University has been described previously.[16]

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Registry No. 1, 126709-14-6; 2, 134418-71-6; 5, 68536-67-4; 6, 4132-26-7; ethanol, 64-17-5; methanol, 67-56-1; 1,1,1,3,3,3-hexafluoro-2-propanol, 920-66-1; pyridine, 110-86-1; 2,2,2-trifluoroethanol, 75-89-8.

Supplementary Material Available: A plot of k_{obs} versus [pyridine] in CH_3CN and a plot of k_{obs} versus [CH_3OH] at constant [pyridine] (3 pages). Ordering information is given on any current masthead page.

Direct Formation and Subsequent Substitution of Remote Ketone-Functionalized Organocopper Reagents

Greg W. Ebert* and Walter R. Klein[1]

Department of Chemistry, State University of New York College at Buffalo, 1300 Elmwood Avenue, Buffalo, New York 14222

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Remote ketone-functionalized aryl- and alkylcopper reagents have been synthesized by the use of a highly activated form of zero-valent copper. 5-Bromo-2-pentanone and 4-iodobenzophenone undergo oxidative addition with activated copper to form 5-cuprio-2-pentanone and 4-cupriobenzophenone, respectively. These, in turn, can be cross-coupled with alkyl halides to produce the corresponding alkylated ketones and with acid chlorides to form the corresponding diketones. By use of this methodology, a two-step, one-pot synthesis of methyl (*E*)-9-oxo-2-decenoate and 8-nonen-2-one have been achieved. The former compound is the methyl ester of the "queen substance" of the honey bee, and the latter is part of an "attractant mixture" for cheese mites found in cheddar cheese. These syntheses were accomplished by converting commercially available 6-bromo-2-hexanone to 6-cuprio-2-hexanone followed by cross-coupling with commercially available methyl 4-bromocrotonate and allyl bromide, respectively.

Introduction

Organocopper compounds[2] are an exceptionally useful class of synthetic reagents primarily due to their ability to undergo substitution reactions[3] with alkyl halides and 1,4-conjugate addition reactions[4] with α,β-unsaturated carbonyl compounds. α-Cuprio ketones have been obtained by forming the enolate of the ketone followed by treatment with a suitable copper(I) salt.[5] This approach, obviously, cannot be used for reagents in which the carbonyl is remote from the desired copper site due to the incompatibility of ketones with the lithium or Grignard precursors used to form the organocopper reagents. Such reagents can be formed by traditional methods only if steps are taken to first mask or protect the ketone, adding time and cost to any synthesis and lowering overall yields.

Rieke and Ebert[6] have recently developed a highly reactive form of copper that permits the direct formation of organocopper compounds from organic halides without utilizing the traditional organolithium or Grignard precursors. This active copper is prepared by reducing an ethereal solution of $CuI{\cdot}PR_3$ with an ethereal solution of lithium naphthalenide or biphenylide under argon. The resulting copper is sufficiently reactive to allow direct oxidative addition to alkyl halides (eqs 1 and 2).

Table I. Stability of Ketones in the Presence of Active Copper

entry	ketone	temp, °C	% recovery, 30 min[a]
1	$PhC(O)Ph$	25	86
		−78	92
2	$(CH_3)_3CC(O)C(CH_3)_3$	25	82
		−78	87
3	$CH_3C(O)Ph$	25	26
		−78	75
4	$CH_3C(O)CH_2CH_2CH_3$	25	55
		−78	80
5	$CH_3C(O)CH_3$	25	22
		−78	71

[a] GC yields.

$$\underset{1}{\mathrm{Li^{+}nap.^{\bullet -}}} + \underset{2}{\mathrm{CuI{\cdot}PR_3}} \rightarrow \underset{3}{\mathrm{Cu^0}} + \mathrm{nap.} + \mathrm{PR_3} + \mathrm{LiI} \tag{1}$$

$$2\underset{3}{\mathrm{Cu^0}} + \mathrm{RX} \rightarrow \mathrm{CuR} + \mathrm{CuX} \tag{2}$$

Using this highly reactive copper, Rieke and co-workers have further developed stable primary alkylcopper compounds containing ester, chloro, and nitrile functionalities. They have explored the reactions of these reagents with epoxides, acid chlorides, and α,β-unsaturated ketones.[7]

In our own laboratory, we have also continued to study and develop zero-valent copper and wish to report the

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[1] Department of Chemistry, University of Nebraska—Lincoln, Lincoln, NE 68588-0304.

[2] (a) Posner, G. H. *An Introduction to Synthesis Using Organocopper Reagents*; Wiley: New York, 1980. (b) Bertz, S. H.; Dabbagh, G. *J. Org. Chem.* **1984**, *49*, 1119. (c) Bertz, S. H.; Dabbagh, G. *J. Am. Chem. Soc.* **1988**, *110*, 3668. (d) Lipschutz, B. H.; Wilhelm, R. S.; Kozlowski, J. A.; Parker, D. *J. Org. Chem.* **1984**, *49*, 3928. (e) Lipshutz, B. H.; Kozlowski, J. A.; Wilhelm, R. S. *Ibid.* **1983**, *48*, 546.

[3] Posner, G. H. *Org. React.* (*N.Y.*) **1975**, *22*, 253 and references cited therein.

[4] Posner, G. H. *Org. React.* (*N.Y.*) **1972**, *19*, 1 and references cited therein.

[5] (a) Kauffmann, Th.; Beissner, G.; Berg, H.; Koppelmann, E.; Legler, J.; Schönfelder, M. *Agnew. Chem., Int. Ed. Engl.* **1968**, *7*, 540. (b) Hampton, K. G.; Christie, J. J. *J. Org. Chem.* **1975**, *40*, 3887. (c) Ito, Y.; Konoike, T.; Saegusa, T. *J. Am. Chem. Soc.* **1975**, *97*, 2912. (d) Ito, Y.; Konoike, T.; Harada, T.; Saegusa, T. *Ibid.* **1977**, *99*, 1487. (e) Kobayashi, Y.; Taguchi, T.; Tokuno, E. *Tetrahedron Lett.* **1977**, 3741.

[6] (a) Ebert, G. W.; Rieke, R. D. *J. Org. Chem.* **1984**, *49*, 5280. (b) Ebert, G. W.; Rieke, R. D. *Ibid.* **1988**, *53*, 4482.

[7] (a) Wehmeyer, R. M.; Rieke, R. D.; *J. Org. Chem.* **1987**, *52*, 5056. (b) Wu, T.-C.; Wehmeyer, R. M.; Rieke, R. D. *Ibid.* **1987**, *52*, 5057. (c) Wu, T.-C.; Rieke, R. D. *Tetrahedron Lett.* **1988**, *29*, 6753. (d) Wehmeyer, R. M.; Rieke, R. D. *Ibid.* **1988**, *29*, 4513.

0022-3263/91/1956-4744$02.50/0

Table II. Cross-Coupling of *p*-Cupriobenzophenone

$$p\text{-}CuC_6H_4C(O)Ph + RX \rightarrow p\text{-}RC_6H_4C(O)Ph$$
$$\underset{\textstyle 4}{}$$

entry	RX	solvent[a]	product: structure	product: no.	product: % yield[b]
1	CH_3I	THF	*p*-methylbenzophenone	6	28
2	CH_3CH_2I	THF	*p*-ethylbenzophenone	7	25
3	CH_3COCl	DME	*p*-acetylbenzophenone	8	68[c]
4	PhCOCl	DME	*p*-benzoylbenzophenone	9	85[c]

[a] THF = tetrahydrofuran, DME = 1,2-dimethoxyethane. [b] Yields are based upon the amount of organocopper present just prior to the addition of cross-coupling reagent. The reactions were run for 30 min at 25 °C and quantitated by GC. [c] Reaction time was 60 min.

successful results of our preliminary studies on the development of remote ketone-functionalized organocopper compounds.

Results and Discussion

Compatibility of Ketones with Activated Copper. A variety of ketones were first tested for their compatibility with active copper. The amount of ketone recovered from a methanol-quenched solution of activated copper was determined by GC as a function of temperature. The results are shown in Table I.

Ketones containing no α-protons (entries 1 and 2) were found to be quite stable regardless of temperature. No other products were detected by GC. Ketones containing α-protons underwent substantial decomposition at 25 °C but were found to persist at low temperatures. A more thorough examination of acetone and acetophenone revealed no condensation products or pinacols but showed substantial amounts of the corresponding reduced products 2-propanol and 1-phenylethanol. These results indicate that remote ketone-functionalized organocopper reagents containing α-protons would require low temperatures for successful formation.

Halobenzophenones. *p*-Bromobenzophenone and *p*-iodobenzophenone undergo reaction with activated copper to produce moderate yields of 4-cupriobenzophenone.

The highest yield of organocopper (46%) was formed when a suspension of 2 equiv of active copper was added to an ethereal solution of *p*-iodobenzophenone at 25 °C (eq 3). This inverse addition of the copper to the ketone

$$\underset{\substack{\textstyle 5\\ X\,=\,Br\ (I)}}{p\text{-}XC_6H_4C(O)Ph} + Cu^0 \rightarrow \underset{\textstyle 4}{[p\text{-}CuC_6H_4C(O)Ph]} \xrightarrow{H^+} \underset{\substack{39\%\\(46\%)}}{PhC(O)Ph} \quad (3)$$

always provided a higher yield of the organometallic than did the normal addition of the ketone to the copper. Interestingly, 3 equiv of activated copper was needed to provide the maximum yield of intermediate with *p*-bromobenzophenone (39%). This additional copper was not needed, and in fact was detrimental, in maximizing the yield of organocopper from the iodo compound.

Table II shows that 4-cupriobenzophenone cross-coupled with alkyl iodides to give somewhat low yields of 4-alkylbenzophenones. Much higher yields were found for the cross-coupling of acid chlorides. One previous example was reported by Rieke and Ebert[6b] in which *p*-cupriobenzophenone, formed from *p*-bromobenzophenone via activated copper in a 42% yield, was cross-coupled with 1-iodobutane to produce *p*-butylbenzophenone in 34% yield.

Table III. Reactions of *p*-XPhC(O)CH$_3$ (10) with Activated Copper[a]

entry	X	temp, °C	% recovery, 10	% yield,[b] *p*-CuArC(O)CH$_3$
1	I	25	29	25
2	Br	25	25	13
3	I	0	39	20
4	Br	0	24	9
5	I	−78	57	10
6	Br	−78	78	4

[a] All reactions were run for 30 min in THF with a Cu/RX ratio of 2/1. Quantitation was by GC. [b] The amount of acetophenone found after quenching the reaction is assumed to be indicative of the amount of organocopper present at the time of the quench.

Table IV. Cross-Coupling Reactions of 5-Cuprio-2-pentanone (12)

$$\underset{\textstyle 12}{Cu(CH_2)_3C(O)CH_3} + RX \rightarrow R(CH_2)_3C(O)CH_3$$

entry	RX	product: structure	product: no.	product: % yield,[a] 60 min
1	CH_3I	2-hexanone	13	26
2	1-iodobutane	2-nonanone	14	22
3	$CH_2{=}CHCH_2Br$	7-octen-2-one	15	49
4	$PhCH_2Br$	6-phenyl-2-hexanone	16	91
5	O_2	2,9-decanedione	17	28[b]

[a] Yields are based upon the amount of organocopper present just prior to the addition of the cross-coupling reagent. [b] Reaction time was 10 min.

4-Haloacetophenones. Only low yields of 4-cupricacetophenone were obtained when 4-haloacetophenones were treated with activated copper. As seen in Table III, at room temperature the decomposition of the ketone itself competes with the formation of the reagent resulting in the consumption of most of the starting material with very little production of the organocopper compound. At low temperatures, the ketone is more resistant to attack by the active copper, but the aryl halide bond is also less susceptible to reagent formation, resulting primarily in the recovery of starting material. Thus, as a class, haloacetophenones do not appear to be viable candidates for conversion to organocopper reagents by our methodology. We are continuing our studies on this problem.

Haloalkanones. We examined the formation of 5-cuprio-2-pentanone from 5-bromo-2-pentanone and activated copper. Although numerous reaction conditions were tested, we were unable to improve upon the procedure reported by Rieke and Wehmeyer[7a] for producing primary alkylcopper reagents from primary alkyl bromides and active copper. This method produced a 67% yield of the organocopper compound. A D$_2$O quench of the organometallic, followed by preparative GC isolation and subsequent NMR and mass spectral analysis, showed 96% deuterium incorporation at the 5-position of the intermediate as shown in eqs 4 and 5.

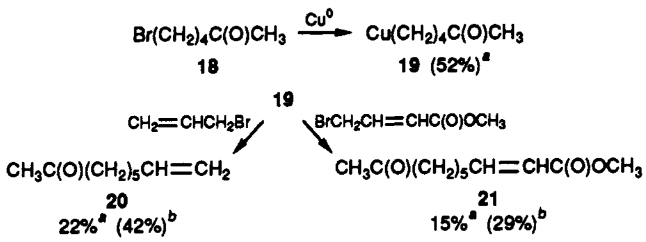
$$\underset{\textstyle 11}{Br(CH_2)_3C(O)CH_3} + 2Cu^0 \rightarrow \underset{\textstyle 67\%}{Cu(CH_2)_3C(O)CH_3} \quad (4)$$

$$\underset{\textstyle 12}{Cu(CH_2)_3C(O)CH_3} + D_2O \rightarrow \underset{\textstyle 96\%}{D(CH_2)_3C(O)CH_3} \quad (5)$$

The organocopper reagent was cross-coupled with various alkyl halides to produce 5-alkylated ketones in various yields as shown in Table IV. Bubbling O$_2$ through a solution of the 5-cuprio-2-pentanone at −78 °C produced the homocoupled dimer 2,9-decanedione in 28% (entry 5).

Natural Product Syntheses. Although this work is in its preliminary stages, we wished to demonstrate the

Scheme I

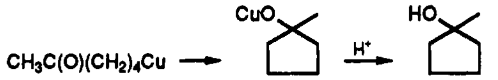


[a] Percent yield based upon starting material 18. [b] Percent yield based upon the amount of organocopper 19 present at the time of the addition of the cross-coupling reagent.

potential of this approach to the syntheses of some natural products (Scheme I). The intermediate 6-cuprio-2-hexanone (19) was produced in a 52% yield from 6-bromo-2-hexanone (18) and activated copper. This intermediate was cross-coupled with allyl bromide to form 8-nonen-2-one (20) and with methyl 4-bromocrotonate to produce methyl (*E*)-9-oxo-2-decenoate (21). The former (20) is part of an "attractant mixture" for cheese mites found in cheddar cheese,[8] and the latter (21) is the methyl ester of the "queen substance" of the honey bee.[9]

While these yields are rather low, that disadvantage is somewhat offset by the fact that these products are produced in two-step, one-pot reactions from commercially available starting materials. We were unable to uncover any previously published syntheses of 21 that did not require three or more steps, and none of these were one-pot reactions.[9]

Unlike 5-cuprio-2-pentanone, which can be consistently prepared in uniformly good yields, 6-cuprio-2-hexanone yields varied from 15 to 55%. We uncovered at least two reasons for this. First, 6-bromo-2-hexanone tends to decompose on standing. The commercially available compound required fractional distillation prior to use, and unused portions of the compound were found to undergo significant decomposition within a period of two weeks. Secondly, once converted to the organocopper reagent, the 6-cuprio-2-hexanone undergoes a competitive cyclization to produce, upon acid quench, yields of up to 44% of 1-methylcyclopentanol (eq 6).



19 22 (6)

Rieke and Wehmeyer[7d] reported similar difficulties with the cyclization of this organocopper reagent. They succeeded in trapping only 19% of the intermediate with benzoyl chloride to form the diketone 1-phenyl-1,6-heptanedione. Fortunately, cyclization is not a competitive process in the formation of 5-cuprio-2-pentanone.

Conclusions

In conclusion, this preliminary work has shown that remote ketone-functionalized organocopper reagents can be prepared in moderate to good yields from appropriate organic halides via activated copper and subsequently utilized in cross-coupling reactions with suitable substrates to yield substituted ketones. This approach alleviates the need to mask or protect the carbonyl group as in cases where organocuprates are produced from the traditional lithium and Grignard precursors. This, in turn, can reduce the number of steps in many syntheses. We are continuing these studies both to improve the cross-coupling yields and to develop additional remote ketone-functionalized organocopper reagents.

Experimental Section

General Information. Our basic laboratory procedures, experimental set-up, method of gas chromatography analysis, formation of lithium naphthalenide and biphenylide (1), formation of CuI·P(*n*-Bu)$_3$ (2), formation of activated copper (3), and workup and identification procedures have been previously reported.[10]

Chemicals. All chemicals purchased were reagent grade or better and used as received unless otherwise stated.

4-Iodobenzophenone (5).[11] The product (6.25 g, 53% yield) was sufficiently pure for our purposes after one recrystallization. However, a portion of the sample was recrystallized two additional times to yield a purer product for analysis: mp 97–98 °C (lit.[11] mp 101–102 °C); IR (KBr) 3030, 1645, 1575, 1280, 720, 690 cm^{-1}; ^{1}H NMR (CDCl$_3$) δ 7–8 (m, ArH); ^{13}C NMR (CDCl$_3$) δ 195.0, 138.2, 132.9, 131.9, 130.3, 128.8, 100.

4-Iodoacetophenone (10):[12] 50% yield; mp 79–81 °C (lit.[12] mp 83–84 °C); bp 145–150 °C (20 Torr) [lit.[12] mp 137–140 °C (9 Torr)].

5-Bromo-2-pentanone (11):[13] 10.5 g, 21% yield; bp 85–90 °C (20 Torr); lit.[13] IR matches that of the sample.

Reaction of Simple Ketones with Activated Copper. To a flask containing active copper (10 mmol) in THF was added an internal standard (decane or dodecane, 3 mmol). The reaction temperature was appropriately adjusted and the ketone (5 mmol) added. Aliquots (1 mL) were removed at timed intervals, quenched with methanol (0.5 mL), and analyzed by GC. Identities of the products were established by comparing them to authentic commercial samples.

Formation and Reactions of *p*-Cupriobenzophenone (4). In a typical reaction, active copper (10 mmol) was produced by the lithium naphthalenide reduction of CuI·P(*n*-Bu)$_3$ in THF or DME. The active copper solution was transferred via syringe to an addition funnel and allowed to slowly drip (25 min) into a stirring solution of 5 (5 mmol) in THF or DME (12 mL). Stirring was continued for 40 min after the addition was complete to achieve the maximum yield of 4. To cross-couple, 3 equiv (15 mmol) of the organic halide substrate was injected, neat, followed by injection of the internal standard (decane, 2 mmol). The cross-coupling reactions utilizing acid chloride substrates were carried out in DME, the rest were run in THF. The reactions were quenched with dilute HCl at the end of 1 h and quantitated by GC. The products were identified by comparing their properties to those of authentic samples. All products were commercially available except for 4-benzoylacetophenone (8), which was synthesized by the method of Zelinski, Turnquest, and Martin.[14]

Formation and Reactions of 5-Cuprio-2-pentanone (12). The 5-cuprio-2-pentanone was formed by the procedure of Wehmeyer and Rieke.[7a] In a typical reaction, activated copper (10 mmol) was produced by mixing a solution of lithium naphthalenide (11 mmol) in THF (15 mL) with a solution of CuI·P(*n*-Bu)$_3$ (10 mmol) and P(*n*-Bu)$_3$ (16 mmol) in THF (5 mL) and allowing the combined mixtures to stir for 5 min. The temperature was lowered to −78 °C, and 11 was added (4 mmol) along with the internal standard (decane, 2.05 mmol). The solution was

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[8] Yoshizawa, T.; Yamamoto, I.; Yamamoto, R. *Botyu-Kagaku* **1970**, *35*, 43.

[9] The following papers and references cited therein describe a wide variety of procedures for the synthesis of the queen substance: (a) Ishibashi, H.; Ohnishi, M.; Senda, T.; Ikeda, M. *Synth. Commun.* **1989**, *19*, 857. (b) Villiéres, J.; Rambaud, M.; Graff, M. *Ibid.* **1985**, *15*, 569. (c) Naoshima, Y.; Ike, H.; Ogawa, T.; Nakayama, T.; Kondo, H. *Agric. Biol. Chem.* **1984**, *48*, 2151. (d) Trost, B. M.; Salzmann, T. W. *J. Org. Chem.* **1975**, *40*, 148.

[10] Ginah, F. O.; Donovan, T. A., Jr.; Suchan, S. D.; Pfennig, D. R.; Ebert, G. W. *J. Org. Chem.* **1990**, *55*, 584.

[11] McCarty, F. J.; Tilford, C. H.; Van Campen, M. G., Jr. *J. Am. Chem. Soc.* **1957**, *79*, 472.

[12] Strassburg, R. W.; Gregg, R. A.; Walling, C. *J. Am. Chem. Soc.* **1947**, *69*, 2141.

[13] Dieter, R. K.; Pounds, S. *J. Org. Chem.* **1982**, *47*, 3174.

[14] Zellinski, R. P.; Turnquest, B. W.; Martin, E. C. *J. Am. Chem. Soc.* **1951**, *73*, 5521.

stirred for 20 min at -78 °C to maximize the yield of 12. To cross-couple, 3 equiv (12 mmol) of the alkyl halide substrate was injected, neat, into the organocopper solution and the reaction continued with stirring at -78 °C for 1 h. To homocouple 12 to form 17, the temperature was maintained at -78 °C and O_2 was bubbled into the solution for 10 min. The reactions were quenched with dilute HCl and quantitated by GC. The products were identified by comparing their properties of those of authentic samples.

2-Hexanone (13): bp 129 °C (lit.[15] bp 127 °C); 2,4-DNP, mp 105-106 °C (lit.[15] mp 106 °C).

2-Nonanone (14): bp 190-193 °C (lit.[16] bp 192 °C); semicarbazone, mp 119-120 °C (lit.[16] mp 119 °C).

7-Octen-2-one (15): bp 102-104 °C (20 Torr) [lit.[17] bp 95-97 °C (12 Torr)]; lit.[17] IR matches that of the sample.

6-Phenylhexan-2-one (16): bp 105 °C (3 Torr) [lit.[18] bp 133-135 °C (13 Torr)]; lit.[18] IR matches that of the sample; ^{13}C NMR ($CDCl_3$) δ 206, 142, 128, 126, 43, 36, 32, 30, 24.

2,9-Decanedione (17): bp 105-110 °C (5 Torr) [lit.[19] bp 137 °C (12 Torr)]; IR (neat) 3000-2860, 1730, 1650, 1470, 1450, 1420, 1365 cm^{-1}. For comparison, an authentic sample was synthesized by the method of Alper, Januszkiewicz, and Smith.[20]

Formation and Reactions of 6-Cuprio-2-hexanone (19). Commercially available 6-bromo-2-hexanone (Lancaster Synthesis) was fractionally distilled shortly before use (bp 110-112 °C (20 Torr)). The procedure was the same as that given for the formation and reactions of 5-cuprio-2-pentanone with the following changes: a solution of lithium biphenylide was used in place of lithium naphthalenide, 6-bromo-2-hexanone replaced 5-bromo-2-pentanone, and the alkyl halide substrates used for cross-coupling were allyl bromide (Aldrich) to produce 8-nonen-2-one and methyl 4-bromocrotonate (Aldrich) to produce methyl (*E*)-9-oxo-2-decenoate.

8-Nonen-2-one (20): bp 102-104 °C (20 Torr) [lit.[21] 95-97 °C (12 Torr)]; 2,4-DNP, mp 47-49 °C (lit.[21] 50 °C); IR (neat) 3070, 2930, 1720, 1640, 1415, 1365, 910 cm^{-1}. For comparison, an authentic sample was synthesized by the method of Conia and Leyendecker.[21]

Methyl (*E*)-9-oxo-2-decenoate (21): bp 255 °C (20 Torr) [lit.[22] bp 86-91 °C (0.0133 mbar)]; lit.[22] IR and ^{1}H NMR match those of the sample. For comparative purposes, 21 was also synthesized by another method of our own design.[23]

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Registry No. 1, 7308-67-0; 2, 21591-31-1; 3, 7440-50-8; 4, 115591-50-9; 5, 6136-66-9; 6, 134-84-9; 7, 18220-90-1; 8, 53689-84-2; 9, 3016-97-5; 10, 13329-40-3; 11, 3884-71-7; 12, 134388-70-8; 13, 591-78-6; 14, 821-55-6; 15, 3664-60-6; 16, 14171-89-2; 17, 16538-91-3; 19, 134361-43-6; 20, 5009-32-5; 21, 1189-64-6; 6-bromo-2-hexanone, 10226-29-6; 4-bromoacetophenone, 99-90-1.

---

(15) Shriner, R. L.; Fuson, R. C. *The Systematic Identification of Organic compounds*; Wiley & Sons: New York, 1948.

(16) Ruzicka, L.; Brugger, W. *Helv. Chim. Acta* **1926**, *9*, 339.

(17) Rouessac, F.; Le Perchec, P.; Conia, J. M. *Bull. Soc. Chim. Fr.* **1967**, *3*, 818.

(18) Cologne, J.; Brunil, J. C. *Compt. Rend.* **1962**, *225*, 161.

(19) Feugeas, C. *Bull. Soc. Chim. Fr.* **1963**, *11*, 2568.

(20) Alper, H.; Januszkiewicz, K.; Smith, D. J. H. *Tetrahedron Lett.* **1985**, *26*, 2263.

(21) Conia, J. M.; Leyendecker, F. *Bull. Soc. Chim. Fr.* **1967**, *3*, 830.

(22) Bestmann, H. J.; Schmidt, M.; Schobert, R. *Synthesis* **1988**, *1*, 49.

(23) Ebert, G. W. *Synth. Commun.*, in press.

Studies Dealing with Cycloaddition and Sigmatropic Reactions of Cyclopropenyl-Substituted Indenes[†]

Albert Padwa,* Diana M. Cordova, and Mitchell J. Pulwer

Department of Chemistry, Emory University, Atlanta, Georgia 30322

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The thermal and photochemical reactions of a number of substituted cyclopropenylindenes have been studied. The thermolysis of these systems resulted in a series of 3,3-sigmatropic rearrangements. The product distribution parallels the expected relative order of thermodynamic stabilities of the indenes. The major product obtained upon extended heating corresponds to the isomer in which the double bonds are in conjugation with the phenyl groups on both the indene and cyclopropene rings. Direct irradiation of 1-methyl-1-(1-methyl-2,3-diphenyl-2-cyclopropen-1-yl)-3-phenylindene afforded a mixture of unsymmetrical cyclopropenes together with a cyclopropa[*cd*]pentalene. The formation of the products can be rationalized in terms of two competing pathways. One path involves σ-bond cleavage to produce a diradical pair which undergoes recombination to give the rearranged cyclopropene. The alternate pathway proceeds by ring opening of the singlet state of the cyclopropene to a vinylcarbene intermediate. Attack of the vinylcarbene carbon on the neighboring double bond produces the cyclopropa[*cd*]pentalene ring skeleton. The sensitized photolysis was found to give intramolecular [2 + 2]-cycloadducts. The observed regiospecificity of the reaction is understandable in terms of formation of the most stable diradical intermediate.

Since its discovery by Cope in the early 1940s,[1] the Cope rearrangement has become one of the most thoroughly investigated chemical reactions.[2-13] Despite all of this study, the mechanism of the 3,3-sigmatropic shift of 1,5-hexadienes still remains clouded.[14-19] At issue is whether

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[†] Dedicated to my colleague David J. Goldsmith on the occasion of his 60th birthday.

(1) Cope, A. C.; Hardy, E. M. *J. Am. Chem. Soc.* **1940**, *62*, 441. Cope, A. C.; Hofmann, C. M.; Hardy, E. M. *Ibid.* **1941**, *63*, 1852. Cope, A. C.; Levy, H. *Ibid.* **1944**, *66*, 1684.