–22.0 Hz) were observed for $\text{MeCu}(\text{CN})\text{Li}$ when recorded under the same conditions. This was interpreted as confirmation of a Cu–CN σ -bond in these species.

EXAFS and XANES spectra both provide strong evidence that addition of cyanide to a dialkylcuprate does not cause a detectable change in the copper center.¹⁷ For solutions of $\text{Bu}_2\text{Cu}(\text{CN})\text{Li}_2$, at least 90% of the copper atoms do not contain coordinated cyanide. To reconcile the higher reactivity of cyanocuprates it was suggested that the higher reactivity of $\text{R}_2\text{Cu}(\text{CN})\text{Li}_2$ compared to $\text{R}_2\text{CuLi}\cdot\text{LiX}$ may be due to catalytic amounts of the former species in solution.

Theoretical calculations considered¹⁸ alternative structures for cuprates with the constitutional formula $(\text{CH}_3)_2\text{Cu}(\text{CN})\text{Li}_2$ (**2**) (Figure 1). The structures considered possessed cyanide bound to lithium through the nitrogen (**3**, **4** and **6**), both carbon and nitrogen (**5**), and the cyanide bound to lithium and copper (**7**–**10**). Calculations suggested that structures **3**–**5** were the most stable, and of these, **3**, in which the nitrogen of cyanide was bound to lithium, was the most stable.

Lipshutz has recently reported¹⁹ that, when LiCN, generated by different methods, is reacted with cuprate Me_2CuLi (**1**) in THF solution, the product exhibits NMR spectroscopic characteristics identical to those obtained for the cuprate $\text{Me}_2\text{Cu}(\text{CN})\text{Li}_2$. Furthermore, signals due to free LiCN were not observed in these experiments. A new mode of bonding was suggested for dimethylcyanocuprates in which, the cyano ligand was σ -bonded to Li^+ and π -bonded to copper. Structures with this bonding are not higher order.

Recent EXAFS and XANES studies²⁰ have shown that the addition of cyanide to dimethylcuprate **1** does not cause a significant change at the copper center. However, addition of methyl *trans*-cinnamate to solutions of **1** led to changes attributed to a cuprate–enoate π -complex. Calculations²¹ suggested that the dimethylcuprate **1**, π -complexed to LiCN, is at least 25 kcal/mol higher in energy than structures **3**–**5**. It was suggested that the rearrangement of this π -complex to more energetically favored **3** was spontaneous.

This paper presents spectroscopic evidence that, when prepared in HMPA containing solutions, cyanocuprates $\text{Me}_2\text{Cu}(\text{CN})\text{Li}_2$ (**2** or $\text{Me}_2\text{CuLi}\cdot\text{LiCN}$) and $(\text{Bu}_3\text{Sn})_2\text{Cu}(\text{CN})\text{Li}_2$ (**11**) exist as mixtures with their corresponding lower order Gilman-like cuprates and lithium cyanide. However, when they are prepared in THF solutions, no free lithium cyanide is detected. Variable temperature ^{13}C -NMR studies of THF–HMPA solu-

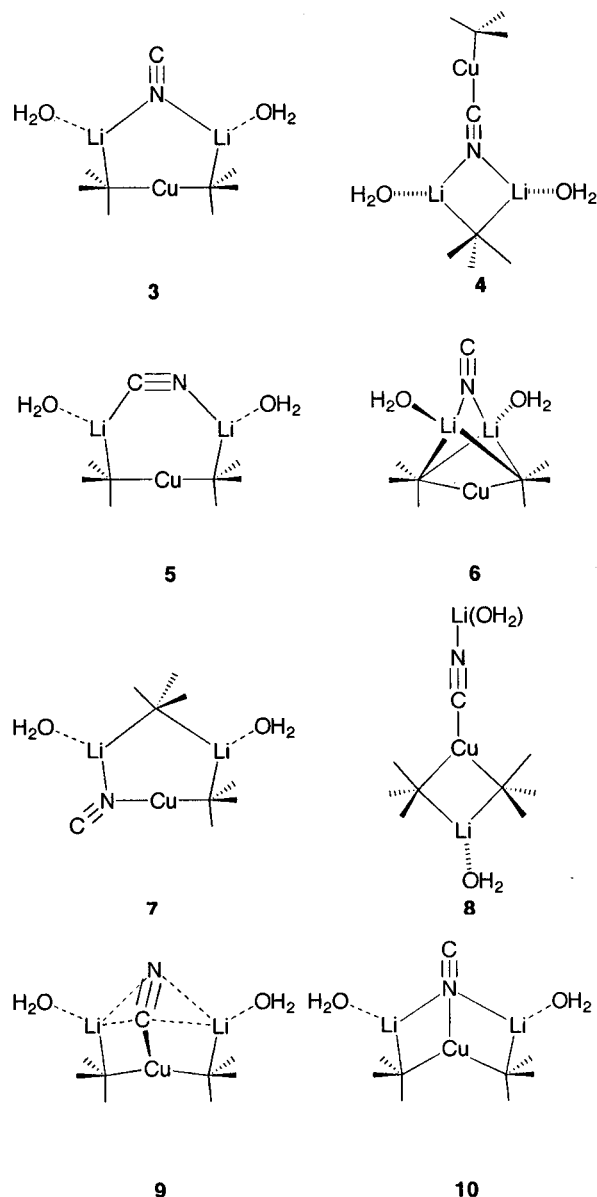


Figure 1.

tions of cuprates $(\text{Bu}_3\text{Sn})_2\text{Cu}(\text{CN})\text{Li}_2$ (^{13}CN)**11**) and $(\text{Bu}_3\text{Sn})\text{MeCu}(\text{CN})\text{Li}_2$ (**12**) have shown that in THF–HMPA solutions with these stoichiometries, cyanide exists in a rapid equilibrium between several species, in some of which, cyanide is bound through its carbon atom presumably to copper, as suggested by the observation of tin satellites in its signals.

A study of intermediates formed in the reaction of **11** with acetylenic ether **13** has resulted in the first observation of a 2J $^{13}\text{C}_{\text{vinyl}}\text{--}^{13}\text{CN}$ coupling constant in a vinylstannylcyanocuprate, showing that the cyano ligand is indeed bound in these intermediates. Although we did not observe 2J $^{13}\text{CN}\text{--}^{119}\text{Sn}$ coupling, we did observe a coupling assigned to 2J $^{13}\text{C}_{\text{vinyl}}\text{--}\text{Sn}$ wherein the tin is bound to the organometallic center.

Results and Discussion

In our previous work²² on the stannylcupration of acetylenic ethers, it was observed that when stannylcyanocuprate **11**, prepared in THF, reacted with acetylenic ether **13** at 0 °C, the ^1H -NMR spectrum of the resulting solution exhibited a major signal for vinylcuprate **14** at 5.06 ppm ($J_{\text{SnH}} = 100$ Hz) (Scheme 2, path a). When the same cuprate was prepared in

(17) Stemmler, T.; Penner-Hahn, J. E.; Knochel, P. *J. Am. Chem. Soc.* **1993**, *115*, 348.

(18) Snyder, J. P.; Spangler, D. P.; Behling, J. R.; Rossiter, B. E. *J. Org. Chem.* **1994**, *59*, 2665.

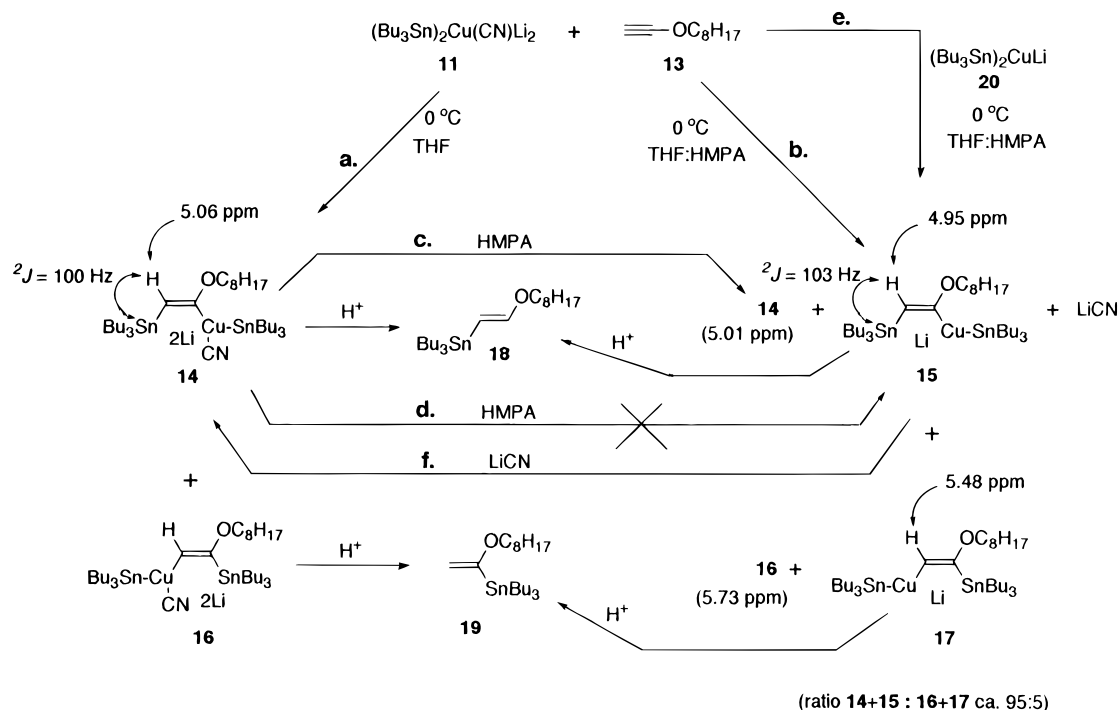
(19) Lipshutz, B. H.; James, B. *J. Org. Chem.* **1994**, *59*, 7585.

(20) Barnhart, T. M.; Huang, H.; Penner-Hahn, J. E. *J. Org. Chem.* **1995**, *60*, 4310.

(21) Snyder, J. P.; Bertz, S. H. *J. Org. Chem.* **1995**, *60*, 4312.

(22) Cabezas, J. A.; Oehlschlager, A. C. *Synthesis* **1994**, *4*, 432.

Scheme 2



the presence of 17 equiv of HMPA (33% v/v) and reacted with **13** at 0 °C, the ^1H -NMR spectrum exhibited two major signals due to intermediates **14** and **15** at 5.01 ($^2J_{\text{SnH}} = 100$ Hz) and 4.95 ($^2J_{\text{SnH}} = 103$ Hz) ppm, respectively (Scheme 2, path b). Smaller amounts of regioisomeric vinylcopper intermediates **16** and **17** were also present in these solutions. Methanolysis of solutions generated by both reaction conditions (Scheme 2, paths a and b) gave vinylstannanes **18** and **19** in a ratio of 95:5 in 94% yield. Gradual addition of HMPA (17 equiv) to THF solutions of intermediate **14** shifted its signals from 5.06 to 5.01 ppm but did not result in formation of the lower order species **15** (Scheme 2, paths c and d). Identity of lower order (L.O.) vinylcuprate **15** was confirmed by spectroscopic comparison with a sample obtained by the reaction, at 0 °C, of **13** with L.O. cuprate $(\text{Bu}_3\text{Sn})_2\text{CuLi}$ (**20**, prepared in the presence of 17 equiv of HMPA, 33% v/v) (Scheme 2, path e). Addition of LiCN(s) to **15** generated vinylcyanocuprate **14** where presumably, cyanide ligand was covalently bound (Scheme 2, path f). An important observation is the difference in the value of $^2J_{\text{SnH}}$ geminal coupling constants observed in these two intermediates, and while this value is 103 Hz for intermediate **15**, it changes to 100 Hz for vinylcyanocuprate **14**, suggesting that cyanide ligand is bound in **14**. If this donor is σ -bound it would be expected to diminish the electropositive character of metal centers in this intermediate, increasing the negative charge in the cuprate. It is known that geminal couplings in alkenes are very dependent upon the nature of the substituents at the other end of the double bond; thus, the less electropositive the substituent the smaller the value of the geminal coupling.²³ This is in accordance with the observed decrease in $^2J_{\text{SnH}}$ geminal coupling when one adds LiCN to **15**.

Since addition of HMPA (17 equiv) to THF solutions of **14** does not convert it to **15** (Scheme 2, path d), it is suggested that the formation of both **14** and **15** from the reaction of **13** and **11** (when the latter is prepared in the presence of HMPA), is due to the conversion of **11** into mixtures of **11** and L.O. cuprate $(\text{Bu}_3\text{Sn})_2\text{CuLi}$ (**20**) and LiCN prior to reaction with **13**.

Thus, when stannyliacetylene **11** is prepared in the presence of HMPA, the cyano ligand dissociates to an appreciable extent ($\sim 40\%$, determined by integration of the ^1H -NMR signals attributed to intermediates **14** and **15**); however, when this reagent is prepared in THF and HMPA added later, no free lithium cyanide is observed.

Additional evidence for the presence of **14**–**17** comes from a ^{13}C -NMR study of the reaction of **11** and the ^{13}C -labeled acetylenic ether $[1-^{13}\text{C}]\text{13}$.²⁴ Thus, when stannyliacetylene **11**, prepared in the presence of HMPA (17 equiv, 33% v/v), was reacted with $[1-^{13}\text{C}]\text{13}$ at 0 °C, two major signals were observed at $\delta = 208.6$ ($J_{\text{CSn}} = 157$ Hz) and 213.4 ppm assigned to intermediates **14** and **15**, respectively (Figure 2a). The two minor signals at 166.8 ($J_{\text{CSn}} = 780$ Hz) and 163.2 ppm ($J_{\text{CSn}} = 793$ Hz) were assigned to the regioisomeric intermediates **16** and **17**, respectively. The magnitude of the tin satellites associated with these signals corroborate the assignments in so far as that tin must be bonded to the α -carbon in these intermediates. Methanolysis of this solution resulted in the generation of vinylstannanes **19** ($\delta = 173.1$, $J_{\text{CSn}} = 475$ Hz, this value is reported as the average obtained from ^{117}Sn and ^{119}Sn) and **18** ($\delta = 156.3$, no tin satellites were observed for this signal) (Figure 2b). The signal at 153.0 ppm corresponds to the α -carbon of octyl vinyl ether, formed during hydrolysis.

To corroborate the assignments in Figure 2a, reaction of acetylenic ether $[1-^{13}\text{C}]\text{13}$ with $(\text{Bu}_3\text{Sn})_2\text{CuLi}$ (**20** prepared in the presence of 17 equiv of HMPA, 33% v/v) was performed at 0 °C (Scheme 2, path e). ^{13}C -NMR analysis of this solution revealed two principal signals at 213.4 and 163.2 ppm (Figure 3a) assigned to intermediates **15** and **17**, respectively,²⁵ and with chemical shifts identical to the signals attributed to these intermediates in Figure 2a. Addition of 1 equiv of LiCN(s) to this solution (Scheme 2, path f) resulted in the emergence of two new peaks at 208.6 ($J_{\text{CSn}} = 157$ Hz) and 166.8 ppm (Figure

(24) $1-^{13}\text{C}$ -Labeled acetylenic ether **13** was prepared by the reaction of 1-[(Diethoxyphosphinyl)oxyl]vinyl octyl ether (obtained from reaction of octyl acetate with LDA and diethylchlorophosphate) with *t*-BuLi according to: Cabezas, J. A.; Oehlschlager, A. C. *J. Org. Chem.* **1994**, *59*, 7523.

(25) The energy difference between these two intermediates, calculated from the ^1H -NMR spectra at 0 °C, was 1.6 kcal/mol.

(23) Williams, D. H.; Fleming, I. In *Spectroscopic Methods in Organic Chemistry*; McGraw-Hill: London, 1989; p 97.

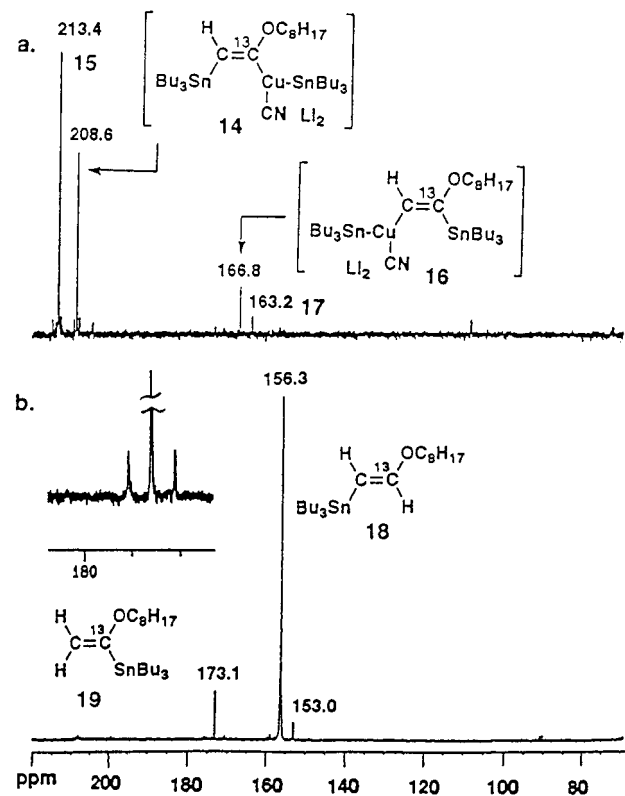


Figure 2. Low-temperature (0 °C) ¹³C-NMR spectra of (a) [1-¹³C]13 + 11 (prepared in THF-HMPA) and (b) solution 2a + MeOH.

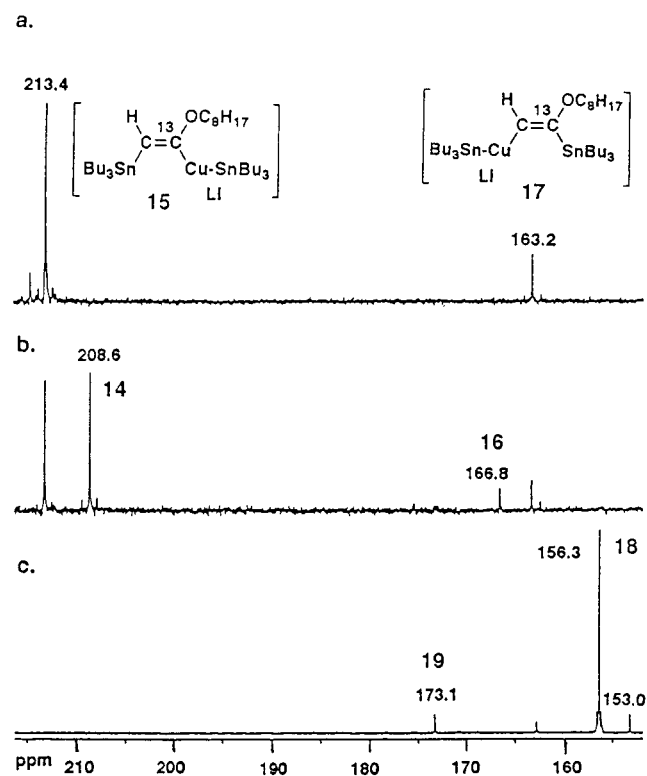


Figure 3. Low-temperature (0 °C) ¹³C-NMR spectra of (a) [1-¹³C]13 + 20 (prepared in THF-HMPA), (b) solution 3a + LiCN (1 equiv), and (c) solution 3b + MeOH.

3b) corresponding to the vinylcuprates 14 and 16, respectively (compare with Figure 2a). Methanolysis of this solution generated vinylstannanes 18 and 19 (Figure 3c). These experiments demonstrate that addition of lithium cyanide to a lower order vinylcuprate results in the formation of a new species, where cyanide is presumably bound, as judged by the lower

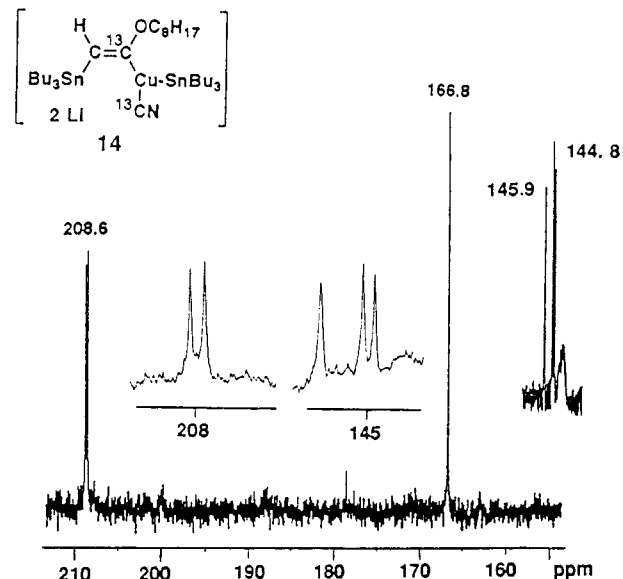


Figure 4. Low-temperature (0 °C) ¹³C-NMR spectrum of (Bu₃Sn)₂Cu-(¹³CN)Li₂ (11, prepared in THF) + [1-¹³C]13.

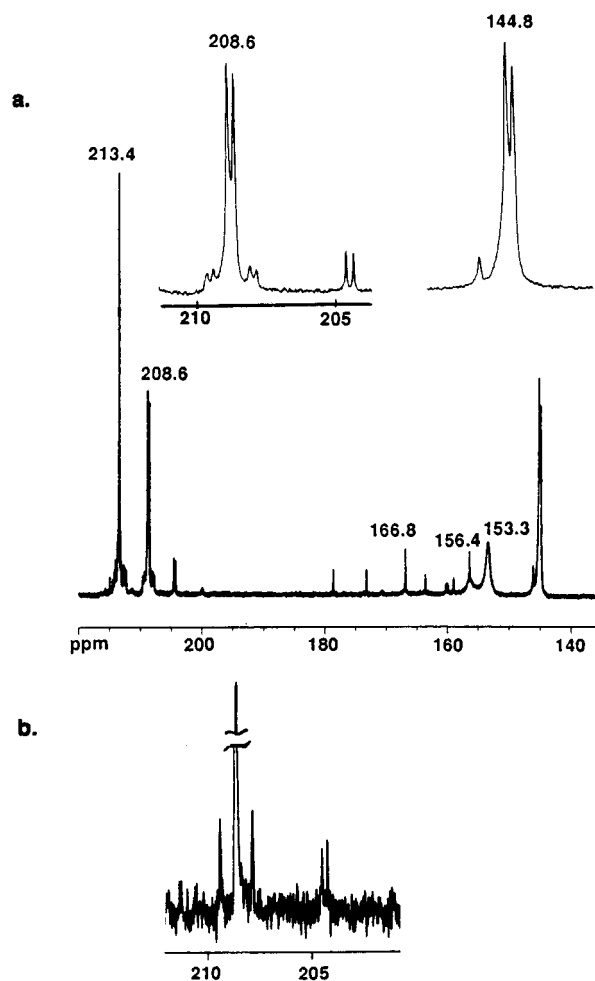


Figure 5. (a) Low-temperature (0 °C) ¹³C-NMR spectrum of (Bu₃Sn)₂Cu(¹³CN)Li₂ (11) (HMPA) + [1-¹³C]13 and (b) expansion of Figure 2a.

geminal Sn-H coupling in intermediate 14 compared to that in 15 (Scheme 2, path f) and the ²J₁₃C¹³CN (see later Figures 4 and 5). Since the ¹³C-NMR spectrum of (*trans*-alkoxyvinyl)-stannane 18 does not show tin satellites in the signal at 156.3 ppm (Figure 2b), the Sn-C couplings observed in the signal due to the same carbon of its precursor 14 (208.6 ppm, Figures

2a and 3b) must be due to a tin atom attached to the organometallic complex in these intermediates which is lost during hydrolysis.

Use of NMR coupling constants is a powerful tool for elucidation of structure. Two-bond $^{13}\text{C}-\text{Cu}-^{13}\text{CN}$ couplings in lower order cyanocuprates were first observed by Bertz.¹⁶ To confirm that the cyanide ligand was covalently bound to copper in intermediate **14**, this vinylcyanocuprate was prepared using ^{13}C -labeled cuprate **11** (prepared from 1 equiv of Cu^{13}CN and 2 equiv of Bu_3SnLi) and the $[1-^{13}\text{C}]$ -labeled acetylenic ether **13**. Thus, reaction of $(\text{Bu}_3\text{Sn})_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**11**, prepared in THF) with $[1-^{13}\text{C}]\text{13}$ was performed at -25°C , and after addition of HMPA (17 equiv), the reaction mixture was allowed to reach 0°C and the ^{13}C -NMR spectrum was recorded. The spectrum contained a pair of singlets at 166.8 and 145.9 ppm (Figure 4) assigned to the α -vinyl ^{13}C and ^{13}CN of **16**, respectively, and a pair of doublets centered at 208.6 and 144.8 ppm ($J^{13}\text{C}^{13}\text{CN} = 24.4\text{ Hz}$) assigned to the α -vinyl ^{13}C and ^{13}CN ligand of intermediate **14** (Figure 4, compare with Figure 2a). The observation of a $^2J^{13}\text{C}^{13}\text{CN}$ confirms that this species (**14**) is sufficiently stable to be observed spectroscopically and has covalently bound cyanide. The coupling observed for this cuprate (24 Hz) is slightly larger than those previously reported by Bertz for lower order cyanocuprates (20–22 Hz).¹⁶ ^1H - and ^{13}C -NMR spectra (0°C) of this sample evidenced that neither free Bu_3SnLi nor Li^{13}CN were present. The spectrum shown in Figure 4 also supported the structural assignments of these intermediates. In regioisomer **16** if the ^{13}CN ligand is attached to copper, it would be three bonds removed from the ^{13}C -vinyl carbon. A $^3J^{13}\text{C}^{13}\text{CN}$ is not observed in **16**, and one observes singlets at 145.9 and 166.8 ppm, respectively, for these carbons.

To further corroborate the identity of the intermediates formed when cuprate **11** is prepared in HMPA, this cuprate was prepared in the presence of 17 equiv (33% v/v) of HMPA using Cu^{13}CN . Reaction with $[1-^{13}\text{C}]\text{13}$ at 0°C , under conditions identical to those used for the reaction whose spectrum is shown in Figure 2a, gave two major signals (Figure 5): a singlet at 213.4 ppm assigned to the ^{13}C -vinyl carbon of **15** and a sextet at 208.6 ppm ($^2J^{13}\text{C}^{13}\text{CN} = 24\text{ Hz}$; $J_{\text{Sn}^{13}\text{C}} = 157\text{ Hz}$) assigned to the ^{13}C -vinyl carbon of **14**. As expected, the tin satellites observed for the ^{13}C -vinyl signals of **14** in Figure 2a (expansion in Figure 5b) are now doublets due to the ^{13}CN (Figure 5a, compare with Figure 5b). A doublet at 144.8 ppm was assigned to the ^{13}CN ligand of **14** and exhibited a coupling identical to that observed for the signal at 208.6 ($^2J^{13}\text{C}^{13}\text{CN} = 24\text{ Hz}$) (Figure 5a).

The multiplicity of the ^{13}CN signal confirms that cyanide is σ -bound in **14**. A doublet with $^2J^{13}\text{C}^{13}\text{CN}$ of 24 Hz confirms that cyanide and the ^{13}C -vinyl carbon are bound to a common atom. In the ^{13}C -NMR of **14**, we also observed tin satellites in the ^{13}C -vinyl carbon signal (208.6 ppm, Figures 2a, 3b, and 5a). These satellites could be due to the tri-*n*-butylstannyl group covalently bound to the β -vinyl carbon or the tin in the organometallic complex attached to the ^{13}C -vinyl carbon. When **14** is hydrolyzed to **18**, the signal due to the ^{13}C -vinyl carbon in the latter (156.3 ppm, Figures 2b and 3c) is observed as a singlet without tin coupling. This suggests the original tin coupling observed for the ^{13}C -vinyl carbon of **14** is due to the tin attached to the organometallic center and not to the tri-*n*-butylstannyl group attached to the β -vinyl carbon of **14**. This suggests that both the ^{13}C -vinyl carbon and tri-*n*-butylstannyl group are attached to a common atom.

If the common atom to which the ^{13}CN and ^{13}C -vinyl carbon are bound is the same as that to which the ^{119}Sn (metal bound) and ^{13}C -vinyl carbon are bound, the cuprate is higher order. In

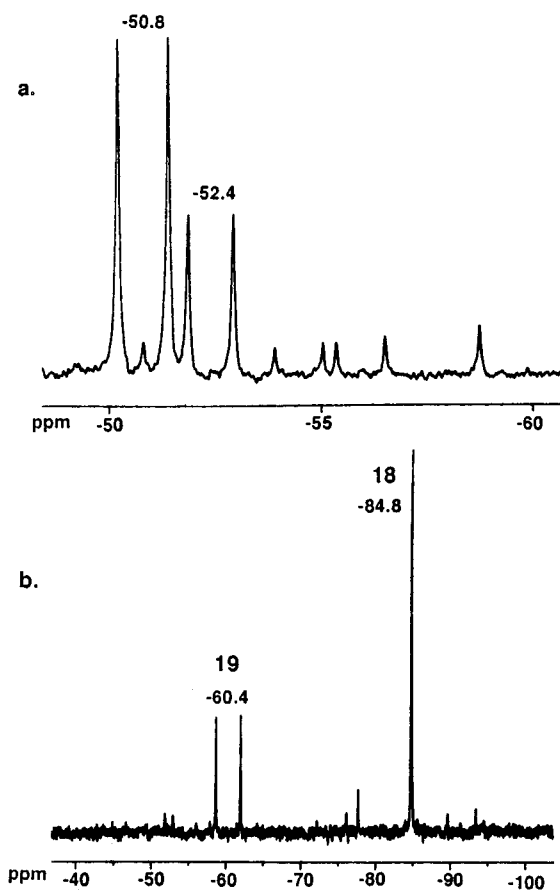


Figure 6. Low-temperature (0°C) ^{119}Sn -NMR spectra of (a) $(\text{Bu}_3\text{Sn})_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**11**) (HMPA) + $[1-^{13}\text{C}]\text{13}$ and (b) solution **6a** + MeOH.

this event, one would expect to observe $^{119}\text{Sn}-^{13}\text{CN}$ (metal bound) coupling. Our failure to observe $^{119}\text{Sn}-^{13}\text{CN}$ coupling does not rule out a H.O. cuprate and allows formulation of **14** as a L.O. species in which the ^{13}CN and ^{13}C -vinyl carbon are bound to one common atom and the coupling ^{119}Sn and ^{13}C -vinyl carbon are bound to a different common atom. It should be noted that, in **18**, ^{119}Sn and a ^{13}C -vinyl carbon are attached to a common carbon but did not exhibit 2J coupling (Figure 2b).

L.O. cuprate structure **5** is most consistent with the observed couplings and the absence of $^{119}\text{Sn}-^{13}\text{C}$ -vinyl carbon coupling. One troubling element of **5** is that coupling of either ^{13}CN or ^{119}Sn to the ^{13}C -vinyl carbon is required to be through lithium.

It has previously been observed that the ^{13}C signal due to CN in lower order alkyl cuprates is near 144.8 ppm while the corresponding signal in higher order dialkyl cuprates is near 159 ppm.^{14–16} In the present study, **14** exhibited a doublet due to the ^{13}CN at 144.8 ppm which is most consistent with a lower order cuprate.

The ^{119}Sn -NMR spectrum of the solution whose ^{13}C spectrum is shown in Figure 5a revealed a doublet at -50.8 ppm (180 Hz) assigned to the tin atom attached to copper in **15** and a doublet at -52.41 ($J^{119}\text{Sn}^{13}\text{C} = 160\text{ Hz}$) assigned to tin bound to the organometallic center in **14** (Figure 6a). The similarity of the ^{119}Sn chemical shifts in **15** and **14** suggest the tin moieties in both species are bound to the same metal which is presumed to be copper. The observed coupling is also seen as tin satellites in the ^{13}C -NMR signal of the ^{13}C -vinyl carbon of **14** at 208.6 ppm (average between ^{117}Sn and ^{119}Sn of 157 Hz). A doublet at -91.5 ppm with a $J^{119}\text{Sn}^{13}\text{C} = 786\text{ Hz}$ was assigned to the tin bound to the ^{13}C -vinyl carbon in **16** (or **17**), corresponding tin

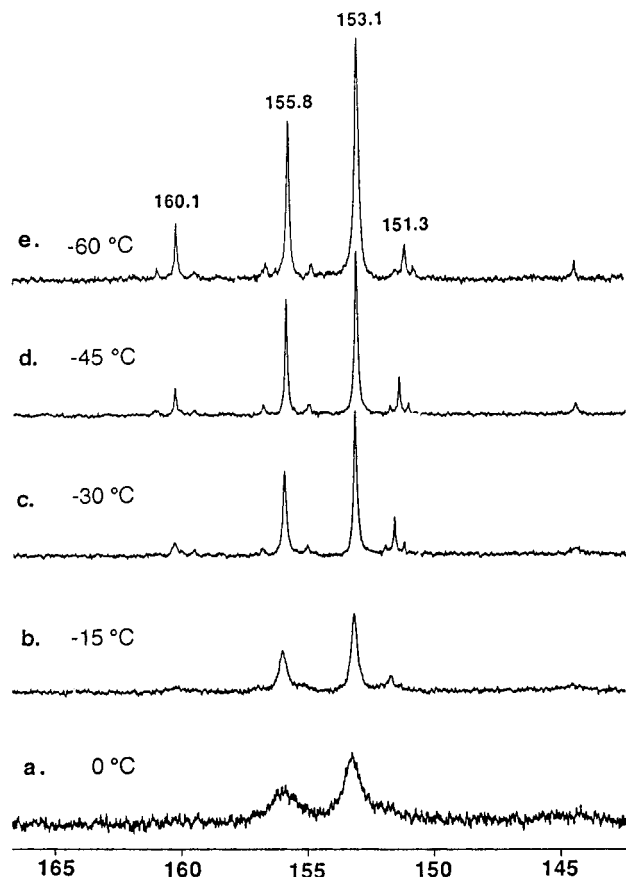


Figure 7. Variable temperature ^{13}C -NMR spectra of a THF-HMPA solution of $(\text{Bu}_3\text{Sn})_2\text{Cu}(^{13}\text{CN})\text{Li}_2$.

satellites were observed in the ^{13}C -NMR spectra of these intermediates (780 and 793 Hz, for **16** and **17** respectively, Figures 2a and 3a). Methanolysis of this solution resulted in the obtention of two vinylstannanes. The major isomer (**18**) exhibited a singlet at -84.8 ppm (Figure 6b). The minor isomer (**19**) showed a doublet at -60.4 ppm with a $J^{119}\text{Sn}^{13}\text{C}$ of 485 Hz (Figure 6b). The multiplicity of the latter signal supports the suggestion that tin is bound to the ^{13}C -vinyl carbon in **19**. The absence of ^{119}Sn - ^{13}C -vinyl carbon coupling in vinylstannane **18** (Figures 2b and 6b) suggests that the ^{119}Sn - ^{13}C -vinyl carbon coupling observed in **14** (Figures 5a and 6a) is due to the ^{13}C -vinyl carbon and tin atom attached to the organometallic center. This is the same conclusion reached (*vide infra*) by examination of the ^{13}C -NMR spectra of **14** and **18**.

Two broad singlets at 153.3 and 156.4 ppm were also observed in ^{13}C -NMR spectrum shown in Figure 5a, and these were assigned to the ^{13}C of unreacted cuprate **11** as described below. The ^{13}C -NMR spectra (0°C) of solutions of **11** (prepared in presence of 17 equiv of HMPA, 33% v/v) exhibited very broad signals at 153 and 156 ppm (~ 2 – 3 ppm width) and are attributable to slow exchange of ^{13}CN (Figure 7a). When the temperature of this solution was lowered to -60°C these signals sharpened and eventually gave rise to four signals²⁶ at 151.3 ($J^{119}\text{Sn}^{13}\text{C} = 72$ Hz), 153.0 (no tin satellites observed), 155.8 ($J^{119}\text{Sn}^{13}\text{C} = 187$ Hz), and 160.1 ($J^{119}\text{Sn}^{13}\text{C} = 157$ Hz) ppm (Figure 7c–e). The ^{119}Sn coupling observed in three of these signals suggested that some species in these solutions contain both Bu_3Sn and ^{13}CN bound to the same atom. Increasing the temperature from -60 to 0°C resulted in obtention of the previous spectra (Figure 7a). These experiments indicate that

(26) Similar behavior was observed for the H.O. cuprate $(\text{Bu}_3\text{Sn})\text{MeCu}(\text{CN})\text{Li}_2$ (**12**). Cabezas, J. A. Ph.D. Thesis, Simon Fraser University, 1994.

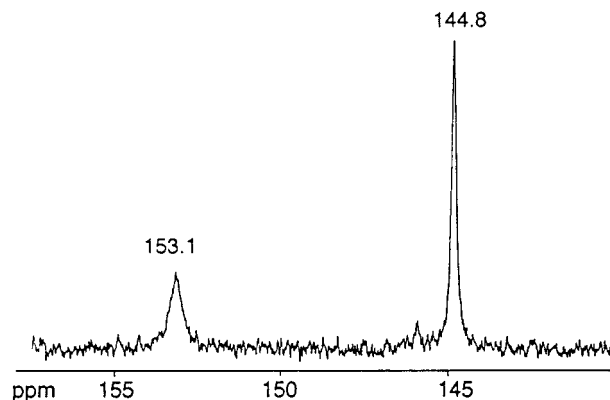


Figure 8. Low-temperature (0°C) ^{13}C -NMR spectrum of $(\text{Bu}_3\text{Sn})_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**11**) + **13**.

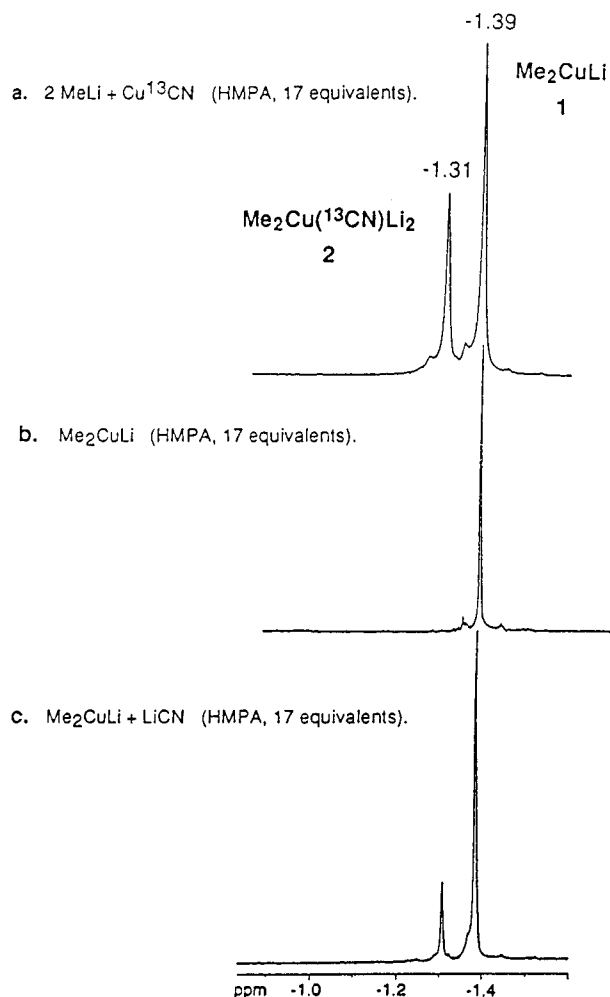


Figure 9. Low-temperature (-40°C) ^1H -NMR spectra of (a) $\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (prepared in THF-HMPA), (b) Me_2CuLi (prepared in THF-HMPA), and (c) Me_2CuLi (THF-HMPA) + LiCN .

cuprate **11** is a mixture of several species some of which have covalently bound cyanide, as evidenced by the observation of ^{119}Sn - ^{13}CN coupling (Figure 7). The signal at 153 ppm which does not exhibit ^{119}Sn - ^{13}CN coupling was assigned to Li^{13}CN coordinated to one of these species, perhaps as proposed in structure **3** (the chemical shift obtained for a THF solution of LiCN containing 17 equiv of HMPA, 33% v/v, was 166.9 ppm). The remaining CN signals are attributable to species in which the cyanide is covalently bound. These results are in agreement with the previous observations which led to the postulation that mixtures of vinylcuprate intermediates with and without co-

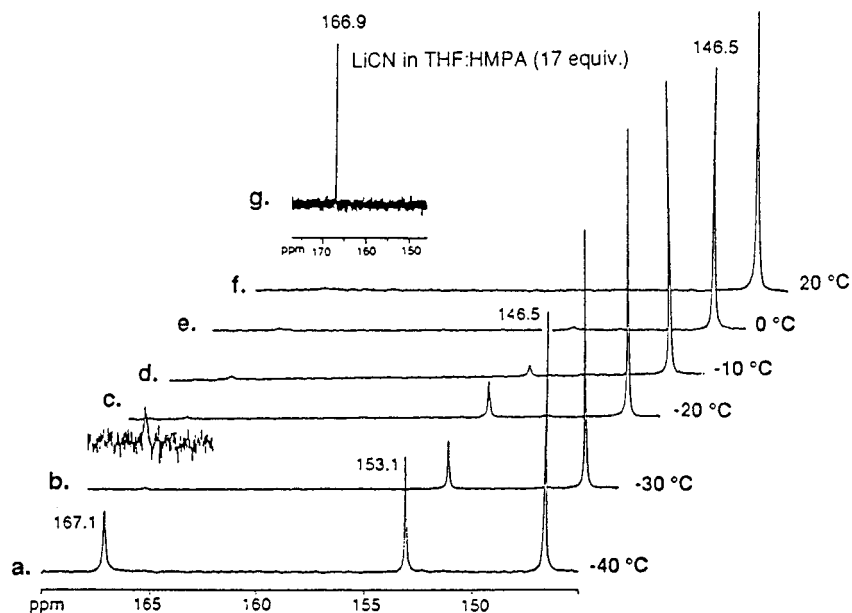


Figure 10. Variable low-temperature ^{13}C -NMR spectra of $\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**2**, prepared in THF-HMPA).

valently bond cyanide (**14** and **15**, respectively) were formed when **11** was prepared in HMPA (Figures 2 and 5). The ^{13}C -NMR spectra (0 °C) of solutions of **12** (prepared with ^{13}CN in presence of 17 equiv of HMPA, 33% v/v) also exhibited very broad signals ($\sim 2\text{--}3$ ppm width) attributable to slow exchange of ^{13}CN .

Addition 1 equiv of acetylenic ether **13** to a HMPA solution of **11** (Figure 7a) at 0 °C, resulted in the disappearance of the broad ^{13}C signals and the appearance of a sharp ^{13}CN signal at 144.8 ppm due to ^{13}CN ligand of **14** (Figure 8, compare with Figures 4 and 5).

To determine if dialkylcyanocuprates behave similarly when prepared in the presence of HMPA, cuprate **2** [$\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$] was investigated. Thus, when the latter was prepared by addition of 2 equiv of MeLi to 1 equiv of Cu^{13}CN , dissolved in THF-HMPA (17 equiv of HMPA, 33% v/v), at -40 °C, the ^1H -NMR spectrum exhibited two major signals at -1.31 and -1.39 ppm (Figure 9a). These were assigned to the cuprate **2** and cuprate **1**, respectively. To confirm the identity of the species giving rise to the high-field signals in the above solutions, cuprate **1** was prepared by addition of 2 equiv of MeLi to a cold (-40 °C) THF suspension of CuI (1 equiv) containing HMPA (17 equiv, 33% v/v). The LiI that formed was removed by filtration at low temperature under argon.²⁷ The low-temperature (-40 °C) ^1H -NMR spectrum of the resulting solution exhibited a singlet at -1.39 ppm (Figure 9b) identical with the one previously obtained from the solution whose spectrum is shown in Figure 9a. Addition of 1 equiv of LiCN (~ 3 M in HMPA) to the cuprate **1** (Figure 9b) gave, after 25 min at -40 °C, a signal at -1.31 ppm assigned to the cuprate **2** (Figure 9c). More significantly, the former spectrum (Figure 9a) was reproduced.

Employment of Cu^{13}CN allowed use of cyanide as a probe, as previously introduced by Bertz.¹⁶ The low-temperature (-40 °C) ^{13}C -NMR spectrum of the solution of cuprate **2** (prepared in HMPA) exhibited 3 principal signals at 146.5, 153.1, and 167.1 ppm (Figure 10a). The signal at 167.1 ppm was assigned to free Li^{13}CN on the basis of comparison with the ^{13}C -NMR spectrum of LiCN in THF-HMPA (17 equiv of HMPA, 33% v/v) (Figure 10g). The presence of free lithium cyanide in this

solution is consistent with the hypothesis that, when prepared in the presence of HMPA, cyanocuprates exist as mixtures with the corresponding cyanide-free cuprates and lithium cyanide (Figure 9a). When the temperature was increased from -40 to 0 °C, the cyano region of the spectrum simplified with the signal at 146 ppm being the only one observed at 0 °C (Figure 10e). The signal at 146 ppm was assigned to the cyano ligand of $\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (or $\text{Me}_2\text{CuLi}\cdot\text{Li}^{13}\text{CN}$). When the temperature of this sample (0 °C) was lowered to -40 °C, the cyano region of the spectrum did not change suggesting that the process of coordination of cyanide is not reversed upon cooling in cuprate **2**. Thus, the coordinated species is deduced to be a thermodynamically more stable species while production of its "CN-free" analog is kinetically favored.²¹

To confirm the assignment of the signal at 146.5 ppm²⁸ in Figure 10, cuprate **2** [$\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$] was prepared by addition of 2 equiv of MeLi to a THF (no HMPA) suspension of Cu^{13}CN (1 equiv) at -40 °C, and after formation of cuprate (ca. 45 min, Figure 11a), successive amounts of HMPA were gradually added while both ^1H and ^{13}C -NMR spectra were recorded. The ^{13}C -NMR spectrum of the THF solution (no HMPA) of cuprate **2** exhibited a signal at 149.6 ppm (Figure 11a) which shifted upfield as the amount of HMPA was increased (no signal attributed to free LiCN was observed in this sample, before or after addition of HMPA²⁹). When 17 equiv of HMPA had been added (Figure 11e), the chemical shift of the cyano carbon was 146.5 ppm, identical to that obtained in Figure 10.

Similarly, the ^1H -NMR of the THF solution of **2** exhibited a major signal at -1.27 ppm (Figure 12a), but as HMPA was gradually added, it broadened and shifted to -1.31 ppm (17 equiv) (Figure 12e), a value corresponding to the signal assigned to cuprate **2** in Figure 9a.

(28) It has been reported¹⁴ that the L.O. cuprate $\text{MeCu}(^{13}\text{CN})\text{Li}$ has a ^{13}C -NMR chemical shift value of 146.48 in THF-HMPA solutions. To confirm that this species was not formed when preparation of **2** was attempted with our reaction conditions, this L.O. cuprate $\text{MeCu}(^{13}\text{CN})\text{Li}$ was prepared in the presence of 17 equiv of HMPA. The ^{13}C -NMR spectrum (0 °C) of this sample, indeed exhibited a chemical shift of 146.5 ppm for ^{13}CN ; however, the ^1H -NMR (0 °C) evidenced a broad singlet at -1.43 ppm which did not correspond with any of the chemical shifts of the signals obtained in Figure 9a. For this ^{13}C -labeled sample a doublet ($J = 22$ Hz) has been observed for the ^1H -NMR at -78 °C by Bertz (ref 16).

(29) The absence of free LiCN in solution, when this cuprate is prepared in THF has been already demonstrated by Professor Lipshutz (ref 14).

(27) Shriver, D. F.; Drezdson, M. A. *The Manipulation of Air-Sensitive Compounds*; John Wiley & Sons: New York, 1986; pp 30–35.

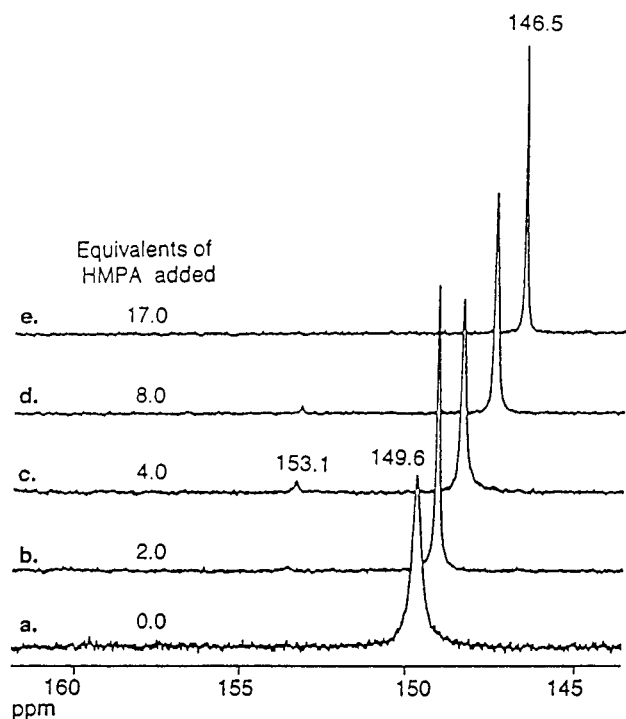


Figure 11. Low-temperature ($-40\text{ }^{\circ}\text{C}$) ^{13}C -NMR spectra of a THF solution of $\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**2**) with successive additions of HMPA.

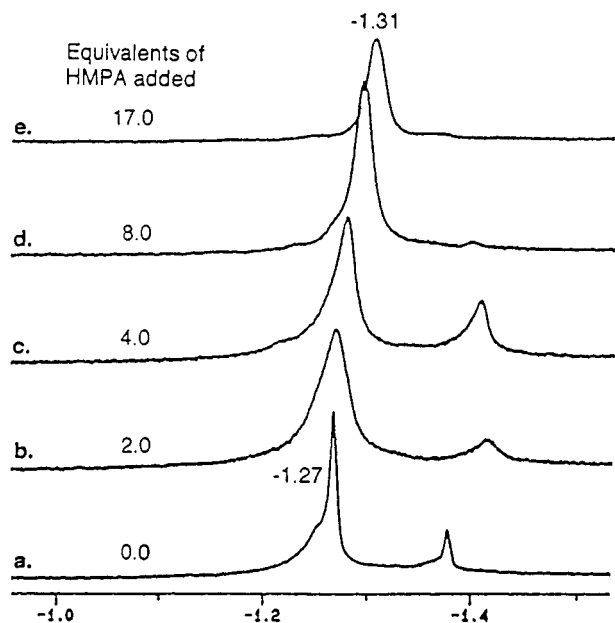


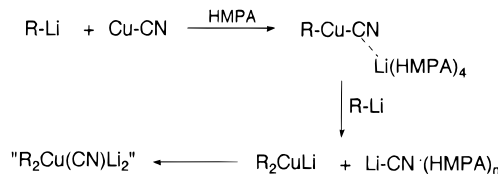
Figure 12. Low-temperature ($-40\text{ }^{\circ}\text{C}$) ^1H -NMR spectra of a THF solution of $\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**2**) with successive additions of HMPA.

The results are consistent with those observed for cuprate **11**. Thus, when **2** is prepared in THF, no free lithium cyanide is observed and neither is it generated upon addition of HMPA. However, when **2** is prepared in HMPA-containing solutions, it exists with the corresponding cyanide-free species and LiCN. The formation of this Gilman reagent can be envisioned as a Li–HMPA-assisted ligand exchange process in which the second alkyllithium replaces the cyanide ligand (Scheme 3).

Conclusions

^1H - and ^{13}C -NMR spectroscopic investigations of cyanocuprates as well as their addition products revealed that, when prepared in the presence of HMPA, these cuprates exist as mixtures with their corresponding cyanide-free cuprates and

Scheme 3



uncoordinated lithium cyanide (for cuprate **2**). NMR analysis suggests that the reaction between these cyanide-free cuprates and LiCN in THF–HMPA is slow at temperatures used for most synthetic cuprate reactions, presumably due to the significant complexation power of HMPA; thus, for synthetic work where the superior reactivity is required, THF (rather than THF–HMPA) is the solvent of choice for preparation of these reagents. When the temperature of solutions of **2** is increased, Gilman cuprate (cyanide-free) and LiCN react irreversibly to form species that does not have free LiCN.

When these species are prepared in THF no free LiCN is observed in solution. These results are in agreement with those of Lipshutz^{14,19} and Betz.¹⁵

The ^{13}C – ^{13}C coupling observed in **14** confirmed that cyanide was bound in this species. For cuprate **11**, NMR spectroscopic data showed the presence of several species (when prepared in HMPA), some of which have covalently bound cyanide. For $\text{Me}_2\text{Cu}(^{13}\text{CN})\text{Li}_2$ (**2**), no $^1\text{H}_{\text{Me}}$ – $^{13}\text{C}_{\text{CN}}$ coupling was observed in the ^1H -NMR spectrum, suggesting the cyanide is not covalently bound in this species. The latter is in agreement with the observations of Bertz.¹⁶ The presence or absence of bound cyanide suggested by the spectra of cuprates **14**, **11**, and **2** might be due to the different substituents on copper.

^{13}C -NMR spectra of vinylcyanocuprate **14** revealed a two carbon ^{13}C – ^{13}C -vinyl carbon coupling ($J = 24.4\text{ Hz}$, Figures 4 and 5), confirming a cyanide and vinyl carbon bound to a common atom. The signal observed for the ^{13}C -vinyl carbon of **14** also showed tin couplings ($J = 157\text{ Hz}$) which were unequivocally assigned to a Bu_3Sn group attached to the organometallic center. This coupling confirmed that the ^{13}C -vinyl carbon and Bu_3Sn group were bound to a common atom. Since we did not observe tin satellites in the ^{13}C -NMR signal for the cyano ligand (144.8 ppm, Figure 5) of **14**, the Bu_3Sn and cyanide groups cannot be firmly established to be connected to a common atom.

The above observations can be interpreted in terms of either a higher order or lower order cuprate. If **14** is a higher order cuprate, then structures **8** and **9** (Figure 1) are most reasonable. A higher order structure requires a Bu_3Sn , the $^{13}\text{C}_{\text{CN}}$, and the ^{13}C -vinyl carbon to be bound to a common atom. In this event, we have no apparent explanation for the absence of ^{119}Sn – $^{13}\text{C}_{\text{CN}}$ coupling in **14**, although we point out that this coupling is also absent in **18** where the common atom is carbon. The lower order structure that is most consistent with the observed spectral characteristics is **5** (Figure 1). This structure allows the $^{13}\text{C}_{\text{CN}}$ and ^{13}C -vinyl carbon to be attached to one common atom and the ^{119}Sn and ^{13}C -vinyl carbon to be attached to a different common atom. The chemical shift observed for the $^{13}\text{C}_{\text{CN}}$ of **14** suggests this group is coordinated in a lower order cuprate. Structure **5** was one of the most stable from theoretical work²¹ and does not have cyanide coordinated with copper as suggested by EXAFS and XANES studies²⁰ of alkylcuprates. The most troubling aspect of **5** is that coupling of either $^{13}\text{C}_{\text{CN}}$ or ^{119}Sn with the ^{13}C -vinyl carbon must be through lithium.

Experimental Section

General Methods. All glassware and syringes were dried in an oven overnight at $140\text{ }^{\circ}\text{C}$ and flushed with argon immediately prior to

use. Transfers of reagents were performed with syringes equipped with stainless-steel needles. All reactions were carried out under a positive pressure of argon. THF was refluxed and freshly distilled from potassium benzophenone ketyl under argon atmosphere. Argon was passed through a Drierite column (40 cm \times 3 cm). HMPA was fractionally distilled under vacuum from calcium hydride, collected, and stored over activated 4A molecular sieves. Methanol was refluxed and distilled under argon from activated magnesium, collected, and stored over activated 4A molecular sieves. Methylolithium and *n*-butyllithium were purchased from Aldrich and titrated according to the method of Watson and Eastham.³⁰ Labeled copper cyanide (Cu^{13}CN) was purchased from Cambridge Isotopes and transferred in a glove bag. THF- d_8 was purchased from Sigma and was dried over activated 3A molecular sieves prior to use. The low-temperature NMR spectra were recorded on a Bruker AMX-400 spectrometer. ^1H - and ^{13}C -NMR spectra were recorded at 400.13 and 100.62 MHz, respectively, and were referenced to THF, $\alpha = 68.4$ ppm, $\beta = 26.5$ ppm for ^{13}C -NMR, and $\alpha = 3.75$ ppm, $\beta = 1.85$ ppm for ^1H -NMR spectra. ^{119}Sn -NMR spectra were referenced to Bu_4Sn (0.0 ppm). Reaction mixtures were prepared following the procedures described below, and an aliquot was transferred *via* cannula under argon to dry 5-mm NMR tubes equipped with septa, previously flushed with argon and maintained at -40 or 0 $^\circ\text{C}$.

Preparation of Me_2CuLi (1). To a suspension of CuI (0.190 g, 1 mmol) in THF- d_8 (5 mL) at -40 $^\circ\text{C}$ was added dropwise a solution of MeLi (1.43 mL, 2 mmol). The solution was stirred at this temperature for 45 min. After this time, the CuI formed was removed by filtration through a fritted glass at low temperature under argon using Schlenk techniques. The clear yellow solution was transferred into a dry 5-mm NMR maintained under argon at -40 $^\circ\text{C}$, and the spectra were recorded.

Preparation of $\text{Me}_2\text{Cu}^{13}\text{CNLi}_2$ (2). A 1.4 M solution of MeLi (1.43 mL, 2 mmol) was added dropwise to a cold (-40 $^\circ\text{C}$) solution

of Cu^{13}CN (0.090 g, 1 mmol) in a 1:1 mixture (6 mL) of THF–HMPA (17 equiv of HMPA) and stirred at this temperature for 1 h. After this time, an aliquot was transferred *via* cannula into a dry 5-mm NMR tube maintained at -40 $^\circ\text{C}$ under argon, and the spectra were recorded at this temperature.

Preparation of Tri-*n*-butyltin Lithium (Bu_3SnLi). *n*-Butyllithium in hexanes (2.45 M, 0.82 mL, 2.0 mmol) was added to a cold (-30 $^\circ\text{C}$) solution of diisopropylamine (0.30 mL, 2 mmol) in THF (4 mL) and stirred at this temperature for 20 min. After this time, the temperature was lowered to -40 $^\circ\text{C}$ and tri-*n*-butylstannyl hydride (0.54 mL, 2.0 mmol) was added dropwise, and the solution was stirred at this temperature for 1 h.

Preparation of $(\text{Bu}_3\text{Sn})_2\text{Cu}(\text{CN})\text{Li}_2$ (11). A THF solution of Bu_3SnLi (2.0 mmol), prepared as described above, was added, *via* cannula under argon, to a cold (-40 $^\circ\text{C}$) suspension of CuCN (0.090 g, 1.0 mmol) in 6 mL of THF (or 6 mL of a 1:1 mixture of THF–HMPA) and stirred at this temperature for 45 min. The resulting solution was warmed to 0 $^\circ\text{C}$, and the cuprate formed was reacted with **4** at the later temperature.

Preparation of $(\text{Bu}_3\text{Sn})_2\text{CuLi}$ (20). To a solution of CuI (0.190 g, 1 mmol) in THF–HMPA (17 equiv of the latter) at -40 $^\circ\text{C}$ was added *via* cannula a THF solution of Bu_3SnLi (2.0 mmol), prepared as described before. The resulting solution was stirred at -40 $^\circ\text{C}$ for 45 min.

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(30) Watson, S. C.; Eastham, J. F. *J. Organomet. Chem.* **1967**, *9*, 165.