were not provided by this study. Since no Ru_2Mo_2 species were observed, it is believed that both ruthenium carbonyl groups were eliminated rapidly. Most of the ruthenium was isolated as $Ru_3(CO)_{12}$. This could have passed through $Ru(CO)_5$ since this is known to convert into $Ru_3(CO)_{12}$ under the reaction conditions. Small amounts of ruthenium were used in the formation of higher nuclearity products.[13]

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Registry No. 1, 105121-22-0; 2, 111189-74-3; 3, 92067-61-3; 4, 109013-40-3; 5, 109064-30-4; $Ru_7(CO)_{20}(\mu_4\text{-}S)_2$, 109466-69-5; $[CpMo(CO)_3]_2$, 12091-64-4; $[CpMo(CO)_2]_2$, 56200-27-2.

Supplementary Material Available: Tables of positional parameters for compound 1, positional parameters of the hydrogen atoms for compounds 2 and 3, C–C and C–O distances for 1 and 2, and anisotropic thermal parameters for 1–3 (14 pages); listings of observed and calculated structure factor amplitudes for 1–3 (86 pages). Ordering information is given on any current masthead page.

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Preparation and Reactivity of Sodium Organocuprates[1]

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Sodium organocuprates, R_2CuNa, can be prepared from organosodium reagents (RNa) and CuCN or $CuBr{\cdot}SMe_2$ at −50 °C in THF. The resulting reagents show typical cuprate reactivity; however, they are less reactive toward a typical α-enone than the corresponding Li cuprates. Organocuprate reactivity toward 2-iodoheptane appears to be controlled by the counterion (CN^- vs I^-) rather than by the metal ion (Na^+ vs Li^+). Both $Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiCN$ are very stable and react quantitatively with PhCOCl. Whereas treatment of di-*tert*-butyl thioketone with BuNa or BuLi yields predominately reduction product, treatment with the corresponding cuprates yields a substantial proportion of thiophilic addition product. The effects of 15-crown-5 and 12-crown-4 on $Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiCN$ are also described.

Organocuprates arguably are the most important of the transition-metal organometallic reagents, and they are among the most important of all the many reagents currently applied to organic synthesis.[2] While the counterion in the Cu(I) precursor (X in Scheme I) has been varied widely (e.g., halide,[3-5] cyanide,[6] acetylide,[7] methanide,[8] mesitylenide,[9] alkoxide,[10] mercaptide,[10] amide,[11] phosphide,[11,12] triflate[13]), the only metal ions that have been partners with Cu in previous cuprates have been Li, Mg, and, to a *very* limited extent, Zn,[14,15] Cd,[15] Zr,[16] B,[17] and Hg.[18] Other metals have been added to organocopper reagents in the form of Lewis acids.[19] We have been able to prepare sodium cuprates by the addition of organosodium reagents to CuCN or $CuBr{\cdot}SMe_2$. These new species possess typical organocuprate reactivity but have some significant differences from the corresponding lithium cuprates.

Scheme I

$$CuX + 2RM \rightarrow R_2CuM{\cdot}MX \text{ (or } R_2Cu(X)M_2\text{)}$$

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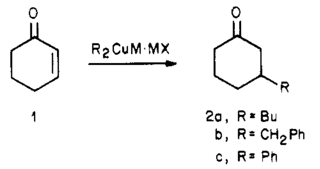
Scheme II



Results

The requisite alkylsodium reagents (butylsodium, BuNa, and pentylsodium, PeNa) were prepared by the reaction of the corresponding Li reagents with sodium *tert*-butoxide.[20,21] We found that it was necessary to modify the literature procedure (see Experimental Section) in order to obtain a product low in Li. Benzylsodium was prepared from BuNa and toluene.[21] Phenylsodium was prepared from diphenylmercury and sodium metal.[22] To make sodium cuprates, these organosodium reagents were mixed in a 2:1 ratio with cuprate precursors CuCN or $CuBr{\cdot}SMe_2$ in a drybox and sealed in vials with rubber septa. Cold tetrahydrofuran (THF) was added at −50 °C under Ar, and the reaction mixtures were stirred for 12–15 min before substrates were added. The Na cuprates were nearly identical in appearance with the corresponding Li cuprates. Poor results were obtained with CuI as the cuprate precursor, and CuOTf gave only violent decomposition. We have not been able to prepare Na cuprates in diethyl ether due to the insolubility of Na reagents in this solvent.[23] While 1,2-dimethoxyethane (DME) was used successfully for benzylsodium, it was not useful for BuNa.

When 2-cyclohexen-1-one (**1**, Scheme II) was added to a THF solution of $Bu_2CuNa{\cdot}NaCN$ (or $Bu_2Cu(CN)Na_2$)[24] at −78 °C, little (4–5%) conjugate addition product, 3-butylcyclohexanone (**2a**), was present after 15 min. In contrast, the reaction of **1** and $Bu_2CuLi{\cdot}LiCN$ went to completion within 15 min at −78 °C. When the sodium cuprate reaction mixture was transferred to a −50 °C bath, a 69% yield of **2a** was obtained after 15 min. Repeating this procedure at −25 °C and at 0 °C did not improve the yield. When **1** was added at −50 °C rather than −78 °C, an 81% yield of **2a** was obtained in both of a pair of duplicate experiments, and 12–15% of **1** was recovered. An 82% yield of **2a** (and 17% recovered **1**) was obtained from $Bu_2CuNa{\cdot}NaBr$, the reagent prepared from 2 equiv of BuNa and 1 equiv of $CuBr{\cdot}SMe_2$ under the same conditions.

The reagent prepared from 1 equiv each of BuNa and CuCN (i.e., BuCu(CN)Li)[24] was homogeneous, similar in appearance to the "higher order" reagent prepared from 2 equiv of BuNa, but it did not alkylate **1** (0.6% yield after 15 min at −50 °C, 2% after 15 min at 0 °C).

While the yield of **2a** from $Bu_2CuNa{\cdot}NaCN$ and **1** was low at −78 °C, an 81% yield of **2a** was obtained upon hydrolysis of the 16:1 mixture of TMS enol ethers that resulted when the reaction was run at −78 °C in the presence of chlorotrimethylsilane[25] (TMSCl) for the same period of time (15 min). The major TMS enol ether from the sodium cuprate was obtained exclusively from the reaction of $Bu_2CuLi{\cdot}LiCN$ and **1** upon quenching with TMSCl after 15 min at −50 °C (cf. Discussion).

Table I. Comparison of Sodium vs Lithium Butylcuprates

		yields (%)[a] of **2a** and **3a**[b]		
reagent	temp, °C	CuCN	$CuBr{\cdot}SMe_2$	CuI
2BuNa	−50	30	12	34 (19)[b]
	−78	1.6	0.6	2.6 (58)
2BuLi	−50	100	93	77 (29)
	−78	27	69	46 (21)
BuNa	−50	0.5	1.8	5.0 (5.9)
	−78	0.2	0.8	0.2 (<0.1)
BuLi	−50	0.5	4.4	43 (<0.1)
	−78	0.3	0.3	12 (1.1)

[a] Measured by GLC using the internal standard method. [b] Parenthetical values are yields of **3a**.

No 1,2-addition product, 1-butylcyclohex-2-en-1-ol (**3a**), was detected by GLC with either the Na or Li cuprates prepared from CuCN, provided that the substrate was not added too early: in one case in which the 2BuNa/CuCN/THF mixture was stirred for 6 min before the addition of **1**, 21% of **3a** resulted. In the absence of Cu, both BuNa and BuLi gave predominately **3a**; nevertheless, 0.6% and 1.4% of **2a**, respectively, were observed in these cases.

In a carefully controlled series of experiments, both "higher order" and "lower order" sodium and lithium cuprates were prepared from CuCN at −50 °C for 12 min and then treated with 1 equiv of **1** for 1.0 min at −50 °C and, in a separate series of experiments, for 1.0 min at −78 °C. The corresponding data were also collected starting with $CuBr{\cdot}SMe_2$ and CuI, as summarized in Table I. All the higher order lithium cuprates are clearly more reactive than the corresponding sodium cuprates at both −50 and −78 °C. The cyanocuprates are generally more reactive than the bromocuprates, except for Bu_2CuLi at −78 °C where the bromocuprate is more reactive. In the case of the cuprates prepared from CuI, both **2a** and **3a** result when the counterion is Li as well as Na. The data on the lower order cuprates demonstrate that these species did not contribute significantly to the products from the higher order species except in the case of BuCu/LiI.[24]

The CuI used was an "ultrapure" grade, which had been recrystallized twice. The production of 1,2-adduct with this precursor suggests the presence of free BuNa or BuLi, which was supported by experiments in which cyclohexanone was added instead of **1**. After 1.0 min at −78 °C, the yield of 1-butylcyclohexan-1-ol from CuI + 2BuNa was 40%; it was 36% from CuI + 2BuLi. While increasing the formation time of the lithium cuprate from 12 min to 1 h at −50 °C only decreased the yield of **2a** from 97% to 88%,[26a] these conditions led to the decomposition of the sodium cuprate: only 3% of **2a** and 5% of **3a** resulted upon treatment with **1** (15 min/−50 °C). In contrast, the sodium cuprates prepared from CuCN and $CuBr{\cdot}SMe_2$ were much more stable; 56–57% yields of **2a** were obtained under the same conditions. The use of CuBr in place of its dimethyl sulfide complex gave results that were similar to those obtained starting from CuI, since 20% of **3a** was observed along with 11% of **2a**.

Sodium cuprates were also prepared from CuCN and 2 equiv of benzylsodium in THF or DME at −50 °C.

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[24] The structures of the cyanocuprates have not been determined. We prefer Fleming's representation $R_2CuLi{\cdot}LiCN$ (ref 6b), as it contains the essential information that the CN remains complexed to the cuprate cluster, and it still retains the classic (empirical) formula used for cuprates prepared from Cu(I) halides, which should be written as $R_2CuLi{\cdot}LiX$ to show explicitly which precursor (CuX) was used. Alternatively, the formula $R_2Cu(X)Li_2$ could be used in analogy with $R_2Cu(CN)Li_2$ (ref 6c). For the "lower order" cyanocuprate we prefer RCu(CN)Li to $RCu{\cdot}LiCN$, although they should be considered semantically equivalent. For those solutions that contain copper reagents and LiX but not in the same clusters we propose RCu/LiX or R_2CuLi/LiX. The same principles apply when Li is replaced by Na.

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Table II. The Effect of Crown Ethers[a] on Butylcyanocuprates

reagent	% $1^{b,c}$	% $2a^{b,d}$	% $3a^{b,e}$
CuCN + 2BuNa	12	81	<0.1
(CuCN + 2BuNa) + 12-C-4	24	38	<0.1
(CuCN + 2BuNa) + 15-C-5	53	11	<0.1
(CuCN + 12-C-4) + 2BuNa	14	6.2	0.3
(CuCN + 15-C-5) + 2BuNa	1.4	0.3	1.1
CuCN + 2BuLi	<0.1	100	<0.1
(CuCN + 2BuLi) + 12-C-4	<0.1	99	<0.1
(CuCN + 2BuLi) + 15-C-5	6	94	<0.1
(CuCN + 12-C-4) + 2BuLi	6	26	48
(CuCN + 15-C-5) + 2BuLi	3	15	58

[a] 12-C-4 denotes 12-crown-4 and 15-C-5, 15-crown-5. [b] Determined by GLC using the internal standard method. [c] 2-Cyclohexenone. [d] 3-Butylcyclohexanone. [e] 1-Butylcyclohex-2-en-1-ol.

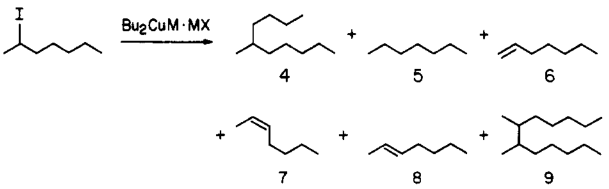
Whether they were stirred for 15 or 45 min, a substantial proportion of 1,2-addition product, 1-benzylcyclohex-2-en-1-ol (**3b**), was observed along with the 1,4-addition product, 3-benzylcyclohexanone (**2b**), upon treatment with 1 at −50 °C (15 min). For example, with a 15-min cuprate age, the yields of **3b** were 31% and 18% in THF and DME, respectively, while the corresponding yields of **2b** were 32% and 47%. When **1** was added at 0 °C, the yields were lower and 1,2-adduct predominated.

Sodium diphenylcuprate prepared from CuCN yielded 16% of 3-phenylcyclohexanone (**2c**) when treated with **1** for 15 min at −50 °C and 33% of **2c** upon warming to 0 °C during 1.5 h. In contrast, lithium diphenylcuprate prepared from CuCN afforded a 100% yield of 3-phenylcyclohexanone.[26a] Running the sodium cuprate reaction in the presence of TMSCl for 15 min at −50 °C afforded a quantitative yield of **2c** after hydrolysis of the single TMS enol ether formed.

The effect of crown ethers on sodium and lithium dibutylcyanocuprates can be appreciated by reference to Table II. In some experiments the cuprates were prepared for 0.2 h at −50 °C. Crown ether was added at this stage, and, after 0.1 h at −50 °C, the reaction mixtures were treated with **1** (15 min/−50 °C). In other experiments the crown ether was added to the CuCN first and then the BuNa or BuLi. After 0.3 h, the **1** was added as above. Adding the crown ethers first had a much larger effect in both the Na and Li systems. With the sodium cuprates there was a shift from 1,4-addition to enolization (see next paragraph), or both products and starting material were eliminated (perhaps because of polymerization). With the lithium cuprates the course of the reaction was shifted from 1,4- to 1,2-addition, when the crown ether was added first. Whether the crown ethers were added after the Bu alkali or before it, 15-crown-5 reduced the yields of **2a** more than 12-crown-4 did. Furthermore, the yields of **2a** from the sodium cuprates were affected more than those from the corresponding lithium cuprates in each case.

Direct injection into a GLC of an aliquot of a solution of $Bu_2CuNa{\cdot}NaCN$ to which 15-crown-5 had been added (as described above) only detected butane, as expected. After the addition of **1** (15 min), a second such injection showed an increase in the butane along with 9% of **1**. Finally, when this reaction mixture was quenched, a third injection measured 53% of **1** and substantially more butane. Thus, it would appear that in the presence of 15-crown-5, at least 44% of **1** is converted to its enolate, which reverts to **1** upon quenching. Similarly, without any crown ether, direct GLC injection ~15 min after addition of **1** indicated only 2% of it still present; however, a GLC injection after quenching revealed 12% of recovered **1**.

Scheme III



Scheme IV

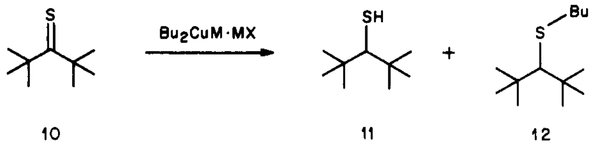


Table III. Product Distributions from 2-Iodoheptane and Cuprates

reagent	yields[a] (%) 4^b	5^c	6^d	7^e	8^f	9^g
$Bu_2CuNa{\cdot}NaCN$	17	9	2	1	2	3
$Bu_2CuLi{\cdot}LiCN$	32	8	2	0	2	2
$Bu_2CuNa{\cdot}NaI$	18	27	25	3	12	8
$Bu_2CuLi{\cdot}LiI$	20	25	14	2	6	8

[a] Yields were determined by GLC calibrated with an internal standard and authentic products. Reaction mixtures were 0.1 M in Bu and substrate and 0.05 M in Cu. [b] 5-Methyldecane. [c] Heptane. [d] 1-Heptene. [e] *cis*-2-Heptene. [f] *trans*-2-Heptene. [g] 6,7-Dimethyldodecane.

Table IV. Product Distributions from 2-Iodoheptane and BuNa or BuLi

reagent	yields[a] (%) 4	5	6	7	8	9
BuNa	27	19	23	3	11	6
BuLi	26	24	26	3	13	9

[a] Yields were determined by GLC calibrated with an internal standard and authentic products. Reaction mixtures were 0.10 M in both reactants.

The results of treating Na and Li butylcuprates prepared from CuCN and from CuI with 2-iodoheptane are summarized in Table III. As illustrated in Scheme III, the products were 5-methyldecane (**4**), heptane (**5**), 1-heptene (**6**), *cis*-2-heptene (**7**), *trans*-2-heptene (**8**), and 6,7-dimethyldodecane (**9**). The product profiles for $Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiCN$ are very similar. The main difference is the higher yield of substitution product **4** obtained with the Li cyanocuprate. The product profiles for $Bu_2CuNa{\cdot}NaI$ and $Bu_2CuLi{\cdot}LiI$ are also very similar, but in this case the main differences are in the yields of alkenes. The results for BuNa and BuLi (Table IV) are also very similar to each other, and they are much closer to the iodocuprate results than they are to the cyanocuprate results.

Treatment of di-*tert*-butyl thioketone[27] (**10**, Scheme IV) with BuNa, BuLi, or the corresponding organocuprates for 1 h at −50 °C yielded mixtures of di-*tert*-butylmethanethiol (**11**) and butyl 2,2,4,4-tetramethyl-3-pentylsulfide (**12**), as summarized in Table V. The Na cuprate yielded less

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Table V. Product Distributions from Di-*tert*-butyl Thioketone

	yield[a] (%)		
reagent[b]	**11**[c]	**12**[d]	100 × **12**/**11**
BuNa	93 (92)[e]	2.0 (2.0)[e]	2.2 (2.2)[e]
BuLi	98 (98)	1.5 (1.8)	1.5 (1.8)
$Bu_2CuNa{\cdot}NaBr$	3.4 (16)	0.90 (1.8)	26 (11)
$Bu_2CuLi{\cdot}LiBr$	12 (26)	5.9 (5.7)	49 (22)

[a] Yields were determined by GLC calibrated with an internal standard and authentic products. Reactions were run for 1 h at −50 °C and then 1 h at 0 °C (parenthetical values). [b] $CuBr{\cdot}SMe_2$ (Aldrich) was used to prepare the cuprates. [c] Di-*tert*-butylmethanethiol (2,2,4,4-tetramethyl-3-pentanethiol). [d] Butyl 2,2,4,4-tetramethyl-3-pentyl sulfide. [e] Parenthetical values are for samples taken after an additional 1 h at 0 °C, see footnote *a*.

reduction product (**11**) and less thiophilic addition product (**12**) than the Li cuprate at both −50 and 0 °C (parenthetical values). Both BuNa and BuLi afforded high yields of **11** along with small amounts of **12**. Approximately 50% of starting material was recovered in the cuprate reaction mixtures.

The thermal stabilities of $Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiCN$ were compared according to the procedure that was recommended for other butylcuprates.[11a] The reaction mixtures were stirred at successively higher temperatures: −50, −25, 0, and 25 °C. After 30 min at each temperature, a sample was quenched with excess benzoyl chloride at −50 °C (15-min reaction time). The yields *based on butyl* were 100%, 98%, 93%, and 91% for $Bu_2CuNa{\cdot}NaCN$ at the four temperatures, respectively, and for $Bu_2CuLi{\cdot}LiCN$ they were 99%, 97%, 100%, and 89%.

Discussion

In spite of their synthetic importance, relatively little detail is known about the mechanisms by which organocuprates react with typical substrates such as α-enones or alkyl halides. Smith and Kraus[28] have presented kinetic evidence that Li^+ has an activating role in the conjugate addition of Li organocuprates to α-enones. We believe that the sodiocuprates $Bu_2CuNa{\cdot}NaCN$ and $Ph_2CuNa{\cdot}NaCN$ are less reactive than the corresponding lithium cuprates toward **1** because Na^+ is less effective than Li^+ at activating an α-enone. This order of reactivity is consistent with IR data,[29] which show that a Li–carbonyl complex is more tightly bound than the corresponding Na–carbonyl complex, and theoretical calculations,[30] which show that the LUMO energy is lower for the Li complex.

Corey and Boaz[25b] have attributed the enhancement of the conjugate addition reaction by TMSCl to the trapping of a Cu(III) intermediate (they prefer a Cu(III)–π-allyl complex). Ullenius and co-workers[31] have observed a Cu–olefin π-complex by NMR spectroscopy in the case of Me_2CuLi and *tert*-butyl *trans*-cinnamate. Unfortunately, the mechanism of TMSCl activation has not been unambiguously established. Nevertheless, we believe that the conjugate additions of $Bu_2CuNa{\cdot}NaCN$ and $Ph_2CuNa{\cdot}NaCN$ are dramatically enhanced by TMSCl for the same reason or reasons that the reactions of the Li cuprates are facilitated. The fact that TMSCl has the same effect on both Na and Li cuprates implies that both react by essentially the same mechanism, whatever the details may be.

Only one TMS enol ether was obtained from $Bu_2CuLi{\cdot}LiCN$, whereas a mixture of TMS enol ethers was obtained from $Bu_2CuNa{\cdot}NaCN$. Thus, the α-enolate formed by conjugate addition of the Na cuprate to the α-enone equilibrates with the α′-enolate faster than the corresponding Li enolate under the same conditions. Apparently, significant **1** is converted to its enolate upon treatment with $Bu_2CuNa{\cdot}NaCN$, and we believe that the base responsible for the deprotonation of **1** is the enolate of **2a**, which also provides a mechanism for equilibration of the α and α′-enolates of **2a**.

Whitesides et al.[4b] reported that 5–25% yields (based on butyl) of 1-butanol were produced when "$Bu_2CuLi{\cdot}LiI$" solutions were treated with dioxygen, indicating that 5–25% of free butyllithium had been present. In consonance with these results, we have observed as much as 20% of **3a** upon treatment of this copper reagent with **1**.[26a] As far as the sodium cuprates are concerned, we observe 1,2-addition with the butylcuprates prepared from CuI and CuBr (but not $CuBr{\cdot}SMe_2$) and with the benzylcuprate prepared from CuCN. Neither the butylcuprate nor the phenylcuprate prepared from CuCN gave any 1,2-adduct.

Lipshutz et al.[32] have reported that free MeLi is present in the reagent prepared from 1 equiv each of MeLi and halide-free MeCu but that free MeLi is not present when LiI is present. The effect of LiI in the Me case provides evidence that iodide is involved in the cuprate cluster. Furthermore, the addition of LiI to the phenylamidocuprate prepared from a homochiral amine and CuCN raised the ee in the product from 0 to 30%, much closer to the 40% ee observed for the corresponding cuprate prepared from CuI.[33] Thus, we could represent the iodocuprates as $R_2Cu(I)Li_2$ and bromocuprates as $R_2Cu(Br)Li_2$, in analogy with Lipshutz's representation of the cyanocuprates as $R_2Cu(CN)Li_2$.[6c] We prefer the symbolism $R_2CuLi{\cdot}LiI$ and $R_2CuLi{\cdot}LiCN$, since it preserves the traditional cuprate formula—R_2CuLi—and also shows which Cu(I) salt was used in the preparation. Neither formulation conveys information about the actual bonding involved; they are both essentially empirical formulae. In the absence of definitive evidence that halide is not involved in cuprate clusters in solution, we see no reason to treat halocuprates differently from cyanocuprates, especially in view of the fact that their reactivity in most cases is similar.[26]

In their study of the influence of 12-crown-4 upon the reaction of Me_2CuLi with 4-methyl-2-cyclohexene-1-one, Ouannes et al.[34a] found that the addition of 2.2 equiv of the crown ether resulted in recovered starting material (unspecified amount) and no conjugate addition product (vs 90% of the latter without crown ether). They do not specify when the 12-crown-4 was added or even which Cu(I) salt was used to prepare the cuprate.[24] With $Bu_2CuNa{\cdot}NaCN$ we see a shift from conjugate addition product (81% maximum) toward starting material **1** (53% maximum) upon the addition of crown ether. Addition of [2.2.1]cryptand to an alkyllithium reagent changes the course of its reaction with a saturated ketone such as cyclohexanone from 1,2-addition to enolization.[34b] In the case

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of $Bu_2CuLi{\cdot}LiCN$, the major change upon addition of crown ether is from 1,4- to 1,2-addition. It has also been demonstrated[34c] that crown ethers change the selectivity of cuprate additions to chiral aldehydes from "Cram" to "anti-Cram" stereochemistry.

The Na-specific 15-crown-5 has a larger effect on the sodium cuprate than Li-specific 12-crown-4, as expected; however, 15-crown-5 also has a larger effect on the lithiocuprate. These observations are consistent with the available thermodynamic data: log K_s for the Na complexes of 15-crown-5 and 12-crown-4 are, respectively, 5.28 and 3.32 in acetonitrile[35] and 3.24 and 1.7 in methanol.[36] The values of log K_s for the Li complexes of 15-crown-5 and 12-crown-4 are respectively, 3.60 and 3.40 in acetonitrile,[35] 1.23 and ~0 in methanol,[37] and 3.59 and 1.62 in acetone.[37] Although data are not available for THF, it appears to be a general phenomenon that Li is bound more tightly by 15-crown-5 than by 12-crown-4 in a number of solvents.

The results from treating 2-iodoheptane with Na and Li dibutylcuprates prepared from CuCN and from CuI (Table III) prove that the counterion (CN vs I) is the controlling factor in these reactions. In order to measure the degree of similarity or difference between two data sets, it is useful to define the "distance" between them. The "city-block" distance[38] between the yields y_p of products p (p = **4**, **5**, ..., **9**) from reagent Y and the corresponding yields z_p from reagent Z is defined as $d = \sum_p|y_p - z_p|$. The distances between the results for the four reagents — $Bu_2CuNa{\cdot}NaCN$ (Na/CN), $Bu_2CuLi{\cdot}LiCN$ (Li/CN), $Bu_2CuNa{\cdot}NaI$ (Na/I), and $Bu_2CuLi{\cdot}LiI$ (Li/I)—are calculated in Table VI (supplementary material) and summarized in the distance matrix **D**. The distances between pairs of cuprates with the same counterion ($Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiCN$, d = 18; $Bu_2CuNa{\cdot}NaI$ and $Bu_2CuLi{\cdot}LiI$, d = 22) are significantly less than between pairs with the same metal ion ($Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuNa{\cdot}NaI$, d = 59; $Bu_2CuLi{\cdot}LiCN$ and $Bu_2CuLi{\cdot}LiI$, d = 53). One of the totally mismatched pairs ($Bu_2CuLi{\cdot}LiCN$ and $Bu_2CuNa{\cdot}NaI$, d = 75) shows the largest distance between results; however, the distance between the other mismatched pair ($Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiI$, d = 41) is surprisingly low.

$$\mathbf{D} = \begin{array}{cccc|l} \text{Na/CN} & \text{Li/CN} & \text{Na/I} & \text{Li/I} & \\ 0 & 18 & 59 & 41 & \text{Na/CN} \\ & 0 & 75 & 53 & \text{Li/CN} \\ & & 0 & 22 & \text{Na/I} \\ & & & 0 & \text{Li/I} \end{array}$$

In order to verify these results, which are based on the degree of difference, a similarity index has also been calculated. While it was developed to compare the similarity of graphs and molecules,[39] **SI**(1) appears to be well-suited to the task at hand. The values of this index, which vary between 0 (no similarity) and 1 (complete similarity or identity), are summarized in Table VII (supplementary material) and in the similarity matrix **SM**(1). These results reinforce the conclusions based on distance.

$$\mathbf{SM}(1) = \begin{array}{cccc|l} \text{Na/CN} & \text{Li/CN} & \text{Na/I} & \text{Li/I} & \\ 1 & 0.64 & 0.37 & 0.42 & \text{Na/CN} \\ & 1 & 0.23 & 0.27 & \text{Li/CN} \\ & & 1 & 0.77 & \text{Na/I} \\ & & & 1 & \text{Li/I} \end{array}$$

The results of treating 2-iodoheptane with BuNa or BuLi are summarized in Table IV, and the distance data in Table VIII (supplementary material) demonstrate that the results for these two reagents are very close to each other (d = 14). The results for these reagents are also close to the results for both the Na and the Li iodocuprates (d = 14–28). On the other hand, the results for both cyanocuprates are much farther from BuNa and BuLi (d = 54–68) than the results for the iodocuprates. From this analysis of the distances in Tables VI and VIII, it may be concluded that BuNa, BuLi, $Bu_2CuNa{\cdot}NaI$, and $BuCuLi{\cdot}LiI$ belong to one class and $Bu_2CuNa{\cdot}NaCN$ and $Bu_2CuLi{\cdot}LiCN$ belong to another class.

These results suggest that the cuprates with the same counterion react via the same mechanistic pathway and that the active agent (or at least a major player) in the iodocuprate reactions is the corresponding Na or Li reagent. In contrast to the reaction with an α-enone, the reaction with an alkyl halide is not dependent upon the alkali metal. Evidence has been adduced that secondary iodides such as 2-iodoheptane react with Li organocuprates by a pathway involving electron transfer and free radicals.[40]

Ohno and co-workers[27] found that di-*tert*-butyl thioketone (**10**) was reduced quantitatively to **11** upon treatment with BuLi in hexane at 25 °C. Furthermore, they showed that it is a β-H of the BuLi that is transferred to the thiocarbonyl C.[27] While reduction is the major pathway under our conditions, thiophilic addition product (**12**) is also formed, albeit in low yields (see Table V). Comparison of the entries in Table V leads to the conclusion that reduction is less prevalent for the cuprates than the corresponding Na or Li reagents, perhaps because the β-H atoms of the cuprates are less accessible. We have demonstrated that Cu(I) dramatically shifts the regiochemistry of addition to the C–S double bond in dithioesters from exclusively thiophilic to completely carbophilic.[13] The very substantial steric hindrance at the C end of the C–S bond in **10** appears to preclude the addition of butyl to C.

The thermal stability study not only establishes that both sodium and lithium cyanocuprates are among the most stable of butylcuprates, it also demonstrates that they react *quantitatively based on butyl* with benzoyl chloride, a typical acid chloride. In fact, this reaction is one of the few that efficiently uses *both* of the alkyl groups of a dialkylcuprate.[13,41]

Summary

Sodium cuprates have been prepared from sodium reagents (e.g., butylsodium, pentylsodium, benzylsodium, and phenylsodium) and Cu(I) salts CuCN and $CuBr{\cdot}SMe_2$. The reactivity exhibited by these new reagents is roughly parallel to that of the corresponding Li cuprates; however, the degree of similarity is determined by the substrate. For example, the corresponding Na and Li cuprates have very similar reactivities toward 2-iodoheptane but different reactivities toward 2-cyclohexenone. These reactivity differences might be used to obtain selective reactions and

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to further probe mechanistic questions concerning organocuprates.

Experimental Section

Butylsodium and Pentylsodium. The procedure of Lochmann et al.[20,21] was followed with several modifications. The sodium *tert*-butoxide was sublimed once rather than twice, and hexane was used as the solvent rather than heptane. A 1.4–1.5× excess of BuLi (or PeLi) was used instead of 1.3×, and the filtration step was carried out in a drybox. It was necessary to resuspend the solid filter cake in fresh hexane, collect it a second time, and wash it repeatedly with hexane in the sintered glass funnel (~500 mL of hexane total) in order to obtain a product low in lithium (0.15–0.3 wt % by AA spectroscopy). Gilman double-titration[42] indicated an equivalent weight of 81.7–84.3 mg/mmol for BuNa (FW 80.1) and 97.1 mg/mmol for PeNa (FW 94.1).

Benzylsodium. A 6-g (0.07-mol) quantity of BuNa, which was too high in Li (11 mol % Li, prepared without the second filtration), was suspended in 70 mL of toluene in a 125-mL Erlenmeyer flask capped with a rubber septum and stirred magnetically for a week in a drybox at room temperature. Filtration yielded 7 g of benzylsodium, which double titration[42] indicated was 92% pure; AA spectroscopy showed that it contained 3 mol % Li. A portion of this benzylsodium was dissolved in dry THF at −78 °C under Ar, and chlorotrimethylsilane was added. Only one silane was detected by capillary GLC; it was identical with the product afforded by benzyllithium (Organometallics, Inc.) under the same conditions.

Double Titration Procedure.[42] For the total base analysis a ca. 1-mmol sample of sodium reagent was weighed into a 125-mL Erlenmeyer flask in a drybox, and the flask walls were washed down with 15 mL of hexane. The flask was sealed with a rubber septum and removed from the drybox. Then it was vented with a needle, and 10 mL of methanol was added. The flask was opened, and its contents were rinsed down with deionized water and titrated to a phenolphthalein end point with 0.100 M HCl. The residual base determination was accomplished in an analogous manner, except that 1,2-dibromoethane (~5 mL, dried over molecular sieves) was used in place of methanol. The active base is calculated as total base minus residual.

Preparation of Sodium Organocuprates (Typical Procedure). A 4-dram vial (*borosilicate glass* only, Wheaton No. 224886) was charged with 89.8–90.2 mg (1.00–1.01 mmol) of CuCN (Baker Reagent) and 163.5 mg (2.00 mmol) of 98.0% BuNa and sealed with a rubber septum in a drybox. The vial was attached to an Ar line and placed in a −50 °C bath (dry ice/2-propanol or acetone). Cold THF (9 mL) from a flask in the cold bath was added by using a B-D disposable syringe cooled with dry ice. (In order to be effective at low temperatures, a disposable syringe must have a plunger with two seals.) The magnetically stirred reaction mixture became light yellow and homogeneous. Typically, it was stirred for 12–15 min at −50 °C before substrate was added. (The corresponding Li cuprate prepared at the same time looked much the same.) This procedure was also used with pentylsodium, benzylsodium, and phenylsodium.

Reaction of Sodium Organocuprates with 2-Cyclohexen-1-one (Typical Procedure). Sodium dibutylcyanocuprate(I), prepared as above, was treated with 1.0 mL of a solution of 96.2 mg (1.00 mmol) of 2-cyclohexen-1-one (Aldrich, distilled) and 38.0 mg of undecane (internal standard) which was delivered from a B-D disposable syringe cooled with dry ice. After the desired time (usually 1.0 or 15.0 min) at the desired temperature (−50 or −78 °C), the rapidly stirred solution was quenched with 2 mL of 3 M ammonium chloride (purged with nitrogen). The reaction mixture was warmed to room temperature, and the organic layer was separated and dried over anhydrous sodium sulfate. GLC analyses were carried out on a 50 m × 0.2 mm cross-linked methylsilicone (0.33-μm film) capillary column (Hewlett-Packard) with the temperature program 40–250 °C at 10 °C/min followed by 250 °C for 10 min. Typical retention times were 11.5 min for 2-cyclohexen-1-one, 15.25 min for undecane, 17.0 min for 1-butylcyclohex-2-en-1-ol, and 18.0 min for 3-butylcyclohexanone.

Reactions Involving Crown Ethers. These reactions were run essentially as described in the previous two "Typical Procedures" with the following modifications. In the experiments labeled (CuCN + crown) + 2BuNa, the crown ether (1 equiv based on Cu of 12-crown-4 or 15-crown-5, distilled from activated molecular sieves) was added via syringe to the same vial containing the CuCN (45.0 mg). THF (3 mL) was added, the mixture was cooled to −50 °C, and 98% pure BuNa (82.0 mg) dissolved in 2 mL of cold (−78 °C) THF was added via a dry ice cooled syringe. After 0.3 h at −50 °C, 2-cyclohexenone (48.9 ± 0.1 mg) and undecane (25 μL, weighed to the nearest 0.1 mg) dissolved in 1 mL of THF was added (dry ice cooled syringe). After an additional 15 min at −50 °C, the reaction mixture was worked up as usual. In those experiments labeled (CuCN + 2BuNa) + crown, the crown ether (1 equiv based on Cu of 12-crown-4 or 15-crown-5) dissolved in 1 mL of THF was added via syringe (cooled with dry ice) to a −50 °C solution of $Bu_2CuNa\cdot NaCN$ (0.2-h formation time). After 0.1 h at −50 °C, **1** was added and the experiment continued as above.

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Registry No. **1**, 930-68-7; **2a**, 39178-69-3; **2b**, 85450-51-7; **2c**, 20795-53-3; **3a**, 88116-46-5; **3b**, 98369-87-0; **4**, 13151-35-4; **5**, 142-82-5; **6**, 592-76-7; **8**, 14686-13-6; **9**, 20904-59-0; **10**, 54396-69-9; **11**, 57602-97-8; **12**, 111113-24-7; **12-C-4**, 294-93-9; **15-C-5**, 33100-27-5; BuNa, 3525-44-8; PeNa, 1822-71-5; $PhCH_2Na$, 1121-53-5; *t*-BuONa, 865-48-5; $Bu_2CuNa\cdot NaCN$, 111140-18-2; $(PhCH_2)_2CuNa\cdot NaCN$, 111140-19-3; $Ph_2CuNa\cdot NaCN$, 111140-20-6; PhNa, 1623-99-0; $Bu_2CuLi\cdot LiCN$, 80473-69-4; $Bu_2CuNa\cdot NaI$, 111140-21-7; $Bu_2CuLi\cdot LiI$, 111140-22-8; $Bu_2CuNa\cdot NaBr$, 111140-23-9; $Bu_2CuLi\cdot LiBr$, 65254-08-2; cyclohexanone, 25512-62-3; 1-butylcyclohexanol, 5445-30-7; 2-iodoheptane, 18589-29-2.

Supplementary Material Available: Table VI, calculation of city-block distances, Table VII, calculation of similarity index **SI**(1), and Table VIII, similarity of BuNa and BuLi to cuprates (1 page). Ordering information is given on any current masthead page.

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