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Preparation of σ - and π -Allylcopper(III) Intermediates in S_N2 and S_N2' Reactions of Organocuprate(I) Reagents with Allylic SubstratesErika R. Bartholomew, Steven H. Bertz,^{*,†} Stephen Cope, Michael Murphy, and Craig A. Ogle^{*}

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The reactions of organocuprate(I) reagents with allylic substrates have been among their most valuable synthetic applications,¹ and consequently, they have been scrutinized from experimental² as well as theoretical³ points of view. Nevertheless, the outcome is difficult to predict for each new case, as the partition between S_N2 and S_N2' products is a complex function of the experimental parameters. Both σ - and π -allylcopper(III) intermediates have been proposed, and a detailed understanding of their roles can only accelerate progress in this important area, for example, in the development of enantioselective reactions.

Copper(III) intermediates have been shown to play a central role in the conjugate addition⁴ and S_N2 reactions^{5–7} of organocuprate(I) reagents. σ -Allyl Cu^I compounds are well-known,⁸ but π -allyl Cu^I compounds appear to be unknown;⁹ thus, the corresponding Cu^{III} complexes have theoretical as well as practical interest. We can now report that, by using rapid injection NMR spectroscopy (RI-NMR),^{10,11} we have been able to prepare and characterize the first examples of both η^1 σ -allyl and η^3 π -allyl Cu^{III} complexes and to study their reactions.

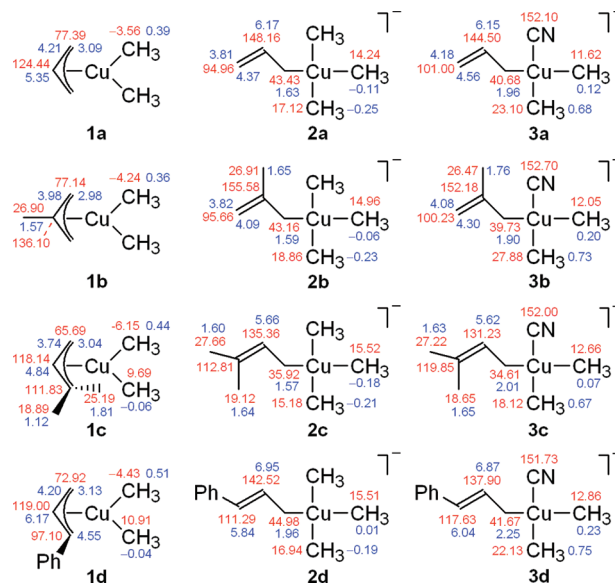
Prototypical π -allyl Cu^{III} complex, (η^3 -allyl)dimethylcopper(III) **1a** (Chart 1), was prepared by injecting a solution of allyl chloride in THF-*d*₈ into a solution of iodo-Gilman reagent Me₂CuLi·LiI (**A**) in THF-*d*₈, spinning in the probe of an NMR spectrometer at -100 °C. A σ -allyl Cu^{III} species, lithium (η^1 -allyl)trimethylcuprate(III) **2a**, also appeared rapidly ($\sim 50\%$ maximum yield, 0.1 h), but then disappeared by the time **1a** reached its maximum yield ($\sim 80\%$, 0.5 h). Complex **1a** slowly decomposed to 1-butene.

Likewise, substituted π -allyl Cu^{III} compounds **1b–d** and σ -allyl Cu^{III} *ate* complexes **2b–d** were prepared from **A** and the corresponding allyl chlorides. As in reactions involving **A** and EtI,^{5,6} the main side product with excess **A** was Ashby's cuprate, Me₃Cu₂Li;¹² otherwise it appeared to be MeCu(Cl)Li.

When the organocuprate(I) reagent was Me₂CuLi·LiI/PBu₃, the product was **2a** ($>90\%$) and the side product was MeCuPBu₃. No **1a** was present: PBu₃ appears to inhibit the conversion of **2a** to **1a** by complexing MeCu (vide infra). No copper(III)–phosphine complex was observed, in contrast to the result with this reagent and EtI, where the product was *trans*-EtMe₂Cu(PBu₃)₂.⁶

Structures of the new compounds were assigned by using 1D and 2D NMR (see Supporting Information). Especially noteworthy are the ¹³C NMR chemical shifts to higher shielding from TMS in **1a–d** (Chart 1). The ¹³C NMR shifts for the methyl (-3.56 ppm) and allyl (77.39 ppm for C1/C3) groups in **1a** are similar to the corresponding values for π -complexes of **A** with α -enones.^{10,13,14} The lack of a clear demarcation between NMR shifts for Cu^I and Cu^{III} compounds is not surprising, as Snyder has calculated that the charges on Cu in what are *formally* organocuprate(III) complexes are actually ca. +1.¹⁵

Chart 1. New Compounds Prepared in This Study with NMR Chemical Shifts for ¹³C (Red) and ¹H (Blue) in THF-*d*₈ at -100 °C (The Li⁺ counterions in **2** and **3** have been omitted for clarity.)



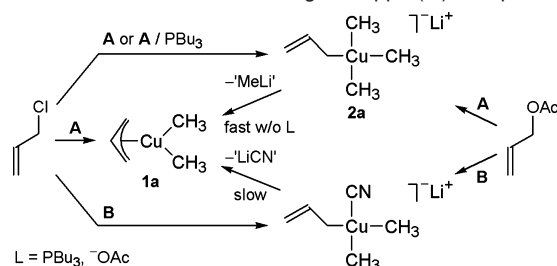
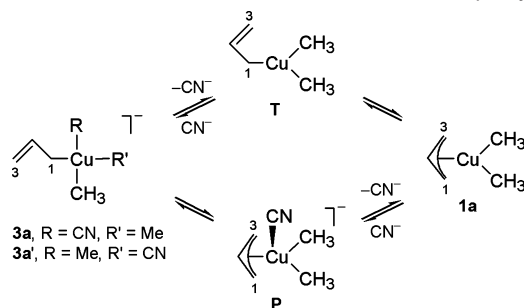
Lithium *cis*-(η^1 -allyl)cyanodimethylcuprate(III) **3a** was obtained in essentially quantitative yield (0.3 h) from allyl chloride and cyano-Gilman reagent Me₂CuLi·LiCN (**B**) in THF-*d*₈ at -100 °C. At longer times, minor amounts of **2a** appeared as Me replaced CN. Substituted cyano *ate* complexes **3b–d** were prepared analogously from **B** and the corresponding allyl chlorides. In contrast to the *cis*-cyano complexes formed here, *trans*-EtMe₂Cu(CN)Li was formed in the reaction of **B** with EtI.⁵

Two-bond ¹³C–¹³C coupling constants ²*J* across copper have been invaluable for structural studies of organocuprate(I)^{13,16} and organocuprate(III) compounds.^{4–6} In the case of labeled **1a**, (η^3 -¹³CH₂CH¹³CH₂)(¹³CH₃)₂Cu, a single two-bond coupling constant, ²*J* = 9.7 Hz,¹³ was measured between C1/C3 of the π -allyl group and the carbon atoms of the (equivalent) methyl groups. Its magnitude lies between typical values for *cis* and *trans* two-bond couplings in square planar complexes of copper(III).^{4–6} For example, in labeled **2a**, (η^1 -¹³CH₂CH¹³CH₂)(¹³CH₃)₃CuLi,¹⁷ the methylene–methyl *trans* coupling was ²*J* = 34.2 Hz, while the methylene–methyl *cis* coupling was too small to be resolved. The methyl–methyl *cis* coupling was ²*J* = 2.3 Hz.

In labeled **3a**, (η^1 -¹³CH₂CH¹³CH₂)(¹³CH₃)₂Cu(¹³CN)Li,¹⁷ two-bond ¹³C–¹³C couplings between the cyano group and the methyl groups *cis* and *trans* to it were ²*J* = 4.2 and 38.0 Hz, respectively. The methylene–methyl *trans* coupling was ²*J* = 31.1 Hz. The rest of the *cis* couplings were not resolved.

Addition of allyl acetate to **A** in THF-*d*₈ at -100 °C gave a good yield ($>90\%$) of **2a** (Scheme 1). In the absence of acetate or

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Scheme 1. Alternative Routes to Organocopper(III) Complexes**Scheme 2.** Dissociative versus Associative Reaction Mechanisms (The Li^+ counterions are not shown for the sake of simplicity.)

PBu_3 , methyl is rapidly removed from **2a**, perhaps by a soluble form of MeCu (e.g., $\text{Me}_3\text{Cu}_2\text{Li}$). Substituted *ate* complexes **2b–d** were prepared analogously from the corresponding allyl acetates.

Under the same conditions, allyl acetate and **B** gave an essentially quantitative yield of **3a**. Substituted *cis*-cyano complexes **3b–d** were prepared in good yields from **B** and the corresponding allyl acetates, although prenyl acetate required higher temperatures. Small amounts of π -allyl complexes **1** appeared at longer times or higher temperatures; presumably, **3** loses cyanide in a soluble form such as Li_2CN^+ .¹⁸

Addition of either prenyl acetate or dimethylvinylcarbinol acetate to a solution of **B** in THF-d_8 at -60°C yielded **3c** exclusively. Upon warming the reaction mixture to -40°C , 2-methyl-2-pentene appeared as the only alkene.

In a related experiment, addition of allyl-1- d_1 acetate to **B** in THF-d_8 at -100°C gave **3a- d_1** in which the label was scrambled between C1 and C3.

Since **1a** and **3a** are 16-electron d^8 species, either dissociative or associative mechanisms can account for the results from **B** and allylic substrates (Scheme 2). The former involves a trigonal 14-electron species **T**^{3,15} and the latter a pyramidal 18-electron one, **P**.^{19,20} Allyl isomerization occurs when C3 in **3a** (or **T**) attaches to Cu to form a π -allyl moiety in **P** (or **1a**), and then C1 detaches.

In principle, **3a** can be formed via capture of cyanide by **1a** or via rearrangement of **3a'**, produced by the same concerted mechanism that yields *trans*- $\text{EtMe}_2\text{Cu(X)Li}$ from $\text{Me}_2\text{CuLi}\cdot\text{LiX}$ and EtI .⁵ The *trans* to *cis* isomerization is observed for some X, but not X = CN; hence, allyl must play a key role if **3a'** is involved. Rearrangement could occur by a mechanism analogous to one of those above. For example, coordination of the double bond in **3a'** gives a pyramidal intermediate with Me in the apical position (i.e., **P'**), which affords **3a** when this methyl group replaces the coordinated double bond *trans* to the cyano group.

Addition of cinnamyl chloride to **A** in THF-d_8 at -100°C resulted in a mixture of **1d** and **2d** (1:2, 0.5 h; 1:1, 2 h; 2:1, 3.5 h).

Upon warming to -90°C (0.5 h), 90% of **2d** had been converted to **1d** and alkenes (1:3), 3-phenylbutene **4** ($\text{S}_{\text{N}}2'$ product) and (*E*)-1-phenylbutene **5** ($\text{S}_{\text{N}}2$ product, ca. 20:1 at -100°C). Upon warming to -70°C , **1d** decomposed at a significant rate to afford the final mixture of **4** and **5** (1:1, 1 h). The ratio of **4** to **5** from **1d** at -70°C was 1:3.

The analogous reaction of cinnamyl chloride with **B** gave only **3d** at -100°C . It slowly decomposed at -80°C to **4** and **5** (1:14, 2 h), as a small amount (15% max) of π -allyl complex **1d** appeared.

Thus, in the reaction of **A** with cinnamyl chloride, the π -allyl Cu^{III} intermediate **1d** gave mainly $\text{S}_{\text{N}}2$ product, whereas the σ -allyl Cu^{III} intermediate **2d** gave mainly $\text{S}_{\text{N}}2'$ product. In contrast, σ -allyl Cu^{III} intermediate **3d** from **B** and cinnamyl chloride gave predominantly $\text{S}_{\text{N}}2$ product, which can be rationalized by the intermediacy of **1d**, as in the case of the $\text{S}_{\text{N}}2$ product from **A**.

In summary, we have confirmed the structures proposed for π -allyl Cu^{III} complexes by preparing the first examples. On the other hand, the *ate* structures that we have established for the first σ -allyl Cu^{III} complexes are novel, and they are crucial to understand the reactivity of allylic substrates with organocopper(I) reagents.

Finally, *cis*-cyano σ -allyl Cu^{III} intermediates are found in both the 1,4-addition reaction of **B**/TMSCl with 2-cyclohexenone⁴ and the $\text{S}_{\text{N}}2'$ reaction of **B** with dimethylvinylcarbinol acetate; hence, the two types of conjugate addition are unified by a deep connection, which we conjecture to be π -allylcopper(III).

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Supporting Information Available: NMR spectra for compounds **1a**, **2a**, and **3a**. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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