moval of the solvent under reduced pressure afforded a yellow oil, which was subjected to flash chromatography on a silica gel column using a 20% ethyl acetate–hexane mixture as the eluent to give 2-[(phenylsulfonyl)methyl]-1-cyclopentenyl methyl ketone (**55**) as a pale yellow oil in 43% yield: IR (neat) 3080, 2970, 2860, 1680, 1610, 1320, 1150, 1085, 740, and 690 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.78–1.95 (m, 2 H), 1.92 (s, 3 H), 2.58–2.65 (m, 2 H), 2.72–2.79 (m, 2 H), 4.53 (s, 2 H), 7.48–7.64 (m, 3 H), and 7.83–7.87 (m, 2 H); HRMS calcd for $C_{14}H_{16}SO_3$ 264.0820, found 264.0829.

Preparation of 2-[(Phenylsulfonyl)methyl]cyclohexyl Methyl Ketone (57). A solution containing 200 mg of 3-(phenylsulfonyl)-2-(phenylthio)-1-propene (1) and 0.59 mL of hexamethylphosphoramide in 10 mL of dry tetrahydrofuran was cooled to −78 °C under a nitrogen atmosphere. To this mixture was added 0.52 mL of a 1.6 M *n*-butyllithium solution in hexane. The resulting yellow solution was stirred at −78 °C for 10 min, and then 0.10 mL of 6-bromo-1-hexene was added in one portion. The reaction mixture was allowed to warm to room temperature and was quenched with a saturated ammonium chloride solution. Evaporation of the solvent under reduced pressure left a yellow oil, which was dissolved in ether. The organic solution was washed with water and brine. Removal of solvent under reduced pressure afforded a yellow oil, which was taken up in 50 mL of a 60% aqueous acetic acid solution. The mixture was treated with 800 mg of sodium phenylsulfinate and heated to 100 °C for 16 h. The solution was cooled and extracted with ether. The combined ether extracts were washed with a dilute sodium hydroxide solution, water, and brine and then dried over sodium sulfate. Removal of the solvent under reduced pressure left a clear oil, which was subjected to flash chromatography on a silica gel column using a 20% ethyl acetate–hexane mixture as the eluent. The major fraction was identified as 2-[(phenylsulfonyl)methyl]cyclohexyl methyl ketone (**57**) as a pale yellow oil in 50% yield: IR (neat) 3020, 2950, 2870, 1705, 1430, 1310, 1145, 1090, and 695 cm^{-1}; NMR ($CDCl_3$, 300 MHz) δ 1.19–1.39 (m, 4 H), 1.73–1.81 (m, 2 H), 1.94–1.98 (m, 1 H), 2.11 (s, 3 H), 2.17–2.28 (m, 2 H), 2.47–2.54 (m, 1 H), 3.01 (d, H, J = 5.3 Hz), 7.54–7.68 (m, 3 H), and 7.87–7.90 (m, 2 H); HRMS calcd for $C_{15}H_{20}SO_3$ 280.1133, found 280.1138.

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Registry No. 1, 2525-54-4; **3**, 2525-40-8; **4**, 113881-68-8; **5**, 113881-69-9; **6**, 124418-78-6; **7**, 113881-71-3; **8**, 113881-70-2; **9**, 124418-79-7; **10**, 124418-80-0; **11**, 113881-80-4; **13**, 124418-81-1; **14**, 124418-82-2; **15**, 124418-83-3; **16**, 124418-84-4; **17**, 124418-85-5; (*E*)-**18**, 113881-72-4; (*Z*)-**18**, 113881-73-5; (*E*)-**19**, 113881-74-6; (*Z*)-**19**, 113881-75-7; (*E*)-**20**, 124418-86-6; (*Z*)-**20**, 124419-03-0; (*E*)-**21**, 113881-77-9; (*Z*)-**21**, 113881-78-0; (*E*)-**22**, 113881-76-8; (*Z*)-**22**, 113881-76-8; (*Z*)-**22**, 113921-81-6; (*E*)-**23**, 124418-87-7; (*Z*)-**23**, 124419-04-1; **24**, 113881-82-6; (*E*)-**25**, 124418-88-8; (*Z*)-**25**, 124419-05-2; **26**, 124418-89-9; **27**, 124418-90-2; **29**, 124418-91-3; **30**, 72863-20-8; **31**, 97479-46-4; **32**, 124418-92-4; **33**, 124418-93-5; **34**, 113881-89-3; (*E*)-**35**, 124441-43-6; (*Z*)-**35**, 124441-44-7; **36**, 113881-97-3; **37**, 124418-97-9; **38**, 80945-31-9; **39**, 113881-90-6; **40**, 18955-77-6; **41**, 113881-91-7; **42**, 124418-95-7; **43**, 124418-96-8; **47**, 124419-00-7; (*E*)-**48**, 124419-07-4; (*Z*)-**48**, 124419-08-5; **52**, 124418-98-0; **53**, 124418-99-1; **54**, 124419-09-6; **55**, 124419-01-8; **56**, 124419-10-9; **57**, 124419-02-9; **60**, 124419-06-3; $Br(CH_2)_2Br$, 106-93-4; $Br(CH_2)_4Br$, 110-52-1; $Br(CH_2)_3Br$, 109-64-8; CH_3CH_2SH, 75-08-1; PhSH, 108-98-5; $PhCH_2Br$, 100-39-0; PhCHO, 100-52-7; $Br(CH_2)_3CH{=}CH_2$, 1119-51-3; $CH_3(CH_2)_2C{\equiv}CI$, 14752-61-5; $Br(CH_2)_4CH{=}CH_2$, 2695-47-8; 3-(phenylsulfonyl)-2-(ethylthio)-1-propene, 2525-54-4; 3-methyl-2-(ethylthio)-1-(phenylsulfonyl)-2-butene, 124418-94-6; sodium benzenesulfinate, 873-55-2; sodium *p*-toluenesulfinate, 824-79-3.

1,6-Addition of Organocopper Reagents to 3-Alkynyl-2-cycloalkenones: Regiospecific Syntheses of Dienones and Allenes

Menyan Cheng and Martin Hulce*

Department of Chemistry and Biochemistry, University of Maryland Baltimore County, Baltimore, Maryland 21228

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To investigate the preparation of allenes by means of 1,6-addition reactions to 2-alken-4-ynones, 3-ethynyl-2-cycloalkenones (**5**) were synthesized and reacted with a variety of organocopper nucleophiles. Such nucleophiles undergo regiospecific 1,6-additions to generate intermediate allenyl enolates (**10**), which are regiospecifically and stereoselectively protonated to yield a preponderance of (*Z*)-3-alkenyl-2-cycloalkenones (**6–8**). The reaction is sensitive to the nature of the organocopper reagent used; higher order cyanocuprates derived from organolithium reagents are the reagents of choice. The intermediate allenyl enolates (**10**) can be trapped as their enol triflates (**13**), which in turn can be converted into enallenes (**14**). Non-organocopper nucleophiles also can add to the terminal carbon of the alkynyl moiety of the enynones studied, but the mechanism may be distinct from that of 1,6-addition: (phenylthio)lithium adds to 3-ethynyl-2-methyl-2-cyclopentenone (**5a**) by a syn-carbometalation-like mechanism and upon protic quenching yields a preponderance of (*E*)-2-methyl-3-(2-(phenylthio)ethenyl)-2-cyclopentenone (**6h**).

Conjugate addition reactions of organometallic nucleophiles to α,β-unsaturated carbonyl substrates in aprotic solvents are powerful, versatile synthetic tools extensively exploited by organic chemists.[1-3] In contrast, vinylogous conjugate additions such as 1,6-additions to $\alpha,\beta,\gamma,\delta$-unsaturated carbonyl substrates and, more generally, 1,(4 + 2n)-additions to more extensively conjugated polyenones

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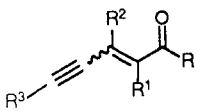
have received comparatively little attention.[1c,4,5] Such additions are potentially important, however, not only because of their possible value in organic synthesis but also because of their role in the alkylation of B-DNA by sequence-selective, minor groove binding antitumor agents such as CC-1065 (rachelmycin).[6] Reported examples using 2,4-dienones as substrates indicate that the ratio of 1,2-, 1,4-, or 1,6-addition modes depends upon a number of factors,[4c,i,p,7] including nucleophile identity, relative steric environments of the electrophilic carbons of the dienone, and substrate planarity. In searching for a new, nucleophilic addition route to supplement the classic S_N2[8] and addition–elimination[9] approaches used to prepare allenes,[10,11] our attention was drawn to a potential 1,6-addition route via 2-alken-4-ynones 1. Although 1,6-addi-



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tions to enynones 1 had not been explored, the relative steric congestion of the electrophilic carbons of these substrates suggested that nucleophiles prone to conjugate addition such as organocopper reagents would react with high regioselectivity[1c] and in a 1,6 fashion. We report here the preparation of representative enynones 1, the regiochemistry of the reaction of enynones with various organocopper nucleophiles, the stereochemistry of protonation of the conjugate enolate intermediates formed upon 1,6-addition, and the application of this 1,6-addition method to the synthesis of allenes.

Results and Discussion

Synthesis of 3-Ethynyl-2-cycloalkenones (5). A number of methods are available to prepare 2-en-4-ynones[12,13] as well as similar aldehydes[14] and esters.[15] Our requirements for a general synthesis of gram quantities of relatively stable and preferably crystalline enynones of pure *E* or *Z* configuration led to the choice of preparing 3-ethynyl-2-cycloalkenones (**5**) by nucleophilic addition of metal acetylides to alkyl enol ethers of 1,3-cycloalkanediones **2**[12c,16] (Scheme I). Not suprisingly, it was found that the choice of metal acetylide[17] was critical for successful ethynylation of enol ethers **2**: when the ether-insoluble disodium salt of acetylene was reacted with **2c**, enolate formation[18] preempted nucleophilic addition to the carbonyl moiety and subsequent conjugate addition–elimination led to formation of dimer **3** as the major product. Use of the ethylenediamine complex of lithium acetylide resulted in slow ethynylation of **2b** and **2c**; acid-catalyzed dehydration and hydrolysis of the crude propargylic alcohols resulted in modest yields of enynones **5b** (43%) and **5c** (42%). Lithium acetylide itself, prepared by the Midland method,[19] proved to be far more reactive as a nucleophile; in analogy with the literature preparation[12b] of **5c**, enynone **5a** could be prepared in 56% yield. The lithium salt of (trimethylsilyl)acetylene[20] proved to be superior to all of the above. Efficient ethynylation of, for instance, **2b** resulted in enynone **4b** in 82% yield; subsequent desilylation using aqueous fluoride proceeded nearly quantitatively. The later two-step synthesis of enynones was found to be especially appealing, not only

Scheme I

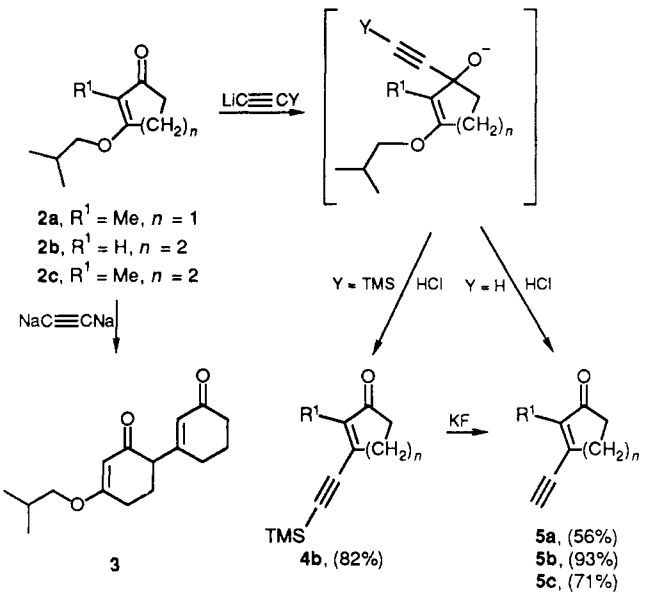

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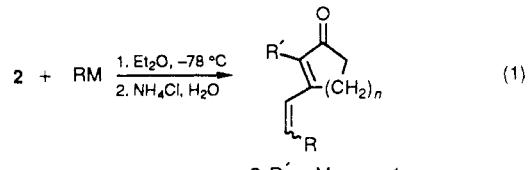
Table I. 1,6-Additions to Enynones 1, 2, and 4

RM	product	n	R	R^1	yield,[a] %	ratio Z:E[b]
$(CH_3)_2CuLi$	**6a**	1	CH_3	CH_3	44–82	2:1
	8a	2	CH_3	CH_3	84, 97[c]	2:1
$CH_3Cu(CN)Li$	**6a**	1	CH_3	CH_3	95[c]	2:1
	8a	2	CH_3	CH_3	86[c]	2:1
$(CH_3)_2Cu(CN)Li_2$	**6a**	1	CH_3	CH_3	91, 99[c]	2.5:1
	7a	2	CH_3	H	75, 95[c]	1.2:1
	8a	2	CH_3	CH_3	89	2.5:1
$C_2H_5Cu(CN)MgBr$	**6b**	1	C_2H_5	CH_3	41	4:1
$(C_2H_5)_2Cu(CN)(MgBr)_2$	**6b**	1	C_2H_5	CH_3	77, 87[c]	3:1
$(i\text{-}C_3H_7)_2Cu(CN)(MgCl)_2$	**6c**	1	$i\text{-}C_3H_7$	CH_3	87	4:1
	8c	2	$i\text{-}C_3H_7$	CH_3	81	6:1
$(n\text{-}C_4H_9)_2CuLi$	**8d**	2	$n\text{-}C_4H_9$	CH_3	64[c]	7:1
$(n\text{-}C_4H_9)_2Cu(CN)(MgBr)_2$	**8d**	2	$n\text{-}C_4H_9$	CH_3	68[c]	7:1
$(n\text{-}C_4H_9)_2Cu(CN)Li_2$	**8d**	2	$n\text{-}C_4H_9$	CH_3	81	7:1
$(t\text{-}C_4H_9)_2CuLi$	**8e**	2	$t\text{-}C_4H_9$	CH_3	49	35:1
$(t\text{-}C_4H_9)_2Cu(CN)Li_2$	**8e**	2	$t\text{-}C_4H_9$	CH_3	89	35:1
	7e	2	$t\text{-}C_4H_9$	H	83	9:1
	6e	1	$t\text{-}C_4H_9$	CH_3	93	34:1
$(C_6H_5)_2CuMgBr$	**6f**	1	C_6H_5	CH_3	46[c]	*d*
	8f	2	C_6H_5	CH_3	80	all Z
$(C_6H_5)_2CuMgBr\cdot(CH_3)_2S$	**6f**	1	C_6H_5	CH_3	45	all Z
$(C_6H_5)_2Cu(CN)(MgBr)_2$	**6f**	1	C_6H_5	CH_3	39, 83[c]	6:1
$(C_6H_5)_2Cu(CN)Li_2$	**6f**	1	C_6H_5	CH_3	88	6:1
	8f	2	C_6H_5	CH_3	81	all Z
$(CH_2{=}CH)_2CuMgBr\cdot(CH_3)_2S$	**6g**	1	$CH_2{=}CH$	CH_3	48[c]	1.5:1
$(CH_2{=}CH)_2Cu(CN)(MgBr)_2$	**6g**	1	$CH_2{=}CH$	CH_3	43	*d*
$(CH_2{=}CH)_2Cu(CN)(MgBr)_2 + BF_3\cdot(C_2H_5)_2O$	**6g**	1	$CH_2{=}CH$	CH_3	39	*d*
$(CH_2{=}CH)_2Cu(CN)Li_2$[e]	**6g**	1	$CH_2{=}CH$	CH_3	59	5.1:1
$(CH_2{=}CH)Cu(CN)Li_2$	**6g**[f]	1	$CH_2{=}CH$	CH_3	83	*d*
	8g	2	$CH_2{=}CH$	CH_3	82	3:1
	8g[f]	2	$CH_2{=}CH$	CH_3	84	*d*
C_6H_5SLi	**6h**	1	C_6H_5S	CH_3	52	1:17

[a] Isolated yields unless otherwise noted. [b] Determined by ^1H NMR and GC or HPLC. [c] GC or HPLC yield. [d] Not determined. [e] From $(CH_2{=}CH)_4Sn$. [f] Isolated as 2,4-dinitrophenylhydrazone.

because of higher overall yields but also because of the stability of the intermediate silyl enynone **4b** which, unlike its desilylated analogue **5b**, does not decompose upon standing. A supply of **4b** therefore could be prepared and **5b** generated as needed immediately before use.

Reactions of Enynones 5. When ether solutions of **5** were added dropwise to various dialkylcopper reagents at −78 °C, a usually rapid reaction occurred wherein all of **5** was consumed as monitored by TLC. Quenching at −78 °C with aqueous ammonium chloride resulted in conjugated dienones **6**–**8** (eq 1, Table I), indicating exclusive



(1)

6, R′ = Me, *n* = 1
7, R′ = H, *n* = 2
8, R′ = Me, *n* = 2

attack of the nucleophile at the terminal sp-hybridized carbon of the starting enynones. In a survey to determine the organometallic reagents of choice for the addition reaction, some clear trends could be discerned. First, higher order organocopper reagents[21] formed from copper(I) cyanide were almost universally superior to lower order Gilman-type reagents formed from copper(I) iodide or copper(I) bromide–dimethyl sulfide complex,[22] forming adducts more rapidly, with good reproducibility and in very good to excellent isolated yields (77–93%). The Gilman-type reagents, in contrast, often resulted in lower, variable yields of products **6**–**8**; it was not unusual for there to be a doubling of the amount of adduct present in the crude product mixture when the higher order reagent was substituted for its lower order analogue. Second, it was found that the specific organometallic reagents used to generate the organocopper reagents for the addition reactions exerted noticable—and sometimes profound—influence upon the success of the reaction. Although in some cases (C_2H_5, $i\text{-}C_3H_5$) involving sp^3-hybridized nucleophiles the reaction proceeded efficiently using higher order organocopper reagents derived from Grignard reagents, organocopper reagents derived from organolithium reagents usually were superior. For instance, in the case of addition of $n\text{-}C_4H_9$, when the higher order organocopper reagent was formed from *n*-butylmagnesium bromide, the adduct was isolated in 68% yield. Formation of the organocopper reagent using *n*-butyllithium reliably and repeatedly raised the yield of the adduct by 10–15%. This sensitivity to the identity of the counterion was particularly acute in the case of sp^2-hybridized nucleophiles. For instance, vinylmagnesium bromide derived lower and higher order organocopper reagents gave very poor conversion to vinyl adduct **6g** when reacted with **5a**, even when the adjuvant BF_3-etherate was used.[23] The use of vinyllithium prepared from tetravinyltin[24] augments adduct formation, but the small amount of organotin species still present appears to be deleterious to the success of the addition reaction. Only vinyllithium itself resulted in adduct formation in yields equivalent to those obtained for the sp^3-hybridized nucleophiles. Sensitivity of conjugate-type additions to the means by which an organometal

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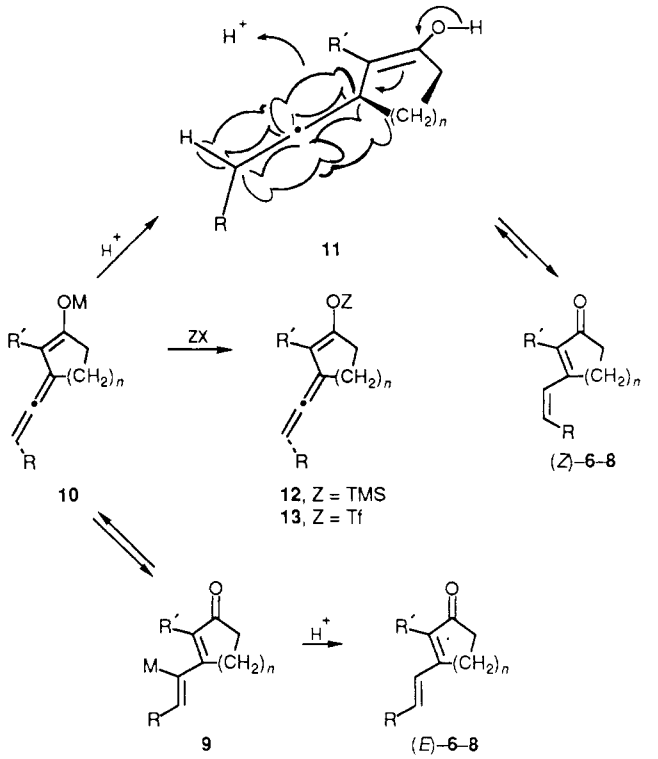
nucleophiles is prepared has been noted previously,[25] as has sensitivity to the counterion present in conjugate donor organocopper reagents.[26] While the reasons for such behavior remain to be determined, our results indicate a probable routine superiority of organo*lithium*-derived higher order organocoppers in conjugate-type addition processes.[27] Last, in generating the data comprising Table I, it was possible to compare the relative reactivity of **5a** to **5c**. Similar to the trend observed for 1,4-additions of organocopper reagents to cycloalkenones,[2a,c] cyclopentenone **5a** was noticeably more reactive toward organocopper addition than cyclohexenone **5c**: all addition reactions using **5a** were essentially complete as soon as addition of the nucleophile was accomplished, whereas additions were slower when **5c** was employed and reaction times from 1.5 to 3 h were required for complete consumption of starting material. For enynone **5c**, phenyl, vinyl, and butyl organocopper reagents were most reactive overall; methyl and *tert*-butyl reagents were intermediate in reactivity, and the isopropyl organocopper reagent was least reactive.

The regiospecific alkylation of enynones **5** also was found to proceed stereoselectively. In each case, organocopper-mediated addition resulted in a preponderence of the thermodynamically less stable *Z* geometry of the 3-alkenyl moiety in products **6–8**. Moreover, this stereoselectivity is a function of the steric bulk of the alkyl group added: the ratio of (*Z*)-**6**:(*E*)-**6** increases from 2.5:1 to 34:1 when R is varied from methyl to *tert*-butyl; an identical trend is seen for products **8**. Perhaps most telling are the differences in the amounts of *Z* isomers formed when the substrates were reacted with the same organocopper reagent. Comparing the addition of $(t\text{-}C_4H_9)_2Cu(CN)Li_2$ to substrates **5b** and **5c**, ratios (*Z*)-**7e**:(*E*)-**7e** and (*Z*)-**8e**:(*E*)-**8e** are 9:1 and 35:1, respectively. A similar large difference in stereoselectivity is seen when comparing $(C_6H_5)_2Cu(CN)Li_2$ additions to subtrates **5a** and **5c**; product ratios (*Z*)-**6f**:(*E*)-**6f** and (*Z*)-**8f**:(*E*)-**8f** are 6:1 and ≥50:1, respectively. These results can be rationalized qualitatively by examining the consequences of a predominent 1,6-addition mode for nucleophilic organocopper attack upon **5** (Scheme II). Addition of group R initially gives rise to vinylmetallic species **9** by syn-carbocupration.[28] Facile isomerization leads to a resonance-stabilized allenyl enolate (**10**) that upon protic quenching forms a transient allenyl enol (**11**).[29] As suggested in the equilibrations of β-allenyl esters[30] and analogous addition reactions to α,β-acetylenic carbonyl substrates,[31] enol **11** then isomerizes to its thermodynamically more stable, fully conjugated isomeric form (**6–8**) by preferential protonation from the less hindered face of the sp-hybridized carbon of the allene moiety, resulting in the predominent *Z* geometry of the 3-alkenyl substituents of **6–8**. The unusually depressed stereoselectivity for *Z* isomer formation in the case of synthesis of **7e** can be rationalized by invoking a less favorable equilibration from **9** to **10**: α-methyl substituents are known to stabilize conjugate enolates formed by 1,4-additions of organocopper reagents to 2-cycloalkenones;[2a,c,32] when **10** is not additionally stabilized by α-methyl substitution, equilibration from **9** to **10** becomes less favorable and a greater portion of the product **7e** is formed by protonation of intermediate **9**, leading to proportionately more (*E*)-**7e**. Similar reasoning can be used to explain the depressed *Z* stereoselectivity observed when synthesis of **6f** is compared to that of **8f**. Addition of a phenyl group to **5c** results in a vinylmetallic species **9** that may be stabilized by π-arene–metal coordinative effects;[33] additionally, when the ring size of intermediate **10** is varied from five to six carbons, the amount of ring strain generated from the exocyclic allenic functional group can be expected to diminish.[34] In the case of substrate **5c**, the

Scheme II



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(27) Although not examined in this study, higher order mixed organocopper reagents with mixed counterions, e.g., R(2-thienyl)Cu(CN)-LiMgBr, have been reacted with enones; they are less reactive than the corresponding R(2-thienyl)$Cu(CN)Li_2$ reagents: Lipshutz, B. H.; Parker, D. A.; Nguyen, S. L.; McCarthy, K. E.; Barton, J. C.; Whitney, S. E.; Kotsuki, H. *Tetrahedron* **1986**, *42*, 2873.

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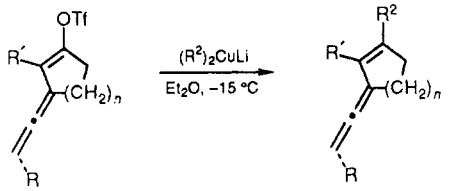
delocalization of the negative charge to give species **10** more than compensates for the loss of stabilizing π-arene–metal coordination in **9**, and the amount of ring strain generated from the exo allene is minimal; (*Z*)-**8f** greatly predominates. In the case of substrate **5a**, charge delocalization in **10** is offset by more significant ring strain generated by the *exo* allene; the equilibrium between **10** and the π-arene-stabilized vinylmetallic **9** is less perturbed, and more (*E*)-**6f** is generated.

To determine if the position of the putative equilibrium between **9** and **10** could be altered chemically, as implied by the above argument, a heteroatom nucleophile was chosen that would favor formation of the localized vinyl anion **9** by stabilization through a combination of electron-withdrawing effects and moderate coordination potential.[35] Favored formation of **9** consequently would result in production of (*E*)-**6**–**8** as the major stereoisomer. When (phenylthio)lithium was reacted with **5a**, the formation of (*E*)-**6h** was favored significantly (ratio (*Z*)-**6h**:(*E*)-**6h** 1:17), suggesting that the otherwise preferred conjugate addition pathway can be usurped by syn-carbometallation given appropriate circumstances.

Trapping of Enolate 10 and Mechanism. To verify that the addition reaction was proceeding in a 1,6 fashion to generate allenyl enolates **10**, spectroscopic and trapping studies were undertaken. In an experiment to determine if the presence of **10** could be determined by ^{13}C NMR, the −78 °C proton-decoupled ^{13}C NMR spectra of enynone **5a** in d_8-THF and **5a** plus 1.5 equiv of $(CH_3)_2Cu(CN)Li_2$ in d_8-THF were compared. The carbonyl carbon (δ 208) and sp-hybridized carbon (δ 96, terminal C_{sp}; δ 80, internal C_{sp}) resonances disappeared upon introduction of the organometallic reagent, and a new set of signals appropriate for those of an allenyl enolate were observed, including those for an sp-hybridized allene carbon[36] (δ 198) and four resonances in the alkene region of the spectrum (δ 166, enolate carbonyl carbon; δ 150, internal allene carbon; δ 115, α-carbon; δ 89, terminal allene carbon). This result was encouraging but not unambiguous, due to the considerable overlap of the diagnostic regions for carbonyl and allene sp-hybridized carbon resonances. Therefore, trapping studies were undertaken to demonstrate the existence of intermediate **10**.

Considerable effort to trap the allenyl enolate as a silyl enol ether[2c,37] (**12**) using a variety of silylating reagents and conditions uniformly led to the same result: an allenyl enol silyl ether could be detected in the crude product, but the ether was prone to facile hydrolysis and invariably reverted to its enone **6**–**8** when purification was attempted.[38] In a typical experiment, **5c** was treated with $(CH_3)_2Cu(CN)Li_2$, and the reaction quenched with the supernatant of a centrifuged mixture of chlorotrimethylsilane, triethylamine, and HMPA. Cold bicarbonate workup gave a crude product containing allene **12a** (R, R′ = CH_3; n = 2), as indicated by IR (1950 cm^{-1}), ^1H NMR (δ 5.57 (q, 1 H)), and mass spectrum ($M^{\bullet+}$ 222). Two-dimensional TLC (3:1 hexane:ether) indicated the formation of a major, nonpolar product with R_f = 0.8 which decomposed to enone **8a** upon elution in the second dimension. In fact, no method could be found to isolate **12a** in chemically pure form.

The successful generation of enol triflates[39] from conjugate enolates formed from organocopper additions to enones using N-phenyltrifluoromethanesulfonimide[40] appeared to be a possible alternative method to trap enolate **10**. Indeed, organocopper additions to **5c** followed by quenching using the triflimide reagent in 1,2-dimethoxyethane led to allenyl enol triflates **13**, which were sufficiently stable to be isolated by preparative TLC. Thus, both the intermediacy of an enolate species such as **10** during the addition reaction and the viability of 1,6-additions to enynones as an allene-generating method were confirmed. Triflates **13** in turn can be used to prepare enallenes **14** by regiospecific, organocopper-mediated substitution reactions[41] (eq 2); this synthetic conversion

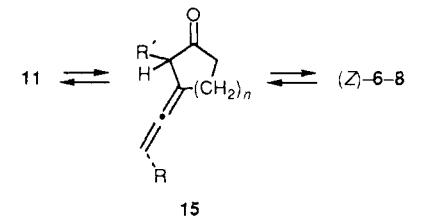


(2)

13a, R,R′ = Me, n = 2 **14a**, R,R′,R^2 = Me, n = 2
13d, R = *n*-Bu, R′ = Me, n = 2 **14d**, R = *n*-Bu, R′, R^2 = Me, n = 2

was confirmed by the preparation of representative enallenes **14a** and **14d**. As has been observed[42] for other lower molecular weight enallenes, **14a** and **14d** are of moderate thermal instability and degrade in air. Consequently, they were characterized spectroscopically immediately after isolation.

During the study of the characteristics of enol triflates **13**, a question arose regarding the manner by which the analogous, transient allenyl enol species **11** equilibrated to (*Z*)-**6**–**8**: Did ketonation proceed such that protonation occurred only at the sp-hybridized carbon of the allene (analogous to the γ-carbon of a dienol), or did an intermediate nonconjugated ketoallene **15** form from protonation at the α-carbon (eq 3)?[43] This question was answered



(3)

15

by straightforward deuterium incorporation studies using enynone **5b**. Deuterium-labeled *2-d*-**5b** was reacted with $(t\text{-}C_4H_9)_2Cu(CN)Li_2$, and the reaction quenched with ammonium chloride; this allowed all vinylic resonances in the ^1H NMR spectrum to be assigned unambiguously. In a complementary experiment, **5b** was reacted with $(t\text{-}C_4H_9)_2Cu(CN)Li_2$, the reaction was quenched with d_4-ammonium chloride (96 at. % deuterium), and both the location and percent incorporation of deuterium were determined by ^1H NMR and GC/MS (eq 4). No deuterium was incorporated in the α-position; deuterium was observed only at C1 of the 3,3-dimethylbutenyl substituent of the product, implying exclusive equilibration of enol **11** by protonation at the sp-hybridized carbon of the allene

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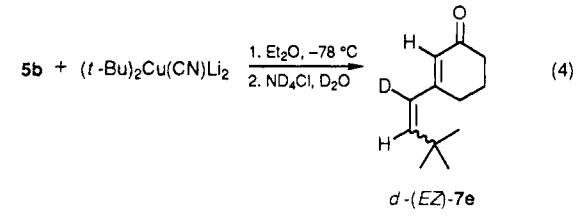

(4)

d-(EZ)-7e

moiety. Overall deuterium incorporation for *Z* and *E* isomers was 70%, corresponding to a deuterium isotope effect (k_H/k_D) of 10. Allenyl enol species such as **11**, then, and their corresponding enolates **10** are interesting examples of dienols and dienolates that do not undergo normally kinetically preferred α-protonation.[44] As a consequence of this observation, it would be interesting to inquire as to the regiospecificity of additions of electrophiles to enolate species **10**;[45] such studies are underway in our laboratory and will be reported in due course.

In a final series of experiments to determine if it were possible to enrich the *Z* isomer content of some of the less stereoselectively formed dienes **6–8**, known methods were used to reequilibrate compounds **6a** and **8a**. While (*Z*)-**8a** could be equilibrated to (*E*)-**8a** by using LDA[46] as expected, it was anticipated that use of neutral γ-alumina[30b,46,47] would have the complementary effect of enriching the *Z* isomer. Unfortunately, this anticipation was not borne out: (*Z*)-**6a** slowly but efficiently equilibrated to the more thermodynamically stable *E* isomer when stirred with γ-alumina in ether at room temperature (Table II). Dienone **8a** also underwent this equilibration, but much more slowly. Nonetheless, other methods[48] may prove to be more effective in *Z* isomer enrichment.

Summary

It has been demonstrated that 3-ethynyl-2-cycloalkenones undergo predominant, regiospecific 1,6-additions of organocopper reagents, generating intermediate conjugate allenyl enolates. These enolates can be regiospecifically protonated, resulting in stereoselective formation of (*Z*)-3-alkenyl-2-cycloalkenones, or isolated as their allenyl enol triflates. Such enol triflates in turn can be alkylated to yield conjugated enallenes. The 1,6-addition demonstrates sensitivity to the nature of the organocopper reagent; higher order cycanocuprates derived from organolithium reagents are the organocopper reagents of choice. Certain nucleophiles such as (phenylthio)lithium prefer to add to the substrates studied by means of a syn-carbometalation-like addition to the alkynyl moiety; protonation of the intermediate, which is stabilized by β-inductive and coordinative effects, results in stereoselective formation of (*E*)-3-alkenyl-2-cycloalkenones.

Experimental Section

General Techniques. ^1H NMR and ^1H broad-band-decoupled ^{13}C NMR spectra were obtained on either an IBM NR-80 or a GE GN-500 spectrometer operating at 80 or 500 MHz for ^1H observations and 20 or 125 MHz for ^{13}C observations, respectively. Tetramethylsilane was used as an internal standard. IR spectra were obtained on either a Perkin-Elmer 1420 or 1310 spectrophotometer. UV spectra were obtained on a Gilford Response spectrophotometer. Mass spectral data were obtained on a Hewlett-Packard 5988A system in the EI mode either by direct insertion or by GC/MS using a 30-m, DB-5 column operating at 5 psi He head pressure and at the indicated temperature. Analytical GC was performed using an FID-equipped Varian 2400 instrument with a He carrier gas flow of 30 mL min^{-1}. The following columns were used: column A, 5% FFAP on Chromosorb HP; column B, 5% SE-30 on Chromsorb HP; column C, 5% DC-550 on Chromsorb HP. Yields are reported relative to appropriate internal standards. Analytical HPLC was performed using an Isco ternary gradient system equipped with a variable-wavelength UV detector and 5-μm C18 4.6 × 250 mm column. Yields are reported based upon response vs concentration curves generated by using authentic samples. Responses were monitored at 254 nm. Melting points were obtained on a Mel-Temp apparatus, and temperatures recorded are uncorrected. Elemental analyses were performed by either Atlantic Microlab, Inc., Atlanta, GA, or Galbraith Laboratories, Inc., Knoxville, TN. Preparative TLC was performed using 20 × 20 cm × 1000 μm plates obtained from Analtech, Inc., Newark, DE; plates were not activated before use. Flash chromatography[49] was performed using Merck silica gel 60, 230–400 mesh ASTM. Medium-pressure liquid chromatography[50] (MPLC) was performed using a Merck Lobar size B silica gel column. Ether, 1,2-dimethoxyethane, and THF were freshly distilled from sodium–benzophenone before use.

Table II. Equilibrations of Dienones 6a and 8a

substrate, conditions	time, h	ratio *Z*:*E*	% de
6a + γ-Al_2O_3, ether	0	1.5:1	20
	24	1.2:1	9
	48	1:1.3	13
	91	1:2.8	47
	144	1:3.9	59
	158	1:499	66
	172	1:7.2	76
	220	1:8.7	79
8a + γ-Al_2O_3, THF	0	2.5:1	43
	18	1:1.5	20
	42	1:1.6	23
	71	1:1.4	17
	94	1:1.4	17
	120	1:1.5	20
	140	1:1.5	20

The following organometallic reagents were purchased from Aldrich Chemical Co.: *n*-butyllithium, methyllithium, ethylmagnesium bromide, isopropylmagnesium chloride, *tert*-butyllithium, vinylmagnesium bromide, and tetravinyltin. Other organometallic reagents were purchased as follows: lithium acetylide ethylenediamine complex (Alfa), sodium acetylide (Farchan), and vinyllithium (Oganometallics). All alkyllithium and alkylmagnesium halide reagents were titrated[51] before use. Phenyllithium and phenylmagnesium bromide were prepared from freshly distilled bromobenzene and the appropriate metal in ether. Copper(I) iodide, copper(I) cyanide, copper(I) bromide–dimethyl sulfide complex, benzyltriethylammonium chloride, boron trifluoride etherate, 2,4-dinitrophenylhydrazine, thiophenol, N-phenyltrifluoromethanesulfonimide, HMPA, diisopopylamine, Florisil, and Brockmann activity I neutral γ-alumina also were purchased from Aldrich. Acetylene gas was purified before use by passage through a series of traps consisting of a −78 °C trap, concentrated H_2SO_4, safety trap, and Ascarite. Literature methods were used to prepare 3-ethynyl-2-methyl-2-cyclohexenone[12b] (**5c**) from 3-isobutoxy-2-methyl-2-cyclohexenone[12c] (**2c**) and (trimethylsilyl)acetylene[20] from acetylene.

3-Ethynyl-2-methyl-2-cyclopentenone (5a). A modification of the procedure used to prepare 3-ethynyl-2-methyl-2-cyclo-

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hexenone (**5c**) was used: An oven-dried, N_2-purged 250-mL three-neck round-bottom flask equipped with a gas inlet tube, 100-mL constant-pressure addition funnel, thermometer, N_2 inlet, and magnetic stirring bar was charged with 50 mL of THF. The flask was cooled to −78 °C, and stirring begun as ca. 2.25 L of acetylene was bubbled in at a 100 mL min^{-1} flow rate. To the resultant solution was added dropwise 33.3 mL (31 mmol) of a 0.9 M hexane solution of *n*-butyllithium. Once the addition was complete, the flask contents were stirred at −78 °C for an additional 10 min. A solution of 4.54 g (27 mmol) of 3-isobutoxy-2-methyl-2-cyclopentenone[16a] (**2a**) in 15 mL of THF then was added dropwise to the −78 °C acetylide solution. A yellow solution resulted, which was stirred at −78 °C for 0.5 h and then at room temperature for 1 h. The reaction was quenched by the addition of 10 mL of H_2O, followed by 1 g of K_2CO_3 and rapid stirring for 10 min. The contents of the flask subsequently were diluted with 200 mL of ether and 100 mL of H_2O; the organic layer was separated by using a separatory funnel and was washed once with brine. Drying through $MgSO_4$ and concentration by rotary evaporation gave an orange liquid, which was diluted with 25 mL of ether. A 10-mL portion of 1 N HCl was added, and the the biphase stirred rapidly for 2 h. An additional 20 mL of ether then was added, the aqueous layer removed by using a separatory funnel, and the ether layer washed with 20-mL portions of aqueous saturated $NaHCO_3$, H_2O, and finally brine. Drying ($MgSO_4$) and concentration by rotary evaporation gave the crude product as an orange oil, which was purified by flash chromatography using 91: hexane:ether as eluent to give 1.82 g (56%) of **5a** as a nearly colorless, crystalline solid: mp 61–63 °C; ^1H NMR ($CDCl_3$) δ 3.87 (s, 1 H), 2.6 (m, 2 H), 2.4 (m, 2 H), 1.86 (t, J = 1.9 Hz, 3 H); ^{13}C NMR ($CDCl_3$) δ 208.5, 148.4, 146.4, 92.6, 79.2, 33.8, 29.8, 9.4; IR (KBr) 3190 (s), 2920 (w), 2080 (m), 1680 (s), 1610 (m), 1330 (m) cm^{-1}. Anal. Calcd for C_8H_8O: C, 79.97; H, 6.71. Found: C, 79.71; H, 6.62.

3-Ethynyl-2-cyclohexenone (5b). Method A. A flame-dried 25-mL one-neck round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was flushed with N_2 and charged with 719 mg (7.8 mmol) of lithium acetylide ethylenediamine complex. The complex was suspended in 5 mL of ether by stirring and cooled to 0 °C, at which temperature a solution of 1.01 g (60 mmol) of 3-isobutoxy-2-cyclohexenone[16b] (**2b**) in 5 mL of ether was added dropwise via syringe. Once the addition was complete, the reaction was slowly warmed to room temperature overnight while the ice bath melted; then, the reaction was heated to refux for 3 h. Recooling to room temperature was followed by hydrolysis by pouring the flask contents into 50 mL of H_2O and rapid stirring of the mixture for 1 h and then addition of 25 mL of 50% aqueous H_2SO_4 and continued stirring for an additional 1 h. Separation of the organic layer using a separatory funnel was followed by extraction of the H_2O layer with 40 mL of ether. The organic layers were combined, washed twice with 15 mL of ice-cold aqueous saturated $NaHCO_3$ and once with 15 mL of H_2O; drying ($MgSO_4$) and rotary evaporation gave a brown oil. The oil was taken up in 1:1 hexane:ether and filtered through 5 g of alumina; concentration by rotary evaporation afforded a pale yellow oil, which was purified by flash chromatography using 2:1 hexane:ether as eluent to give 310 mg (43%) of **5b**: GC retention time (column A, 135 °C) 2.8 min; ^1H NMR ($CDCl_3$) δ 6.22 (t, J = 1.4 Hz, 1 H), 3.52 (s, 1 H), 2.4 (m, 4 H), 2.0 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 198.4, 142.1, 133.9, 87.0, 82.4, 37.2, 30.1, 22.4; IR (thin film) 3300 (s), 2910 (m), 2090 (m), 1690 (w), 1605 (m), 850 (s), 730 (m) cm^{-1}. The material decomposes upon standing but can be purified by kugelrohr distillation, bp 30 °C (0.1 mmHg).

Similarly, 3-ethynyl-2-methyl-2-cyclohexenone (**5c**) was prepared in 42% chemical yield: mp 41–43 °C (lit[12b,c] mp 41–43 °C).

Method B. A flame-dried, 250-mL two-neck round-bottom flask equipped with a 60-mL constant-pressure addition funnel, N_2 inlet, magnetic stirring bar and under positive N_2 pressure was charged with 3.86 g (39 mmol) of (trimethylsilyl)acetylene[20] and 65 mL of THF. Stirring was begun, and the flask cooled to 0 °C, at which temperature 25.0 mL of a 1.6 M hexane solution of *n*-butyllithium was added dropwise. Once the addition was complete, stirring at 0 °C for 15 min was followed by cooling to −78 °C and dropwise addition of a solution of 5.70 g (34 mmol) of 3-isobutoxy-2-cyclohexenone[16b] (**2c**) in 20 mL of THF. The resultant solution was stirred at −78 °C for 0.5 h and then at room temperature for 1 h. The reaction was quenched and worked up as described for the synthesis of **5a** to give the crude product as a clear, pale yellow liquid, which was purified by flash chromatography using 9:1 hexane:ether as eluent. 3-(2-(Trimethylsilyl)ethynyl)-2-cyclohexenone (**4b**, 5.36 g, 82%) was isolated as a clear, colorless liquid: GC (column B, 150 °C) retention time 3.5 min; ^1H NMR ($CDCl_3$) δ 6.19 (t, J = 1.2 Hz, 1 H), 2.4 (m, 4 H), 2.05 (m, 2 H), 0.22 (s, 9 H); ^{13}C NMR ($CDCl_3$) δ 198.5, 142.8, 133.0, 105.8, 103.4, 37.2, 30.3, 22.5, −0.5; IR (thin film) 3040 (w), 2950 (s), 2140 (w), 1680 (s), 1585 (m), 1250 (m), 845 (s) cm^{-1}. A sample was kugelrohr-distilled: bp 50–55 °C (0.1 mmHg). Anal. Calcd for $C_{11}H_{16}OSi$: C, 68.69; H, 8.38. Found: C, 68.55; H, 8.43.

A solution of 1.10 g (6 mmol) of **4b** in 30 mL of THF was stirred well with 10 mL of 2 N KF for 3 h in the presence of the phase-transfer catalyst benzyltriethylammonium chloride. The reaction then was diluted with 75 mL of ether, the aqueous layer separated by using a separatory funnel, and the organic layer dried ($MgSO_4$). Concentration by rotary evaporation gave 0.66 g of essentially pure **5b**, which was kugelrohr-distilled to give 0.64 g (93%). The material should be used soon after distillation to avoid its inevitable decomposition.

3-(Deuterioethynyl)-2-cyclohexenone (*2d*-5b). With use of method B for the synthesis of **5b**, 1.11 g (6 mmol) of **4b** was dissolved in 30 mL of THF and was stirred well with 10 mL of a 2 N D_2O solution of KF for 3 h in the presence of the phase-transfer catalyst benzyltriethylammonium chloride. Dilution with 75 mL of ether, separation of the aqueous layer, drying ($MgSO_4$) of the organic layer, and subsequent concentration by rotary evaporation gave 0.74 g of essentially pure *2d*-**5b**, which was kugelrohr-distilled to give 0.61 g (87%): bp 30 °C (0.1 mmHg); GC retention time (column A, 135 °C) 2.7 min; ^1H NMR ($CDCl_3$) δ 6.25 (t, J = 1.9 Hz, 1 H), 2.4 (m, 4 H), 2.05 (m, 2 H); ^{13}C NMR ($CDCl_3$) δ 194.3, 139.9, 132.0, 86.2, 81.8, (t, J = 8.1 Hz), 38.6, 31.7, 24.2; IR (thin film) 3040 (w), 2950 (m), 2550 (m), 1955 (m), 1670 (s), 1590 (s), 960 (m), 890 (m) cm^{-1}. The material should be used soon after distillation to avoid its inevitable decomposition.

3-Isobutoxy-6-(3-oxocyclohexenyl)-2-cyclohexenone (3). A flame-dried 25-mL one-neck round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was purged with N_2 and charged with 2.07 g of an 18 wt % suspension of sodium acetylide in xylene. The xylene was removed by stirring the suspension three times with 5 mL of ether, allowing the acetylide to settle each time, and removing the solvent with a syringe. The acetylide was resuspended in 5 mL of THF and stirred as the flask was cooled to 0 °C. At this temperature, 1.00 g (6 mmol) of 3-isobutoxy-2-cyclohexenone[16b] (**2b**) dissolved in 5 mL of THF was added dropwise via syringe; once the addition was complete, the reaction was left to slowly warm to room temperature overnight as the cold bath was exhausted. Subsequent heating at reflux for 3 h, recooling to 0 °C, and quenching of the reaction by pouring into aqueous NH_4Cl was followed by extraction with ether. All ether extracts were combined, dried ($MgSO_4$), and concentrated by rotary evaporation, yielding a viscous oil, which was purified by flash chromatography using 2:1 ether:hexane as eluent. White, crystalline **3** with R_f = 0.22 was obtained (0.4 g, 51%): mp 72–73.5 °C; ^1H NMR ($CDCl_3$) δ 5.85 (s, 1 H), 5.37 (s, 1 H), 3.61 (d, J = 6.0 Hz, 2 H), 3.13 (t, J = 7.1 Hz, 1 H), 2.2 (m, 11 H), 1.02 (d, J = 6.4 Hz, 6 H); ^{13}C NMR ($CDCl_3$) δ 199.5, 196.9, 177.6, 163.5, 127.9, 102.9, 75.1, 54.0, 37.5, 28.5, 28.1, 27.7, 25.9, 22.8, 19.0; IR (KBr) 3050 (w), 2950 (m), 1670 (s), 1650 (s), 1600 (s), 1380 (m), 1190 (s) cm^{-1}; MS, m/z 262 ($M^{\bullet+}$, 83), 234 (11), 206 (14), 178 (49), 150 (52), 136 (48), 123 (79), 95 (58), 85 (100), 69 (65). Anal. Calcd for $C_{16}H_{22}O_3$: C, 73.25; H, 8.45. Found: C, 73.11; H, 8.47.

General Procedure for the Preparation of 3-Alkenyl-2-cycloalkenones 6–8 from Enynones 5. A flame-dried, one-neck round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was flushed with N_2 and charged with 1.5 mol equiv of the organometal nucleophile to be used in ether solution. Cooling of the flask to −78 °C was followed by dropwise addition of an ether solution of the enynone via syringe; once the addition was complete, the reaction was stirred at −78 °C for 1.5 h. Quenching was accomplished by pouring aqueous saturated NH_4Cl into the flask at −78 °C, removing the cold bath, and stirring vigorously as the flask warmed to room temperature. The contents of the flask were transferred to a separatory funnel and

extracted with 35 mL of ether; the ether extract was washed once with a 10-mL portion of H_2O and was dried ($MgSO_4$). Concentration by rotary evaporation afforded the crude product, the isomeric contents of which was determined by GC or HPLC. The crude product was purified by preparative TLC, and the yield and purity of the product were determined.

2-Methyl-3-propenyl-2-cyclopentenone (6a). From $(CH_3)_2CuLi$. (Dimethylcopper)lithium prepared at 0 °C from 152.9 mg (0.8 mmol) of CuI in 2 mL of ether and 1.15 mL (1.6 mmol) of a 1.4 M ether solution of methyllithium was reacted with 60.4 mg (0.5 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product (65.1 mg) was analyzed by GC (column A, 145 °C): yield, 82%; retention time (*Z*)-**6a** 2.5 min, (*E*)-**6a** 3.3 min; ratio (*Z*)-**6a**:(*E*)-**6a** 1.7:1.

From $CH_3Cu(CN)Li$. (Cyanomethylcopper)lithium prepared at 0 °C from 58.7 mg (0.7 mmol) of CuCN in 2 mL of ether and 740 μL (0.7 mmol) of a 1.0 M ether solution of methyllithium was reacted with 51.5 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 145 °C): yield, 95%; ratio (*Z*)-**6a**:(*E*)-**6a** 2.2:1.

From $(CH_3)_2Cu(CN)Li_2$. (Cyanodimethylcopper)dilithium prepared at 0 °C from 63.2 mg (0.7 mmol) of CuCN in 2 mL of ether and 1.06 mL (1.4 mmol) of a 1.3 M ether solution of methyllithium was reacted with 54.3 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product (61.6 mg) was analyzed by GC (column A, 145 °C): yield, 98%; ratio (*Z*)-**6a**:(*E*)-**6a** 2.5:1. Preparative TLC using 2:1 hexane:ether as eluent gave 56.0 mg (91%) of **6a**, pure by GC: ^1H NMR ($CDCl_3$) δ 6.65 and 6.34 (two d, J = 14.9 Hz and J = 12.8 Hz, 1 H), 6.28 and 5.97 (two d of q, J = 15.9, 6.3 Hz and J = 12.8, 6.8 Hz, 1 H), 2.7 (m, 2 H), 2.4 (m, 2 H), 1.98 (two d, J = 7.0 Hz and J = 6.5 Hz, 3 H), 1.79 and 1.77 (two t, J = 2.8 Hz and J = 2.6 Hz, 3 H); IR (thin film) 3020 (w), 2920 (m), 1690 (s), 1635 (s) cm^{-1}. Anal. Calcd for $C_9H_{12}O$: C, 79.37; H, 8.88. Found: C, 79.78; H, 9.08.

3-Butenyl-2-methyl-2-cyclopentenone (6b). From $C_2H_5Cu(CN)MgBr$. (Cyanoethylcopper)magnesium bromide prepared by cooling a stirred slurry of 63.8 mg (0.7 mmol) of CuCN in 2 mL of ether to −78 °C, dropwise addition of 250 μL (0.7 mmol) of a 2.85 M ether solution of ethylmagnesium bromide, warming to 0 °C, and then recooling to −78 °C was reacted with 53.8 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was examined by ^1H NMR, which indicated a 50% conversion to products and ratio (*Z*)-**6b**:(*E*)-**6b** 4:1. Preparative TLC using 3:1 hexane:ether as eluent gave pure **6b** (27.6 mg, 41%): GC (column A, 135 °C) retention time (*Z*)-**6b** 2.6 min, (*E*)-**6b** 3.6 min; ^1H NMR ($CDCl_3$) δ 6.72 and 6.36 (two d, J = 15.8 Hz and J = 11.9 Hz, 1 H), 6.28 and 5.82 (two d of t, J = 15.6, 5.1 Hz and J = 11.9, 7.4 Hz, 1 H), 2.9–2.1 (m, 6 H), 1.79 and 1.73 (two t, J = 1.6 Hz and J = 1.8 Hz, 3 H), 1.17 and 1.07 (two t, J = 6.9 Hz and J = 7.4 Hz, 3 H); IR (thin film) 3010 (w), 2920 (m), 1690 (s), 1630 (s) cm^{-1}. Anal. Calcd for $C_{10}H_{14}O$: C, 79.96; H, 9.39. Found: C, 79.87; H, 9.41.

From $(C_2H_5)_2Cu(CN)(MgBr)_2$. (Cyanodiethylcopper)bis(magnesium bromide) prepared by cooling a stirred slurry of 60.4 mg (0.7 mmol) of CuCN in 2 mL of ether to −78 °C, dropwise addition of 350 μL (0.7 mmol) of a 1.95 M ether solution of ethylmagnesium bromide, warming to 0 °C, addition of a second 350 μL of ethylmagnesium bromide, stirring at 0 °C for 5 min, and then recooling to −78 °C was reacted with 54.0 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 135 °C): yield 87%; ratio (*Z*)-**6b**:(*E*)-**6b** 3:1. Preparative TLC using 2.5:1 hexane:ether as eluent gave 52.3 mg (77%) of **6b**, pure by GC.

2-Methyl-3-(3-methylbutenyl)-2-cyclopentenone (6c). From $(i\text{-}C_3H_7)_2Cu(CN)(MgCl)_2$. (Cyanodiisopropylcopper)bis(magnesium chloride) prepared by cooling a stirred slurry of 64.2 mg (0.7 mmol) of CuCN in 2 mL of ether to −78 °C, dropwise addition of 890 μL (1.4 mmol) of a 1.6 M THF solution of isopropylmagnesium chloride, stirring at −78 °C for 10 min, warming to 0 °C, and recooling to −78 °C was reacted with 56.8 (0.5 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 140 °C): retention time (*Z*)-**6c** 2.0 min, (*E*)-**6c** 3.0 min; ratio (*Z*)-**6c**:(*E*)-**6c** 4:1. Preparative TLC using 2:1 hexane:ether as eluent gave 67.3 mg (87%) of **6c**: ^1H NMR ($CDCl_3$) δ 6.53 and 6.17 (two d, J = 15.8 Hz and J = 12.0 Hz, 1 H), 6.21 and 5.63 (d of d and t, J = 15.8, 7.0 Hz and J = 11 Hz, 1 H), 2.9–2.5 (m, 2 H), 2.45 (m, 2 H), 1.77 and 1.73 (two t, J = 1.3 Hz and J = 1.9 Hz, 3 H), 1.10 and 1.04 (two d, J = 6.5 Hz and J = 6.0 Hz, 6 H); IR (thin film) 2960 (m), 1690 (s), 1630 (m) cm^{-1}. Anal. Calcd for $C_{11}H_{16}O$: C, 80.44; H, 9.82. Found: C, 80.51; H, 9.82.

2-Methyl-3-(3,3-dimethylbutenyl)-2-cyclopentenone (6e). From $(t\text{-}C_4H_9)_2Cu(CN)Li_2$. (Di-*tert*-butylcyanocopper)dilithium prepared by cooling a stirred slurry of 62.7 mg (0.7 mmol) of CuCN in 2 mL of ether to −78 °C, dropwise addition of 890 μL (1.4 mmol) of a 1.56 M pentane solution of *tert*-butyllithium, warming to 0 °C for 5 min, and then recooling to −78 °C was reacted with 54.3 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 135 °C): retention time (*Z*)-**6e** 2.0 min, (*E*)-**6e** 3.9 min; ratio (*Z*)-**6e**:(*E*)-**6e** 34:1. Preparative TLC using 2:1 hexane:ether as eluent gave 74.6 mg (93%) of **6e**: ^1H NMR ($CDCl_3$) δ 6.50 and 5.59 (two d, J = 16.1 Hz and J = 13.2 Hz, 1 H), 6.27 and 5.77 (two d, J = 15.6 Hz and J = 13.2 Hz, 1 H), 2.6 (m, 2 H), 2.4 (m, 2 H), 1.69 (q, J = 1.3 Hz, 3 H), 1.11 and 1.01 (two s, 9 H); IR (thin film) 2960 (s), 1700 (s), 1655 (m), 1615 (w), 1310 (m) cm^{-1}. Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.72; H, 10.21.

2-Methyl-3-styryl-2-cyclopentenone (6f). From $(C_6H_5)_2CuMgBr$. (Diphenylcopper)magnesium bromide prepared by cooling a stirred slurry of 121.7 mg (0.6 mmol) of CuI in 2 mL of ether to −78 °C, dropwise addition of 450 μL (1.2 mmol) of a 2.6 M ether solution of phenylmagnesium bromide, warming to 0 °C for 5 min, and recooling to −78 °C was reacted with 46.4 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by HPLC (7:3 acetonitrile:H_2O, 0.5 mL min^{-1}): yield 46%; retention time for (*E*,*Z*)-**6f** 10.1 min.

From $(C_6H_5)_2CuMgBr{\cdot}(CH_3)_2S$. The organocopper reagent was prepared as in the previous reaction by using 127.8 mg (0.6 mmol) of $CuBr{\cdot}(CH_3)_2S$ and 475 μL (1.2 mmol) of a 2.6 M ether solution of phenylmagnesium bromide and was reacted with 49.1 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was purified by preparative TLC using 3:1 hexane:ether as eluent to give 36.8 mg (45%) of **6f**, pure by HPLC; GC (column A, 190 °C) retention time (*Z*)-**6f** 4.2 min; the *E* isomer was not detected; ^1H NMR ($CDCl_3$) δ 7.28 (s, 5 H), 6.86 (d, J = 12.2 Hz, 1 H), 6.43 (d, J = 12.0 Hz, 1 H), 2.6–2.2 (m, 4 H), 1.63 (s, 3 H); IR (thin film) 3045 (w), 3020 (w), 2910 (w), 1680 (s), 1620 (m), 1310 (m), 775 (m), 690 (m) cm^{-1}. Crystallization from cold (−20 °C) hexane afforded needles, mp 52–52.5 °C; UV λ_{max} ($CHCl_3$) 293 (ε 19000) and 240 nm (ε 14000). Anal. Calcd for $C_{14}H_{14}O$: C, 84.81; H, 7.12. Found: C, 84.92; H, 7.14.

From $(C_6H_5)_2Cu(CN)(MgBr)_2$. The organocopper reagent was prepared as in the first reaction of the series by using 57.6 mg (0.6 mmol) of CuCN and 800 μL (1.3 mmol) of a 1.6 M ether solution of phenylmagnesium bromide and was reacted with 49.7 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by HPLC (7:3 acetonitrile:H_2O, 0.5 mL min^{-1}), yield 83%. Preparative TLC using 2:1 hexane:ether as eluent gave 31.7 (39%) of (*Z*)-**6f**.

From $(C_6H_5)_2Cu(CN)Li_2$. The organocopper reagent was prepared as in the first reaction of the series by using 60.9 mg (0.7 mmol) of CuCN and 590 μL (1.4 mmol) of a 1.43 M ether solution of phenyllithium and was reacted with 49.6 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by HPLC (7:3 acetonitrile:H_2O, 0.5 mL min^{-1}), yield 87%. Purification by preparative TLC using 9:4 hexane:ether as eluent gave 58.0 mg (71%) of pure (*Z*)-**6f** and 13.9 mg (17%) of pure (*E*)-**6f**; GC (column A, 220 °C) retention time (*Z*)-**6f** 1.6 min, (*E*)-**6f** 4.2 min. (*E*)-**6f**: ^1H NMR ($CDCl_3$) δ 7.30 (d, J = 15.8 Hz, 1 H), 7.05 (d, J = 15.4 Hz, 1 H), 7.56 (d, J = 7.9 Hz, 2 H), 7.40 (t, J = 7.3 Hz, 2 H), 7.35 (d, J = 7.6 Hz, 1 H), 2.8 (m, 2 H), 2.5 (m, 2 H), 1.90 (s, 3 H).

3-(1,3-Butadienyl)-2-methyl-2-cyclopentenone (6g). From $(CH_2{=}CH)_2CuMgBr{\cdot}(CH_3)_2S$. (Divinylcopper)magnesium bromide dimethyl sulfide complex prepared by cooling a slurry of 219.0 mg (1.1 mmol) of $CuBr{\cdot}(CH_3)_2S$ in 3 mL of THF to −78 °C, dropwise addition of 2.15 mL (2.2 mmol) of a 1.0 M THF solution of vinylmagnesium bromide, warming to 0 °C for 20 min,

and then recooling to −78 °C was reacted with 42.5 mg (0.4 mmol) of **5a** in 2 mL of THF according to the general procedure. The resultant crude product was analyzed by GC (column C, 125 °C); yield 48%; retention time (*Z*)-**6g** 4.1 min, (*E*)-**6g** 5.0 min; ratio (*Z*)-**6g**:(*E*)-**6g** 1.5:1.

From $(CH_2{=}CH)_2Cu(CN)(MgBr)_2$. The organocopper reagent was prepared as in the previous reaction by using 115.5 mg (1.3 mmol) of CuCN and 2.55 mL (2.6 mmol) of a 1.0 M THF solution of vinylmagnesium bromide and was reacted with 51.0 mg (0.4 mmol) of **5a** in 2 mL of THF according to the general procedure. The resultant crude product was purified by preparative TLC using 3:1 hexane:ether as eluent to give 27.1 mg (43%) of **6g**, the GC of which indicated decomposition upon standing.

From $(CH_2{=}CH)_2Cu(CN)(MgBr)_2 + BF_3{\cdot}(C_2H_5)_2O$. The organocopper reagent was prepared as in the first reaction of the series by using 47.9 mg (0.5 mmol) of CuCN in 2.5 mL of ether and 1.10 mL (1.1 mmol) of a 1.0 M THF solution of vinylmagnesium bromide. To the −78 °C organocopper reagent was added 62 μL (0.5 mmol) of $BF_3{\cdot}(C_2H_5)_2O$, and the resultant organometallic species reacted with 40.3 mg (0.3 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was purified by preparative TLC using 3:1 hexane:ether as eleuent to give 19.9 mg (39%) of **6g**.

From $(CH_2{=}CH)_4Sn$-Derived $(CH_2{=}CH)_2Cu(CN)Li_2$. A stirred slurry of 54.7 mg (0.6 mmol) of CuCN in 2 mL of ether was cooled to −78 °C, and 1.36 mL (1.2 mmol) of a 0.9 M ether solution of vinyllithium prepared from tetravinyltin added dropwise. Warming to 0 °C for 5 min and recooling to −78 °C gave the organocopper reagent, which was reacted with 44.8 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column C, 145 °C), retention time (*Z*)-**6g** 3.2 min, (*E*)-**6g** 3.9 min; ratio (*Z*)-**6g**:(*E*)-**6g** 5.1:1. Flash chromatography using 4:1 hexane:ether as eluent gave 32.6 mg (59%) of **6g** as an approximate 1:1 mixture of isomers with some decomposition as indicated by GC. This material was repurified twice by using preparative TLC to give a sample of **6g** 86% pure by GC and a 1:3.8 ratio of (*Z*)-**6b**:(*E*)-**6g**. ^1H NMR assignments for the major isomer were made with the assistance of a ^1H–^1H COSY experiment: ^1H NMR ($CDCl_3$) δ 6.74 (d, *J* = 15.4 Hz, 1 H), 6.71 (d of d, *J* = 17.0, 15.0 Hz, 1 H), 6.53 (d of t, *J* = 17.0, 10.1 Hz, 1 H), 5.50 (d, *J* = 17.2 Hz, 1 H), 5.38 (d, *J* = 9.6 Hz, 1 H), 2.8 (m, 1 H), 2.7 (m, 1 H), 2.44 (m, 2 H), 1.81 (t, *J* = 1.5 Hz, 3 H); IR (thin film) 3010 (m), 2920 (m), 1690 (s), 1640 (m), 1610 (m), 750 (s) cm^{-1}. (*E*)-**6g** GC/MS (40–230 °C at 10 °C min^{-1}), *m/z* 148 ($M^{\bullet+}$, 96), 105 (68), 91 (100), 77 (25). (*Z*)-**6g** GC/MS (40–230 °C at 10 °C min^{-1}), *m/z* 148 (M^+, 26), 133 (19), 130 (26), 105 (63), 91 (100), 77 (23).

2,4-Dinitrophenylhydrazone of 6g. From $(CH_2{=}CH)_2Cu(CN)Li_2$. A flame-dried 25-mL one-neck round-bottom flask equipped with stirring bar, sleeve septum, and N_2 inlet was charged with 43.1 mg (0.5 mmol) of CuCN and 2 mL of ether. Stirring was begun as the slurry was cooled to −78 °C, and 530 μL (1.0 mmol) of a 1.8 M THF solution of vinyllithium added dropwise. After 5 min the flask was warmed to −12 °C, held at −12 °C for 5 min, and then recooled to −78 °C. A solution of 38.4 mg (0.3 mmol) of **5a** in 2 mL of ether was added dropwise, and the reaction stirred for 1.5 h. The reaction was quenched at −78 °C by using pH 8 NH_4Cl solution; extraction into ether, drying through $MgSO_4$, and concentration by rotary evaporation afforded 55.9 mg of an oil, which was dissolved in 6 mL of absolute ethanol directly. While the solution was stirred magnetically, 1.54 mL (0.4 mmol) of a 0.25 M solution of 2,4-dinitrophenylhydrazine was added, followed by 3 drops of 20% aqueous H_2SO_4. The mixture was heated at reflux for 30 min and then cooled to room temperature. Rotary evaporation gave a solid, which was taken up in CH_2Cl_2, dried ($MgSO_4$), concentrated by rotary evaporation, and purified by flash chromatography to give 87.2 mg (83%) of the product dinitrophenylhydrazone: mp 173–175 °C; ^1H NMR ($CDCl_3$) δ 11.00 (s, 1 H), 9.12 (d, *J* = 2.9 Hz, 1 H), 8.28 (d of d, *J* = 10.0, 2.2 Hz, 1 H), 7.99 (d, *J* = 9.8 Hz, 1 H), 6.89 (d of t, *J* = 16.6, 10.4 Hz, 0.5 H), 6.70 (d, *J* = 15.5 Hz, 0.5 H), 6.49 (m, 1 H), 6.49 (m, 1 H), 6.31 (m, 1 H), 5.40 (d, *J* = 16.2 Hz, 1 H), 5.30 (d of d, *J* = 22.5, 10.0 Hz, 1 H), 3.0 (m, 1 H), 2.8 (m, 1 H), 2.73 (m, 4 H), 1.99 (d, *J* = 8.2 Hz, 3 H); IR (KBr) 3100 (w), 2930 (w), 1610 (s), 1585 (s), 1510 (m), 1330 (s), 1305 (m), 1125 (m), 830 (w), 740 (w) cm^{-1}; MS, *m/z* 328 ($M^{\bullet+}$, 100). Anal. Calcd for $C_{16}H_{16}N_4O_4$: C, 58.53; H, 4.91; N, 17.06. Found: C, 58.43; H, 4.94; N, 16.97.

2-Methyl-3-(2-(phenylthio)ethenyl)-2-cyclopentenone (6h). (Phenylthio)lithium prepared by cooling a solution of 55 μL (0.5 mmol) of thiophenol in 2.5 mL of ether to 0 °C, dropwise addition of 335 μL (0.5 mmol) of a 1.6 M hexane solution of *n*-butyllithium, stirring for 10 min at 0 °C, and then cooling to −78 °C was reacted with 43.2 mg (0.4 mmol) of **5a** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by HPLC (7:3 acetonitrile:H_2O, 0.6 mL min^{-1}), yield 52%; retention time (*E*)-**6h** 10.5 min, (*Z*)-**6h** 11.5 min; ratio (*Z*)-**6h**:(*E*)-**6h** 1:17. Purification by preparative TLC using 2:1 hexane:ether as eluent gave 43.3 mg (52%) of **6h**, pure by HPLC; ^1H NMR ($CDCl_3$) δ 7.6–7.2 (m, 5 H), 7.02 and 6.78 (two d, *J* = 15.6 Hz and *J* = 10.5 Hz, 1 H), 6.72 and 6.57 (two d, *J* = 15.3 Hz and *J* = 10.0 Hz, 1 H), 2.8–2.5 (m, 2 H), 2.5–2.2 (m, 2 H), 1.72 (t, *J* = 1.5 Hz, 3 H); IR (KBr) 3030 (w), 2905 (w), 1670 (s), 1610 (s), 1380 (m), 1350 (m), 1280 (m), 870 (w), 790 (m), 690 (w). A sample of pure (*E*)-**6h** was prepared by recrystallization from cold (−20 °C) hexane: mp 76–77 °C. Anal. Calcd for $C_{14}H_{14}OS$: C, 73.01; H, 6.13; S, 13.92. Found: C, 72.85; H, 6.18; S, 13.97.

3-Propenyl-2-cyclohexenone (7a). The organocopper reagent $(CH_3)_2Cu(CN)Li_2$ prepared at 0 °C from 59.1 mg (0.7 mmol) of CuCN in 2 mL of ether and 1.01 mL (1.3 mmol) of a 1.3 M ether solution of methyllithium was reacted with 49.8 mg (0.4 mmol) of **5b** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 145 °C), yield 95%; retention time (*Z*)-**7a** 2.6 min, (*E*)-**7a** 3.8 min; ratio (*Z*)-**7a**:(*E*)-**7a** 1.2:1. Purification by preparative TLC using 3:1 hexane:ether as eluent gave 41.6 mg (75%) of **7a**: ^1H NMR ($CDCl_3$) δ 6.24 and 5.92 (two m, 3 H), 2.7–2.3 (m, 4 H), 2.25–1.95 (m, 2 H), 1.91 (t, *J* = 5.2 Hz, 3 H); IR (thin film) 3030 (w), 2940 (s), 2860 (m), 1665 (s), 1635 (s), 1585 (m), 1250 (s), 1190 (m), 965 (s) cm^{-1}. Anal. Calcd for $C_9H_{12}O$: C, 79.37; H, 8.88. Found: C, 79.20; H, 8.93.

3-(3,3-Dimethylbutenyl)-2-cyclohexenone (7e). The organocopper reagent $(t\text{-}C_4H_9)_2Cu(CN)Li_2$ prepared by cooling a stirred slurry of 59.2 mg (0.7 mmol) of CuCN in 3 mL of ether to −78 °C, dropwise addition of 825 μL (1.3 mmol) of a 1.6 M pentane solution of *tert*-butyllithium, warming to 0 °C for 5 min, and recooling to −78 °C was reacted with 50.2 mg (0.4 mmol) of **5b** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 155 °C), retention time (*Z*)-**7e** 2.2 min, (*E*)-**7e** 4.0 min; ratio (*Z*)-**7e**:(*E*)-**7e** 9:1. Purification by preparative TLC using 3:1 hexane:ether as eluent gave 62.2 mg (83%) of **7e**: ^1H NMR ($CDCl_3$) δ 6.19 and 5.48 (two d, *J* = 15.1 Hz and *J* = 12.8 Hz, 1 H), 6.08 and 5.75 (two d, *J* = 16.0 Hz and *J* = 12.7 Hz, 1 H), 5.89 (s, 1 H), 2.5–2.3 (m, 4 H), 2.00 (m, 2 H), 1.06 (s, 9 H); IR (thin film) 3030 (w), 2950 (s), 1670 (s), 1605 (m), 960 (m), 895 (m), 730 (m) cm^{-1}. (*Z*)-**7e** GC/MS (160 °C), *m/z* 178 ($M^{\bullet+}$, 8), 163 (52), 135 (33), 121 (22), 107 (100), 91 (43), 79 (25), 55 (25). (*E*)-**7e** GC/MS (160 °C), *m/z* 178 ($M^{\bullet+}$, 31), 163 (57), 135 (38), 121 (29), 107 (100), 91 (48), 77 (27), 55 (32). Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.99; H, 10.20.

3-(2-Deuterio-3,3-dimethylbutenyl)-2-cyclohexenone (*2d*-7e). The organocopper reagent $(t\text{-}C_4H_9)_2Cu(CN)Li_2$ was prepared as in the previous reaction by using 61.9 mg (0.7 mmol) of CuCN and 864 μL (1.4 mmol) of a 1.6 M pentane solution of *tert*-butyllithium and was reacted with 54.5 mg (0.4 mmol) of *2d*-**5b** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 155 °C), ratio (*Z*)-*2d*-**7e**:(*E*)-*2d*-**7e** 9:1. Purification by preparative TLC using 3:1 hexane:ether as eluent gave 59.4 mg (74%) of *2d*-**7e**, pure by GC; ^1H NMR ($CDCl_3$) δ 6.06 and 5.74 (two s, 1 H), 5.89 (d, *J* = 1.9 Hz, 1 H), 2.5–2.3 (m, 4 H), 2.00 (m, 2 H), 1.06 (s, 9 H). (*Z*)-*2d*-**7e** GC/MS (160 °C), *m/z* 179 ($M^{\bullet+}$, 8), 164 (60), 136 (30), 122 (18), 108 (100), 92 (34), 80 (17), 55 (20). (*E*)-*2d*-**7e** GC/MS (160 °C), *m/z* 179 (M^+, 30), 164 (59), 136 (32), 122 (24), 108 (100), 92 (39), 80 (18), 55 (27).

3-(1-Deuterio-3,3-dimethylbutenyl)-2-cyclohexenone (*1d*-7e). The organocopper reagent $(t\text{-}C_4H_9)_2Cu(CN)Li_2$ was prepared as in the previous reaction by using 61.7 mg (0.7 mmol) of CuCN and 860 μL (1.4 mmol) of a 1.6 M pentane solution of *tert*-butyllithium and was reacted with 55.8 mg (0.5 mmol) of **5b** in 2 mL of ether according to the general procedure. The reaction

was quenched at −78 °C by rapid addition of 15 mL of a 1 M solution of 96 mol *d* % ND_4Cl and was worked up according to the general procedure to give a crude product which was analyzed by GC (column A, 155 °C), ratio (*Z*)-*1d*-**7e**:(*E*)-*1d*-**7e** 9:1. Purification by preparative TLC using 3:1 hexane:ether as eluent gave 64.7 mg (78%) of *1d*-**7e**, pure by GC; ^1H NMR ($CDCl_3$) δ 6.18 and 5.47 (two s, 1 H), 5.89 (s, 1 H), 2.5–2.3 (m, 4 H), 2.00 (m, 2 H), 1.06 (s, 9 H). (*Z*)-*1d*-**7e** GC/MS (160 °C), *m/z* 179 ($M^{\bullet+}$, 8), 164 (53), 136 (31), 122 (23), 108 (100), 92 (36), 80 (20), 55 (27). (*E*)-*1d*-**7e** GC/MS (160 °C), *m/z* 179 ($M^{\bullet+}$, 31), 164 (56), 136 (34), 122 (28), 108 (100), 92 (40), 80 (21), 55 (33). The deuterium enrichment observed varied from 54 to 62% for the *Z* isomer and from 67 to 70% for the *E* isomer, depending upon run.

2-Methyl-3-propenyl-2-cyclohexenone (8a). From (CH_3)$_2$CuLi. (Dimethylcopper)lithium prepared at 0 °C from 115.2 mg (0.6 mmol) of CuI in 2 mL of ether and 900 μL (1.3 mmol) of a 1.4 M ether solution of methyllithium was reacted with 50.2 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 130 °C), yield 97%; retention time (*Z*)-**8a** 1.9 min, (*E*)-**8a** 3.7 min; ratio (*Z*)-**8a**:(*E*)-**8a** 2:1. Purification by flash chromatography using 9:1 hexane:ether as eluent gave 48.1 mg (86%) of **8a**, pure by GC.

From $CH_3Cu(CN)Li$. (Cyanomethylcopper)lithium prepared at 0 °C from 50.0 mg (0.6 mmol) of CuCN in 2 mL of ether and 450 μL (0.6 mmol) of a 1.4 M ether solution of methyllithium was reacted with 50.0 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 130 °C), yield 86%; ratio (*Z*)-**8a**:(*E*)-**8a** 2:1.

From (CH_3)$_2$Cu(CN)Li$_2$. (Cyanodimethylcopper)dilithium prepared at 0 °C from 50.0 mg (0.6 mmol) of CuCN in 2 mL of ether and 900 μL (1.3 mmol) of a 1.4 M ether solution of methyllithium was reacted with 50.0 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The essentially pure crude product was analyzed by GC (column A, 130 °C), ratio (*Z*)-**8a**:(*E*)-**8a** 2.5:1. Kugelrohr distillation at 78 °C (0.5 mmHg) gave 49.6 mg (89%) of **8a**: ^1H NMR ($CDCl_3$) δ 6.61 and 6.05 (two d, *J* = 16.5 Hz and *J* = 11.5 Hz, 1 H), 6.20 and 5.71 (two m, 1 H), 2.73–2.26 (m, 5 H), 2.10–1.90 (m, 4 H), 1.89 (s, 3 H); IR (thin film) 2940 (s), 1660 (s), 1630 (m) cm^{-1}. Anal. Calcd for $C_{10}H_{14}O$: C, 79.95; H, 9.39. Found: C, 79.88; H, 9.45.

2-Methyl-3-(3-methylbutenyl)-2-cyclohexenone (8c). From (*i*-C_3H_7)$_2$Cu(CN)(MgCl)$_2$. (Cyanodiisopropylcopper)bis(magnesium chloride) prepared by cooling a stirred slurry of 98.2 mg (1.1 mmol) of CuCN in 2 mL of ether to −78 °C, dropwise addition of 1.41 mL (2.3 mmol) of a 1.6 M THF solution of isopropylmagnesium chloride, stirring at −78 °C for 10 min, warming to 0 °C, and recooling to −78 °C was reacted with 50.3 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was purified by flash chromatography using 9:1 hexane:ether as eluent to give 52.4 mg (81%) of **8c**: GC (column A, 140 °C) retention time (*Z*)-**8c** 2.0 min, (*E*)-**8c** 4.0 min; ratio (*Z*)-**8c**:(*E*)-**8c** 6:1; ^1H NMR ($CDCl_3$) δ 6.54 and 5.90 (two d, *J* = 16.0 Hz and *J* = 11.8 Hz, 1 H), 6.19 and 5.40 (d and d of d, *J* = 7 Hz and *J* = 9.6, 9.4 Hz, 1 H), 2.56–2.17 (m, 4 H), 2.12–1.98 (m, 3 H), 1.72 (s, 3 H), 1.0 (d, *J* = 7.0 Hz, 6 H); IR (thin film) 2950 (s), 1650 (s), 1625 (m) cm^{-1}. Anal. Calcd for $C_{12}H_{18}O$: C, 80.85; H, 10.18. Found: C, 80.74; H, 10.20.

3-Hexenyl-2-methyl-2-cyclohexenone (8d). From (*n*-C_4H_9)$_2$CuLi. (Di-*n*-butylcopper)lithium prepared by cooling a stirred slurry of 126.0 mg (1.1 mmol) of CuI in 2 mL of ether to −78 °C, dropwise addition of 2.00 mL (2.4 mmol) of a 1.2 M hexane solution of butyllithium, warming to 0 °C for 10 min, and recooling to −78 °C was reacted with 100.0 mg (0.8 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 140 °C), yield 64%; retention time (*Z*)-**8d** 4.3 min, (*E*)-**8d** 8.4 min; ratio (*Z*)-**8d**:(*E*)-**8d** 7:1.

From (*n*-C_4H_9)$_2$Cu(CN)(MgBr)$_2$. The organocopper reagent was prepared as in the previous reaction by using 65.0 mg (0.7 mmol) of CuCN and 880 μL (1.3 mmol) of a 1.4 M ether solution of butylmagnesium bromide and was reacted with 50.0 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 140 °C), yield 68%; ratio (*Z*)-**8d**:(*E*)-**8d** 7:1.

From (*n*-C_4H_9)$_2$Cu(CN)Li$_2$. The organocopper reagent was prepared as in the first reaction of the series by using 50.0 mg (0.6 mmol) of CuCN and 1.00 mL (1.6 mmol) of a 1.6 M hexane solution of butyllithium and was reacted with 50.0 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was purified by flash chromatography using 9:1 hexane:ether as eluent to give 56.4 mg (81%) of **8d**: GC (column A, 140 °C) ratio (*Z*)-**8d**:(*E*)-**8d** 7:1; ^1H NMR ($CDCl_3$) δ 6.58 and 6.02 (two d, *J* = 16.0 Hz and *J* = 11.8 Hz, 1 H), 6.15 and 5.57 (two m, 1 H), 2.57–2.20 (m, 4 H), 2.11–1.76 (m, 5 H), 1.70 (s, 3 H), 1.55–1.04 (m, 6 H); IR (thin film) 2910 (s), 1650 (s) cm^{-1}. Anal. Calcd for $C_{13}H_{20}O$: C, 81.25; H, 10.42. Found: C, 81.10; H, 10.68.

2-Methyl-3-(3,3-dimethylbutenyl)-2-cyclohexenone (8e). From (*t*-C_4H_9)$_2$Cu(CN)Li$_2$. The organocopper reagent was prepared by cooling a stirred slurry of 50.2 mg (0.6 mmol) of CuCN in 2 mL of ether to −78 °C, dropwise addition of 895 μL (1.4 mmol) of a 1.6 M pentane solution of *tert*-butyllithium, warming to 0 °C for 5 min, and recooling to −78 °C and was reacted with 50.0 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 140 °C): retention time (*Z*)-**8e** 2.5 min, (*E*)-**8e** 4.1 min; ratio (*Z*)-**8e**:(*E*)-**8e** 35:1. Purification by flash chromatography using 9:1 hexane:ether as eluent gave 61.3 mg (89%) of **8e**: ^1H NMR ($CDCl_3$) δ 5.78 (d, *J* = 12.9 Hz, 1 H), 5.35 (d, *J* = 11.8 Hz, 1 H), 2.55–2.20 (m, 4 H), 2.08–1.80 (m, 2 H), 1.75 (m, 3 H), 0.98 (s, 9 H); IR (thin film) 2950 (s), 1665 (s), 1610 (m) cm^{-1}. Anal. Calcd for $C_{13}H_{20}O$: C, 81.25; H, 10.42. Found: C, 81.14; H, 10.44.

From (*t*-C_4H_9)$_2$CuLi. The organocopper reagent was prepared as in the previous reaction by using 213.1 mg (1.2 mmol) of CuI and 1.38 mL (2.4 mmol) of a 1.7 M pentane solution of *tert*-butyllithium and was reacted with 100.0 mg (0.8 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 140 °C), ratio (*Z*)-**8e**:(*E*)-**8e** 35:1. Purification by preparative TLC using 9:1 hexane:ether as eluent gave 68.0 mg (47%) of **8e**, pure by GC.

2-Methyl-3-styryl-2-cyclohexenone (8f). From (C_6H_5)$_2$CuMgBr. (Diphenylcopper)magnesium bromide prepared by cooling a stirred slurry of 216.2 mg (1.1 mmol) of CuI in 4 mL of ether to −78 °C, dropwise addition of 1.24 mL (2.3 mmol) of a 1.9 M ether solution of phenylmagnesium bromide, warming to room temperature, and recooling to −78 °C was reacted with 100.0 mg (0.8 mmol) of **5c** in 3 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 180 °C), retention time (*Z*)-**8f** 6.2 min; the *E* isomer was not observed. Purification by preparative TLC using 9:1 hexane:ether as eluent gave 126.9 mg (80%) of **8f**: ^1H NMR ($CDCl_3$) δ 7.26 (m, 5 H), 6.61 (d, *J* = 12.5 Hz, 1 H), 6.26 (d, *J* = 12.5 Hz, 1 H), 2.56–2.21 (m, 4 H), 2.10–1.81 (m, 2 H), 1.81–1.65 (m, 3 H); IR (thin film) 2940 (m), 1650 (s), 770 (m), 690 (m) cm^{-1}. Anal. Calcd for $C_{15}H_{16}O$: C, 84.87; H, 7.60. Found: C, 84.78; H, 7.61.

From (C_6H_5)$_2$Cu(CN)Li$_2$. The organocopper reagent was prepared as in the previous reaction by using 65.0 mg (0.7 mmol) of CuCN and 1.42 mL (1.5 mmol) of a 1.1 M ether solution of phenyllithium and was reacted with 50.2 mg (0.4 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column A, 180 °C); only the *Z* isomer was detected. Purification by preparative TLC using 9:1 hexane:ether as eluent gave 62.4 mg (81%) of **8f**, pure by GC.

3-(1,3-Butadienyl)-2-methyl-2-cyclohexenone (8g). (Cyanodivinylcopper)dilithium prepared by cooling a slurry of 140.0 mg (1.6 mmol) of CuCN in 4 mL of ether to −78 °C, dropwise addition of 1.74 mL (3.2 mmol) of a 1.8 M THF solution of vinyllithium, warming to 0 °C for 5 min, and recooling to −78 °C was reacted with 100.0 mg (0.8 mmol) of **5c** in 2 mL of ether according to the general procedure. The resultant crude product was analyzed by GC (column C, 155 °C), retention time (*Z*)-**8g** 2.4 min, (*E*)-**8g** 4.1 min; ratio (*Z*)-**8g**:(*E*)-**8g** 3.0:1. Purification by preparative TLC using 9:1 hexane:ether as eluent gave 98.5 mg (82%) of **8g**: ^1H NMR ($CDCl_3$) δ 6.73 and 6.08 (two d, *J* = 14.2 Hz and *J* = 11.1 Hz, 1 H), 6.63–6.57 and 6.53–6.44 (two m, 1 H), 6.37–6.29 and 6.53–6.44 (two m, 1 H), 5.4 and 5.28 (two d, *J* = 17.3 and 9.3 Hz, 1 H), 5.32 and 5.22 (two d, *J* = 17.5 and 9.5 Hz, 1 H); IR (thin film) 2920 (s), 2860 (m), 1655 (s), 1590 (m) cm^{-1}.

2,4-Dinitrophenylhydrazone of 8g. From $(CH_2{=}CH)_2Cu(CN)Li_2$. A flame-dried 25-mL one-neck round-bottom flask equipped with stirring bar, sleeve septum, and N_2 inlet was charged with 135.0 mg (1.5 mmol) of CuCN and 4 mL of ether. Stirring was begun as the slurry was cooled to −78 °C and 1.74 mL (3.1 mmol) of a 1.8 M THF solution of vinyllithium added dropwise. After 5 min the flask was warmed to 0 °C, held at 0 °C for 10 min, and then recooled to −78 °C. A solution of 100.0 mg (0.8 mmol) of **5c** in 3 mL of ether was added dropwise, and the reaction stirred for 1.5 h. The reaction was quenched at −78 °C by using NH_4Cl solution; extraction into ether, drying through $MgSO_4$, and concentration by rotary evaporation afforded 141.8 mg of an oil, which was dissolved in 10 mL of absolute ethanol directly. While the solution was stirred magnetically, 3.60 mL (0.9 mmol) of a 0.25 M solution of 2,4-dinitrophenylhydrazine was added, followed by 5 drops of 20% aqueous H_2SO_4. The mixture was heated at reflux for 30 min and then cooled to room temperature. Rotary evaporation gave a solid, which was taken up in CH_2Cl_2, dried ($MgSO_4$), concentrated by rotary evaporation, and purified by flash chromatography using 1.5:1 CH_2Cl_2:hexane as eluent to give 216.5 mg (84%) of the product dinitrophenylhydrazone: mp 160–162 °C; ^1H NMR ($CDCl_3$) δ 11.30 (d, J = 23.9 Hz, 1 H), 9.12 (d, J = 2.0 Hz, 1 H), 8.29 (d of d, J = 9.3, 2.0 Hz, 1 H), 8.00 (d of d, J = 9.7, 3.1 Hz, 1 H), 6.80–6.13 (m, 3 H), 5.38–5.19 (m, 2 H), 2.70–2.31 (m, 4 H), 2.21–2.02 (s, 3 H), 2.02–1.75 (m, 2 H); IR (KBr) 2910 (s), 1610 (s), 1585 (s), 1505 (s), 1335 (s), 1136 (s) cm^{-1}; MS, m/z 342 ($M^{\bullet+}$, 87), 129 (55), 91 (93), 55 (93), 44 (100). Anal. Calcd for $C_{17}H_{18}N_4O_4$: C, 59.64; H, 5.30; N, 16.37. Found C, 59.59; H, 5.34; N, 16.32.

2-Methyl-3-propenylidenecyclohex-1-enyl Trifluoromethanesulfonate (13a). A flame-dried 25-mL one-neck round-bottomed flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was purged with N_2 and charged with 378.9 mg (2.0 mmol) of CuI and 5.6 mL of ether. Stirring was begun, and the slurry cooled to 0 °C, followed by dropwise addition of 2.8 mL (4.0 mmol) of a 1.4 M ether solution of methyllithium. Stirring at 0 °C for 10 min was followed by cooling to −78 °C and dropwise addition of 176.9 mg (1.3 mmol) of **5c** in 5.6 mL of ether. After this was stirred at −78 °C for 1.5 h, a solution of 709.0 mg (2.0 mmol) of *N*-phenyltrifluoromethanesulfonimide in 5.6 mL of 1,2-dimethoxyethane (DME) was added, and the reaction warmed to 0 °C over 2 h. After stirring at 0 °C overnight (ca. 12 h), the reaction was warmed to room temperature. The solvent was removed from the reaction by rotary evaporation; about 20 mL of ether was added, and the resultant slurry filtered through a pad of Florisil. The filtrate was concentrated by rotary evaporation, and the resultant crude product purified by MPLC using hexane as eluent to give 317.8 mg (85%) of **13a** as a clear, colorless liquid: GC (column C, 100 °C, 8 min; 10 °C min^{-1} to 160 °C; 160 °C, 8 min) retention time 12.1 min; ^1H NMR ($CDCl_3$) δ 5.35 (q, J = 6.7 Hz, 1 H), 2.42 (m, 2 H), 2.32 (m, 2 H), 1.85–1.78 (m, 5 H), 1.68 (d, J = 7.3 Hz, 3 H); ^{13}C NMR ($CDCl_3$) δ 203.7, 144.2, 124.2, 118.4 (q, J = 319.8 Hz), 101.6, 88.9, 30.0, 28.2, 22.5, 14.4, 13.4; IR (thin film) 2950 (m), 2930 (m), 2860 (w), 1950 (w), 1660 (w), 1410 (s), 1240 (s), 1210 (s), 1140 (s) cm^{-1}; MS, m/z 282 ($M^{\bullet+}$, 32), 149 (49), 105 (38), 93 (88), 91 (100), 79 (80), 77 (80), 69 (75), 55 (93); UV λ_{max} (1,4-dioxane) 255 nm (ε 3400). Anal. Calcd for $C_{11}H_{13}F_3O_3S{\cdot}0.7H_2O$: C, 44.80; H, 4.92; S, 10.87. Found: C, 45.04; H, 4.89; S, 10.47.

2-Methyl-3-hex-1-enylidenecyclohex-1-enyl Trifluoromethanesulfonate (13d). A flame-dried 25-mL one-neck round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was purged with N_2 and charged with 264.9 mg (1.4 mmol) of CuI. Ether (4 mL) was added, and stirring begun as the slurry was cooled to −78 °C. Dropwise addition of 2.5 mL of a 1.1 M hexane solution of *n*-butyllithium was followed by warming to 0 °C, stirring at 0 °C for 5 min, and recooling to −78 °C. A solution of 123.8 mg (0.9 mmol) of **5c** in 4 mL of ether was added dropwise, and the reaction stirred at −78 °C for 1.5 h. After this time a solution of 496.7 mg (1.4 mmol) of *N*-phenyltrifluoromethanesulfonimide in 4 mL of DME was added, and the reaction warmed to 0 °C over 2 h. After this was stirred at 0 °C overnight (ca. 14 h), about 20 mL of ether was added, and the flask contents were filtered through a medium-porosity sintered-glass funnel. The filtrate was concentrated by rotary evaporation, and the resultant crude product purified by MPLC using hexane as eluent to give 234.7 mg (79%) of **13d**: GC (column C, 160 °C) retention time 6.4 min; ^1H NMR (C_6D_6) δ 6.37–6.02 (m, 1 H), 2.70–1.92 (m, 2 H), 1.83 (s, 3 H), 1.43–1.04 (m, 8 H), 1.04–0.74 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 202.9, 144.1, 124.1, 118.3 (q, J = 320.8 Hz), 102.0, 94.3, 31.2, 28.6, 28.2, 27.7, 22.5, 22.1, 14.0, 13.4; IR (thin film) 2950 (s), 2912 (s), 2870 (m), 1940 (w), 1590 (m), 1410 (s), 1200 (s), 1140 (s), 1020 (s), 910 (s), 890 (s) cm^{-1}; MS m/z 324 ($M^{\bullet+}$, 1), 282 (51), 149 (100), 121 (17), 91 (64), 69 (75). Anal. Calcd for $C_{14}H_{19}F_3O_3S{\cdot}0.5H_2O$: C, 50.44; H, 6.05; S, 9.62. Found: C, 50.11; H, 6.40; S, 9.49.

1,2-Dimethyl-3-propenylidenecyclohexene (14a). A 25-mL flame-dried one-neck round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was purged with N_2 and then charged with 757.5 mg (4.0 mmol) of CuI and 9.3 mL of THF. Cooling to 0 °C was followed by dropwise addition of 5.6 mL (7.8 mmol) of a 1.4 M ether solution of methyllithium. After 10 min, 317.8 mg (1.1 mmol) of **13a** in 9.3 mL of THF was added dropwise via syringe, and the reaction cooled to −15 °C. After the reaction was stirred at −15 °C for 20 h, it was diluted with ca. 30 mL of hexane, filtered through a pad of Florisil, and concentrated by rotary evaporation to give 137.2 mg (83%) of **14a**, pure by GC: GC (column C, 100 °C) retention time 6.2 min; ^1H NMR ($CDCl_3$) δ 5.22 (q, J = 6.0 Hz, 1 H), 2.41–1.88 (m, 6 H), 1.78–1.54 (m, 9 H); ^{13}C NMR ($CDCl_3$) δ 202.7, 130.9, 122.5, 104.4, 86.8, 32.4, 29.0, 23.0, 20.4, 15.6, 15.1; IR (thin film) 2920 (s), 2860 (s), 2820 (m), 1940 (w), 1440 (m) cm^{-1}; MS, m/z 148 ($M^{\bullet+}$, 95), 133 (98), 119 (31), 105 (100), 91 (79), 77 (29).

1,2-Dimethyl-3-hex-1-enylidenecyclohexene (14d). A flame-dried 25-mL round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was purged with N_2 and charged with 420.3 mg (2.2 mmol) of CuI and 5 mL of THF. Stirring was begun, and the slurry cooled to 0 °C; then, 3.14 mL of a 1.4 M ether solution of methyllithium was added dropwise. After 10 min, the flask was cooled to −15 °C, and a solution of 203.7 mg (0.6 mmol) of **13d** in 5 mL of THF was added dropwise via syringe. After the reaction was stirred at −15 °C for 20 h, it was diluted with ca. 20 mL of hexane, filtered through a pad of Florisil, and concentrated by rotary evaporation to give 98.0 mg (82%) of **14d**, ≥90% pure by GC: GC (column C, 140 °C) retention time 6.1 min; ^1H NMR ($CDCl_3$) δ 5.45–5.08 (m, 1 H), 2.62–1.52 (m, 12 H), 1.52–1.06 (m, 5 H), 1.02–0.73 (m, 4 H); ^{13}C NMR (C_6D_6) δ 201.8, 130.6, 122.4, 104.8, 92.3, 32.4, 31.4, 29.3, 29.2, 23.0, 22.2, 20.4, 15.6, 13.9; IR (thin film) 2960 (s), 2930 (s), 2860 (s), 1940 (w), 1455 (m), 1440 (m), 1380 (m) cm^{-1}; MS, m/z 190 ($M^{\bullet+}$, 35), 175 (5), 161 (8), 133 (59), 119 (72), 105 (99), 91 (100), 77 (44).

Representative Equilibration Studies. Equilibration of (*Z*)-6a to (*E*)-6a Using Alumina. A slurry of 1 g of Al_2O_3, 52.0 mg of a 1.5:1 mixture of (*Z*)-**6a**:(*E*)-**6a** corresponding to a 20% de of (*Z*)-**6a**, and 20 mL of ether was stirred in an N_2-purged one-neck round-bottom flask. At various time intervals indicated in Table II, stirring was stopped, the alumina allowed to settle, and the supernatant analyzed by GC (column A, 145 °C). The ratio (*Z*)-**6a**:(*E*)-**6a** changed as indicated in the table, reaching an ultimate value of 1:8.7 corresponding to a 79% de of (*E*)-**6a**.

Equilibration of (*Z*)-8a to (*E*)-8a Using LDA. A flame-dried 25-mL one-neck round-bottom flask equipped with a magnetic stirring bar, sleeve septum, and N_2 inlet was purged with N_2 and then charged with a solution of 32 μL (0.2 mmol) of diisopropylamine in 2 mL of THF. Cooling to 0 °C was followed by dropwise addition of 130 μL (0.2 mmol) of a 1.6 M hexane solution of *n*-butyllithium. After 30 min, 150 μL of HMPA was added, and the reaction flask cooled to −78 °C. A solution of 16.0 mg (0.1 mmol) of a 2.5:1 mixture of (*Z*)-**8a**:(*E*)-**8a** corresponding to a 43% de of (*Z*)-**8a** in 1.5 mL of THF was added dropwise; the reaction was stirred for 1 h and then poured into 20 mL of ice water. Acidification using cold, dilute HCl was followed by extraction into ether, drying ($MgSO_4$) of the ether extract, and concentration by rotary evaporation. The crude product was purified by preparative TLC using 9:1 hexane:ether as eluent to give 9.4 mg (59%) of a 1.0:3.0 mixture of (*Z*)-**8a**:(*E*)-**8a**, corresponding to a 50% de of (*E*)-**8a**.

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Registry No. (*Z*)-**1d-7e**, 124267-35-2; (*E*)-**1d-7e**, 124267-36-3; **2a**, 22117-97-1; **2b**, 23074-59-1; **2d-5b**, 124267-27-2; (*Z*)-**2d-7e**, 124267-33-0; (*E*)-**2d-7e**, 124267-34-1; **3**, 124267-24-9; **4b**, 124267-25-0; **5a**, 121590-82-7; **5b**, 124267-26-1; **5c**, 89998-56-1; (*Z*)-**6a**, 121590-83-8; (*E*)-**6a**, 75283-44-2; (*Z*)-**6b**, 121590-84-9; (*E*)-**6b**, 121590-89-4; (*Z*)-**6c**, 121590-85-0; (*E*)-**6c**, 121590-90-7; (*Z*)-**6e**, 121590-86-1; (*E*)-**6e**, 121590-91-8; (*Z*)-**6f**, 121590-87-2; (*E*)-**6f**, 111303-28-7; (*Z*)-**6g**, 124267-28-3; (*E*)-**6g**, 124267-29-4; (*Z*)-**6h**, 121590-88-3; (*E*)-**6h**, 121590-92-9; (*Z*)-**7a**, 29179-04-2; (*E*)-7a, 29179-03-1; (*Z*)-**7e**, 124267-31-8; (*E*)-**7e**, 124267-32-9; (*Z*)-**8a**, 124267-37-4; (*E*)-**8a**, 124267-38-5; (*Z*)-**8c**, 124267-39-6; (*E*)-**8c**, 124267-40-9; (*Z*)-**8d**, 124267-41-0; (*E*)-**8d**, 124267-42-1; (*Z*)-**8e**, 124267-43-2; (*E*)-**8e**, 124267-44-3; (*Z*)-**8f**, 124267-45-4; (*Z*)-**8g**, 124267-46-5; (*E*)-**8g**, 124267-47-6; **13a**, 124267-49-8; **13d**, 124267-50-1; **14a**, 124267-51-2; **14d**, 124267-52-3; TMSC≡CH, 1066-54-2; Me_2CuLi, 15681-48-8; MeCu(CN)Li, 41753-78-0; $Me_2Cu(CN)Li_2$, 80473-70-7; EtCu(CN)MgBr, 124267-54-5; $Et_2Cu(CN)(MgBr)_2$, 121589-72-8; $i\text{-}Pr_2Cu(CN)(MgCl)_2$, 121589-74-0; Bu_2CuLi, 24406-16-4; $Bu_2Cu(CN)(MgBr)_2$, 124267-55-6; $Bu_2Cu(CN)Li_2$, 80473-69-4; $t\text{-}Bu_2CuLi$, 23402-75-7; $t\text{-}Bu_2Cu(CN)Li_2$, 87263-84-1; $Ph_2CuMgBr$, 58938-91-3; $Ph_2CuMgBr{\cdot}Me_2S$, 124267-57-8; $Ph_2Cu(CN)(MgBr)_2$, 121589-76-2; $Ph_2Cu(CN)Li_2$, 80473-66-1; $(CH_2{=}CH)_2CuMgBr{\cdot}Me_2S$, 124267-59-0; $(CH_2{=}CH)_2Cu(CN)(MgBr)_2$, 113153-17-6; $(CH_2{=}CH)_2Cu(CN)Li_2$, 80473-65-0; PhSLi, 2973-86-6; 3-(1,3-butadienyl)-2-methyl-2-cyclopenten-1-one 2,4-dinitrophenylhydrazone, 124267-30-7; 3-(1,3-butadienyl)-2-methyl-2-cyclohexen-1-one 2,4-dinitrophenylhydrazone, 124267-48-7.

Preparation of Allylic Acetates from Simple Alkenes by Palladium(II)-Catalyzed Acetoxylation

Sverker Hansson,† Andreas Heumann,*,‡ Tobias Rein,† and Björn Åkermark*,†

Department of Organic Chemistry, Royal Institute of Technology, S-100 44 Stockholm, Sweden, and Faculté de St.-Jérome-ESIPSOI, UA 126, F 13397 Marseille Cedex 13, France

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The scope and limitations of palladium-catalyzed allylic acetoxylation of alkenes has been investigated, using benzoquinone–manganese dioxide as the reoxidation system. Unsubstituted cycloalkenes gave good to excellent yields of allylic acetates. Total yields were also good for many substituted cycloalkenes and for linear alkenes, but these substrates generally gave several isomeric acetates. The exploratory mechanistic studies show that the acetoxylation can proceed via both 1,2-acetoxypalladation and η^3-allylpalladium complex formation. The keen balance between these processes depends on the structure of the alkene.

Introduction

Allylic acetates have become important intermediates in organic synthesis, in particular after it was realized that metal-catalyzed replacement of the acetoxy group by nucleophiles is a facile and efficient reaction.[1] Allylic acetates are usually prepared from the corresponding allylic alcohols, but a number of routes which lead directly from alkenes have been devised. Most of these involve peroxides[2] and/or a variety of metal salts.[3] Due to several factors, such as the necessity for stoichiometric amounts of metal reagents and lack of generality, these reactions have not been used extensively in organic synthesis.

We have recently shown that simple cycloalkenes may be efficiently and selectively converted into allylic acetates, using palladium acetate as catalyst in combination with an oxidation system consisting of benzoquinone and manganese dioxide (Scheme I).[4] In this paper we report on an examination of the scope of this reaction and also on the results of an exploratory study of its mechanism.

Results and Discussion

In order to examine the generality of palladium-catalyzed allylic acetoxylation we have studied a range of olefins (Tables I and II). The reactions were performed in acetic acid solution, using 5% palladium acetate as catalyst, ca. 20% benzoquinone as cooxidant, and 110–200% manganese dioxide as oxidant. For a few alkenes, other ratios between substrate and catalyst were also

Scheme I

1 n = 1 **4** n = 4
2 n = 2 **5** n = 6
3 n = 3 **6** n = 8

studied. The reaction temperature was generally 60 °C, but temperatures as low as room temperature were also used in some cases.

With the exception of cyclooctene, the unsubstituted cycloalkenes gave good yields of allylic acetates (Table I). This is also true for most of the substituted cycloalkenes (Table II) and for the two linear alkenes that were studied, (*E*)-3-hexene and (*E*)-5-decene (Table I).

There are considerable differences in reactivity among the substrates. Cyclopentene, cyclohexene, cycloheptene, and (*E*)-cyclododecene all reacted within 50 h or less at 60 °C to give good yields of allylic acetates (Table I, entries 1, 2, 4, and 7). In contrast, (*Z*)-cyclooctene and (*Z*)-

† Royal Institute of Technology.
‡ Faculté de St.-Jérome-ESIPSOI.

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