$J_{10,11}$ = 15.1 Hz, Hz, $J_{10,9}$ = 10.5 Hz), 5.87–5.56 (m, 4 H), 5.46–5.17 (m, 3 H), 4.54–4.42 (m, 1 H, H-5), 4.23–4.12 (m, 1 H, H-12), 3.61 (s, 3 H, $COOCH_3$), 2.30–2.08 (m, 4 H), 1.87–1.77 (m, 2 H), 1.62–1.37 (m, 4 H), 1.32–1.12 (m, 6 H), 1.10 (s, 9 H, *t*-Bu), 1.05 (s, 9 H, *t*-Bu), 0.85 (t, 3 H, H-20, J = 6.2 Hz); IR (thin film), ν_{max} (cm^{-1}) 3070 (m), 3045 (m), 3015 (m), 2930 (s), 2855 (s), 1739 (s), 1589 (w), 1460 (m), 1425 (s), 1360 (m), 1103 (s), 1070 (s), 992 (m), 815 (m), 732 (m), 695 (m).

Leukotriene B_4 (1). To a magnetically stirred solution of **18** (52 mg, 0.06 mmol) in THF (2.0 mL) at room temperature was added *n*-Bu_4NF (1 M; THF, 0.60 mmol) under an argon atmosphere. The reaction mixture was stirred for 5 h (TLC monitoring) and then diluted with ether (50 mL) and brine (2 mL). The aqueous layer was reextracted with ether (5 × 25 mL) and dried ($MgSO_4$). Concentration of the combined ether solution and purification by either flash column chromatography (silica gel, 5→50% CH_3OH in ether) or preparative-layer chromatography (silica gel, 2% methanol in ether, R_f = 0.22) provided LTB_4 (**1**) (16 mg, 73%). RP-HPLC (Altex ultrasphere, ODS, 5-μm 4.6-mm × 25-cm column; CH_3OH:H_2O:AcOH:concentrated NH_4OH, 67:33:0.08:0.07) showed ≥95% purity for synthetic LTB_4: ^1H NMR (250 MHz, $CDCl_3$, Me_4Si^4) δ 6.47 (dd, J = 14.0 and 12.0 Hz, 1 H, H-8), 1.28 (m, 2 H, H-9, H-10), 6.09 (t, J = 11.0 Hz, 1 H, H-7), 5.78 (dd, J = 15.0 and 6.5 Hz, 1 H, H-11), 5.65–5.25 (m, 4 H, H-6, H-14, H-15, O*H*), 4.62 (m, 1 H, H-5), 4.23 (m, 1 H,, H-12), 2.35 (m, 4 H, CH_2), 2.04 (m, 2 H, CH_2), 1.80–1.15 (m, 12 H, CH_2, O*H*), 0.90 (t, J = 6.5 Hz, 3 H, H-20); IR (thin film) ν_{max} (cm^{-1}) 3360 (s, OH), 3020 (w), 2970 (m), 2935 (s), 2860 (m), 1715 (s, CO). The methyl ester diacetate of LTB_4 exhibited identical ^1H NMR data with those reported previously,[17] and its retention time on the above mentioned reverse-phase HPLC conditions was identical with that of natural LTB_4.[16]

Supplementary Material Available: Listing of selected spectroscopic data (^1H NMR, IR) of compounds **2**, **3**, **19**, and **22–24** (3 pages). Ordering information is given on any current masthead page.

Chloroacetylenes as Michael Acceptors. 3. Mechanism and Synthetic Utility of Enolate Reactions with Halogenated Olefins and Chloroacetylenes

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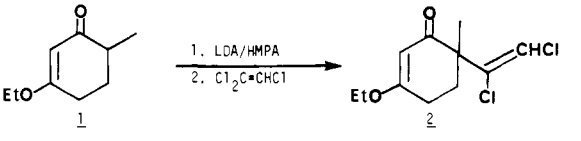
Contribution from the Department of Chemistry, University of Rochester, Rochester, New York 14627, and the Department of Chemistry, Baker Laboratory, Cornell University, Ithaca, New York 14853. *Received May 19, 1983*

Abstract: Condensations of tertiary conjugated enolates with a variety of polyhalogenated olefins were explored. Trichloroethylene led to (*E*)-1,2-dichlorovinyl adducts which could be further converted to acetylenes in good yield. 1,2-Dichloro-1-fluoroethylene (1/1 cis/trans) led to a single regio- and stereoisomeric adduct ((*E*)-2-chloro-1-fluorovinyl) in 30% yield, whereas tetrachloroethylene led to a chloroethynyl adduct in 25% yield. Attempts to broaden the scope of these condensations to include other types of enolates were unsuccessful. Condensations of enolates with hexachlorobutadiene were also examined. The kinetic lithium enolates of ethyl isobutyrate and of 2,6-dimethyl-2-cyclohexen-1-one led to trichloroenyne adducts in 63% and 56% yields, respectively, whereas the sodium enolate of diethyl methylmalonate gave a pentachlorodienyl adduct in 61% yield. The trichloroenyne adducts were shown to arise from a perchlorobutenyne intermediate. Several unusual transformations of the hexachlorobutadiene adducts are also described. A mechanistic investigation demonstrated that the trichloroethylene condensation proceeds by a carbanion chain mechanism involving dichloroacetylene as an obligatory intermediate. This prompted the general examination of enolate condensations with 1-chloroalkynes. Preformed dichloroacetylene and phenylchloroacetylene reacted with a variety of tertiary enolates in 64–90% yields to give α-chloroethynyl and α-phenylethynyl ketones and esters. The chloroethynyl group was smoothly converted to the ethynyl group (74–77% yields) or vinyl group (94–98% yields). 1-Chloro-1-hexyne did not react with enolates, whereas (phenylthio)chloroacetylene reacted to yield α-phenylthioethynyl adducts in 43–75% yields, pointing to a probable addition–elimination mechanism for these additions to 1-chloroalkynes.

The development of new methods for carbon–carbon bond formation is one of the fundamental challenges confronting the synthetic chemist. In this context, condensation chemistry of ketone and ester enolates has been a cornerstone of synthetic methodology.[1] Polyhalogenated ethylenes have enjoyed a much more modest role in carbon–carbon bond formation.[2-4] To date, there are only scattered references to the reaction between simple polyhalogenated ethylenes and carbon nucleophiles. Indeed, this type of reaction is limited to the addition of aryl- and alkyllithiums to polyhalogenated ethylenes to give addition or substitution products.[4] This paper describes our efforts to harness the powerful chemistry of the enolate to the repertoire of halogenated ethylene chemistry.

Results and Discussion

Condensation of Enolates with Trichloroethylene.[5] When the kinetic lithium enolate derived from 3-ethoxy-6-methyl-2-cyclohexenone (**1**) was reacted with 1.0 equiv of trichloroethylene, the major product was the dichlorovinyl ketone **2** (eq 1). The yield



1 2 (1)

† Department of Chemistry, University of Rochester.
‡ Department of Chemistry, Cornell University.

(1) House, H. O. "Modern Synthetic Reactions", 2nd ed.; W. A. Benjamin: Reading, MA 1972; Chapters 9 and 10.
(2) For such condensations involving metalated derivatives with electrophiles see the following examples: (a) Wakefield, B. J. "The Chemistry of Organolithium Compounds"; Pergamon Press: New York, 1974. (b) Tarrant, P.; Johncock, P.; Savory, J. *J. Org. Chem.* **1963**, *28*, 839. (c) Drakesmith, F. G.; Richardson, R. D.; Stewart, O. J.; Tarrant, P. *Ibid.* **1968**, *33*, 286. (d) Köbrich, G.; Flory, K. *Chem. Ber.* **1966**, *99*, 1773. (e) Negishi, E. "Organometallics in Organic Synthesis"; Wiley: New York, 1980; Vol. 1. (f) Sauvetre, R.; Masure, D.; Chuit, C.; Normant, J. F. *C. R. Acad. Sci.* **1979**, *288*, 335. (g) Sauvetre, R.; Masure, D.; Chuit, C.; Normant, J. F. *Synthesis* **1978**, 128. (h) Masure, D.; Chuit, C.; Sauvetre, R.; Normant, J. F. *Ibid.* **1978**, 458.

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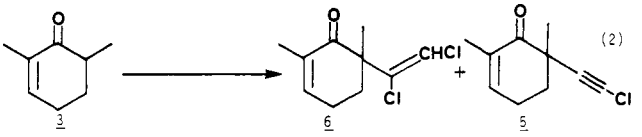
of **2** was 60% after distillation, with the bulk of the remainder being unreacted **1**. The structure of **2** was supported by ^1H NMR, ^{13}C NMR, and mass spectra and elemental analysis. The regiochemistry of the side chain was indicated by the δ 6.36 singlet for the —CCl=C*H*Cl proton, in contrast to the alternative —CH=CCl_2 unit, which should give a proton signal near δ 5.8–5.9.[6]

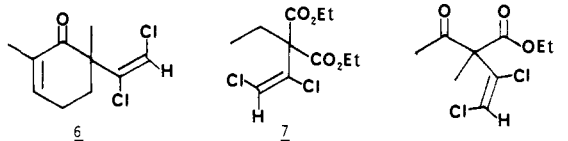
Under similar conditions, 2,6-dimethyl-2-cyclohexen-1-one (**3**) reacted to give a crystalline dichlorovinyl compound **6** in approximately 50% yield with 40% recovered starting material (eq 2). Longer reaction times led to better yields of **6** but were



3 6 5

accompanied by the formation of a second product, identified by IR, mass, ^1H NMR, and ^{13}C NMR spectra as the chloroacetylene **5**.

Although the regiochemistry of the side chain in **6** was deduced from the ^1H NMR spectrum, the stereochemistry could not be so defined. Since dichlorovinyl adduct **6** was a low-melting solid, single-crystal X-ray crystallography was used to confirm the regiochemistry and demonstrate the stereochemistry as *E* (**6**).[5]

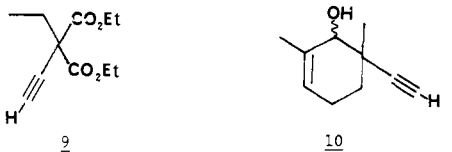


6 7 8

This dichlorovinylation of enolates with trichloroethylene worked well for tertiary enolates of conjugated ketones. However, attempted condensations under similar conditions with enolates derived from (1) a tertiary saturated ketone (2,6-dimethylcyclohexanone) or ester (ethyl isobutyrate), (2) a secondary conjugated ketone (cyclohexenone), or (3) a dimethylhydrazone (i.e., metalloenamine of cyclohexenone) led to unidentifiable products. In all cases, the characteristic proton NMR signal of —ClC=C*H*Cl was not observed.

The enolate of the active methylene compound diethyl ethylmalonate was found to react with trichloroethylene under more vigorous conditions to yield 64% of analytically pure dichlorovinyl derivative **7**. Under similar conditions, ethyl 2-acetylpropionate gave dichlorovinyl derivative **8** in 32% yield. In both cases, the stereochemistry was assumed to be *E*.

Of special interest was the synthetic utility of these dichlorovinyl adducts. Compound **7** was directly converted to the acetylenic derivative **9** in 63% yield with *tert*-butyllithium. Attempts to

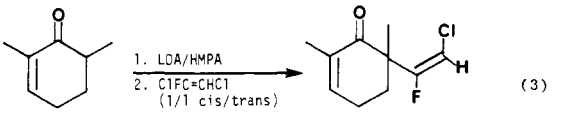


9 10

perform a similar direct transformation using *tert*-butyllithium on dichlorovinyl adduct **6** led only to 1,2-addition of *tert*-butyllithium to the enone. This problem was circumvented by prior carbonyl reduction with diisobutylaluminum hydride, followed by excess *n*-butyllithium to give acetylenic alcohol **10** in 70% yield for the two-step transformation.

Condensation of Enolates with Other Polyhalogenated Ethylenes. Frustrated by the limited scope of the trichloroethylene condensation, we turned our attention to reaction of enolates with other simple polyhalogenated ethylenes. To make comparisons meaningful, we decided to survey the reaction of a single enolate with a variety of ethylenes. Chosen for this purpose was the kinetic C-6 lithium enolate of 2,6-dimethyl-2-cyclohexen-1-one because of its success in the trichloroethylene condensations and its ready availability.

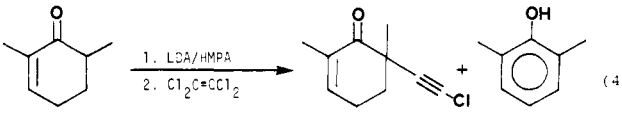
When the lithium enolate of 2,6-dimethyl-2-cyclohexen-1-one was treated with 1 equiv of CClF=CHCl, a single reaction product, identified by ^1H NMR and mass spectrometry[7] as **11**, was isolated in 30% yield after medium-pressure chromatography (with 60–70% recovered starting material) (eq 3). The vinyl



11

proton at 5.98 ppm in the ^1H NMR spectrum of **11** with J_{HF} of 14 Hz established both the regiochemistry and stereochemistry of the side chain as shown.[8] More interesting was the mechanistic implication of this result. We began with a 1/1 mixture of cis/trans CClF=CHCl, yet we obtained a single regio- and stereochemically pure product. The meaning of this observation will be addressed later in this paper.

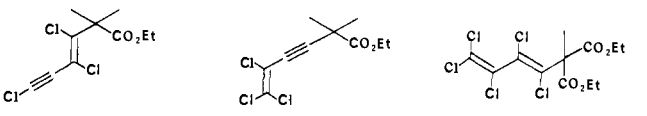
Tetrachloroethylene reacted with the lithium enolate of 2,6-dimethyl-2-cyclohexen-1-one under similar conditions to yield chloroethynyl adduct **5** and 2,6-dimethylphenol (both in 20–25% yield after MPC) (eq 4). The mechanistic interpretation of this



5

result will also be discussed later in this paper. One last example was the reaction of 1 equiv of 1,1-dichloro-2,2-difluoroethylene under identical conditions to give a quantitative yield of 6-chloro-2,6-dimethyl-2-cyclohexen-1-one.

Enolate Condensations with Hexachlorobutadiene (HCBD).[9] When the lithium enolate of ethyl isobutyrate was treated at −78 °C with 1 equiv of HCBD, we observed the formation, in 35% yield, of an adduct with molecular formula $C_{10}H_{11}Cl_3O_2$, having an intense UV absorption at λ_{max} (MeOH) 245 (ϵ 13 500) and 251 nm (ϵ 13 800), ν_{max} (neat) 1740, 1560 cm^{-1}, and mass, ^1H NMR, and ^{13}C NMR spectra consistent with either structure **12** or **13**. Catalytic hydrogenation of this product (5% Pd/C, H_2,



12 13 14

EtOH/Et_3N) gave ethyl 2,2-dimethylhexanoate, confirming the carbon skeleton.

We also observed the formation of a pentachloro adduct $C_{12}H_{13}Cl_5O_4$ (in 61% yield) when the sodio derivative of diethyl methylmalonate (from 1 equiv each of NaH and HMPA) was treated with HCBD under more vigorous conditions (refluxing THF, 35 h). We have assigned structure **14** to this adduct based on ^{13}C NMR and ^1H NMR. The carbon skeleton was again established by perhydrogenation to diethyl *n*-butylmethylmalonate.

Because of the similarity between these initial observations and our earlier results with trichloroethylene, we sought to elucidate the scope and the mechanism of the HCBD reaction. Optimum

(3) For examples of transition metal-catalyzed coupling, see: (a) Ratovelomanana, V.; Linstrumelle, G. *Tetrahedron Lett.* **1981**, 315. (b) Tamao, K.; Sumitani, K.; Kumada, M. *J. Am. Chem. Soc.* **1972**, *94*, 4374. (c) Zweifel, G.; Lewis, W.; On, H. P. *Ibid.* **1979**, *101*, 5101.

(4) For reactions with carbon nucleophiles, see: (a) Dixon, S. *J. Org. Chem.* **1956**, *21*, 400. (b) Okuhara, K. *Ibid.* **1976**, *41*, 1487.

(5) Kende, A. S.; Benechie, M.; Curran, D. P.; Fludzinski, P.; Swenson, W.; Clardy, J. *Tetrahedron Lett.* **1979**, 4513.

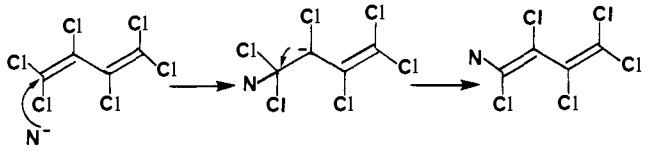
(6) Goldstein, J. H.; Reddy, G. S. *J. Chem. Phys.* **1962**, *36*, 2644.

(7) Williams, H. D.; Fleming, I. "Spectroscopic Methods in Organic Chemistry", 2nd ed.; McGraw-Hill: New York, 1973; p 155.

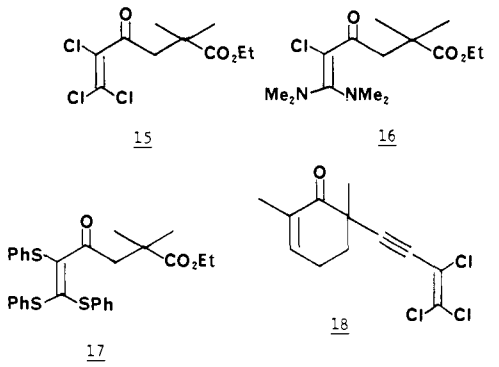
(8) See ref 7, p 141.

(9) For a preliminary communication, see: Kende, A. S.; Fludzinski, P.; Hill, J. H. *J. Am. Chem. Soc.* **1981**, *103*, 2904.

Scheme I. Addition–Elimination Mechanism for Addition to HCBD



yields were obtained when 2 equiv of the lithium enolate of ethyl isobutyrate was treated with 1 equiv of HCBD to give a 63% yield of the adduct. Hydration of the adduct under vigorous conditions gave the highly reactive trichloroenone **15**, thereby establishing

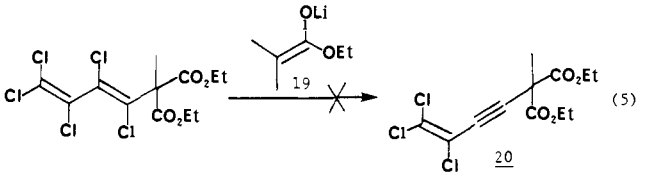


13 as the correct structure for the primary adduct. Treatment of the trichloroenone **15** with an excess of anhydrous dimethylamine or with an excess of sodium thiophenolate gave adducts **16** and **17** in 86% and 65% yields, respectively.

The kinetic C-6 lithium enolate (1 equiv) of 2,6-dimethyl-2-cyclohexen-1-one also reacted with HCBD (0.5 equiv) to give a 56% yield of a condensation product **18** having spectroscopic properties entirely analogous to **13**.

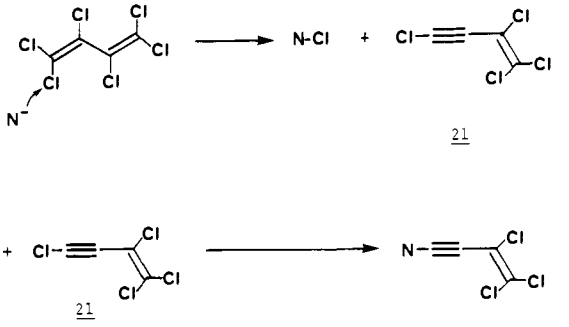
Mechanism of HCBD Condensation. The HCBD condensations exhibit two different product types. The formation of the diethyl (pentachlorobutadienyl)methylmalonate adduct **14** is readily explained on the basis of an addition–elimination mechanism (Scheme I), whereby the enolate nucleophile (N^-) adds to the HCBD acceptor to give an inductively and resonance stabilized perchloroallyl anion, which then ejects halide.[10]

The observed formation of trichloroenyne adduct (**13**) from ethyl isobutyrate is less straightforward. For example, the initial formation of a pentachlorobutadienyl isobutyrate adduct (cf. **14**) followed by reductive dechlorination of the internal dichloro olefin is formally possible, but such high regioselectivity for the hindered internal dichloro olefin in a second reduction step is unreasonable. Indeed, treatment of diethyl (pentachlorobutadienyl)methylmalonate (**14**) with the lithium enolate of ethyl isobutyrate (**19**) failed to produce any of the internal acetylene corresponding to **20** (eq 5).



We propose instead that perchlorobutenyne is an obligatory intermediate in the formation of trichloroenyne adducts **13** and **18**. Thus, the initial step in the condensation would be attack by the isobutyrate enolate (N^-) on HCBD to give ethyl α-chloroisobutyrate and perchlorobutenyne **21**. Reaction of a second molecule of the enolate at the terminal ethynyl carbon, possibly by addition–elimination, would yield the observed product (Scheme II).

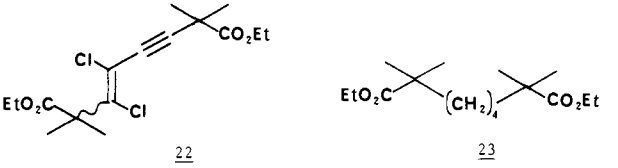
Scheme II. Mechanism Invoking Perchlorobutenyne as an Intermediate in the Condensation with HCBD



The suggested reductive dechlorination of HCBD to form **21** is consistent with the isolation of 62% of ethyl α-chloroisobutyrate from the reaction of 2 equiv of the lithium enolate of ethyl isobutyrate with 1 equiv of HCBD. Subsequent addition–elimination to perchlorobutenyne (**21**) of an enolate molecule is analogous to certain reactions of perchlorobutenyne observed by Roedig for nitrogen and sulfur nucleophiles.[11] Indeed, reaction of the lithium enolate of ethyl isobutyrate with preformed perchlorobutenyne[12] led to product **13** in 76% isolated yield.

An alternative mechanistic possibility is transfer alkylation,[13] whereby perchlorobutenyne would react with a nucleophile to yield a chlorinated nucleophile and an acetylide, followed by displacement to yield product. This possibility was experimentally precluded by the observation that reaction of 1-lithio-1-hexyne with ethyl α-chloroisobutyrate gave no detectable (<10%) ethyl 2,2-dimethyl-3-octynoate. The possibility of electron transfer from enolate to halo olefin (or haloalkyne) in some of the postulated reduction or addition–elimination steps cannot be excluded.[14] However, the intervention of a radical chain mechanism[15] is precluded by the experimental observation that 0.10 equiv of di-*tert*-butylnitroxide led to only a minor decrease in the yield.

It is clear from these results that the formation of a new carbon–carbon bond with HCBD proceeds by at least two mechanisms: direct addition–elimination or secondary condensation with an intermediate 1-chloroalkyne. Furthermore, the choice between these two mechanisms is delicately balanced. Thus, reaction of our initial adduct **13** with 1.1 equiv of the lithium enolate of ethyl isobutyrate led to a 64% yield of a new condensation product, **22**,



as a mixture of *E*/*Z* isomers. Analytical and spectroscopic data, along with perhydrogenation to diester **23**, established the structure of **22** to be the dichloroenyne addition–elimination product shown. This results indicates that the addition–elimination pathway of Scheme I is not limited to the softer malonate anion, but also depends, in a subtle manner, on the structure of the haloolefin acceptor. Unfortunately, attempts to repeat this second condensation between **13** and the lithium enolate of 2,6-dimethyl-

(10) For nucleophilic additions to HCBD, see: (a) Uehara, A. *Sci. Rep. Kanazawa Univ.* **1980**, *25*, 83 (*Chem. Abstr.* **1981**, *95*, 168593*f*). (b) Roedig, A.; Ibis, C.; Zaby, G. *Chem. Ber.* **1981**, *114*, 684. (c) Mizuno, M.; Cava, M. P. *Heterocycles*, **1980**, *14*, 415.

(11) (a) Roedig, A.; Faurē, M. *Chem. Ber.* **1975**, *109*, 2159. (b) Roedig, A.; Zaby, G. *Liebigs Ann. Chem.* **1979**, *1979*, 1606, 1614.

(12) The yield of **13** from HCBD drops precipitously when less than 2 equiv of the lithium enolate of ethyl isobutyrate is used. This is in accordance with our mechanism invoking perchlorobutenyne as an intermediate. For the preparation of perchlorobutenyne, see: Jenkins, D. K. *Chem. Ind.* (*London*) **1971**, 254.

(13) Melvin, L. S., Jr.; Trost, B. M. *J. Am. Chem. Soc.* **1972**, *94*, 1790. Cf. Dickstein, J. I. *Acc. Chem. Res.* **1976**, *9*, 358.

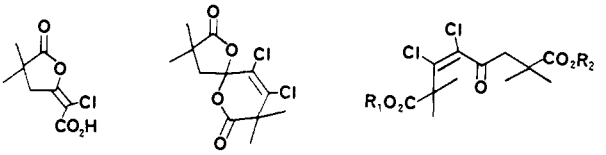
(14) Kornblum, N. *Angew. Chem., Int. Ed. Engl.* **1975**, *14*, 734.

(15) (a) Russell, G. A.; Hershberger, J.; Owens, K. *J. Am. Chem. Soc.* **1979**, *101*, 1312. (b) Russell, G. A.; Jawdosiuk, M.; Ros, F. *Ibid.* **1979**, *101*, 3378. (c) Bard, R. R.; Bunnett, J. F.; Creary, X.; Tremelling, M. J. *Ibid.* **1980**, *102*, 2852.

2-cyclohexen-1-one were unsuccessful and led only to recovered starting materials.

Lactonization of Perchlorobutenyne Adducts. The regiochemistry of the initial HCBD adduct with ethyl isobutyrate was established by hydration to trichloroenone **15**. However, in an attempt to hydrate the triple bond of ester **13** in concentrated H_2SO_4 (room temperature, 24 h), an unexpected transformation occurred to give a 50% yield of a crystalline $C_8H_9ClO_4$ acid (**24**), mp 180.5–181.5 °C, having strong carbonyl stretching frequencies at 1830 and 1695 cm^{-1} as well as a UV absorption in methanol at 234 nm (ϵ 11 700). The ^1H NMR spectrum showed a two-proton singlet at δ 3.24 and a six-proton singlet at δ 1.38. The structure of acid **24** was confirmed by X-ray crystallography.

Treatment of the diester **22** with concentrated H_2SO_4 (room temperature, 51 h) led to 53% yield of a neutral $C_{12}H_{14}Cl_2O_4$ crystalline product (**25**), mp 81–82 °C. The presence of the two lactone rings was suggested by the IR maxima at 1815 and 1780 cm^{-1}, and the presence of the spiroketal unit was supported by the ^{13}C NMR signal of δ 103.9. Reaction of dilactone **25** with methanol occurred at room temperature (24 h, or in 1 h with catalytic HCl) to give a quantitative yield of a crystalline $C_{13}H_{18}Cl_2O_5$ ester acid, mp 137–139 °C. Regiochemistry of ring opening to **26** rather than **27** was supported by the stability of



24 25 26 R_1=CH_3 R_2=H

27 R_1=H R_2=CH_3

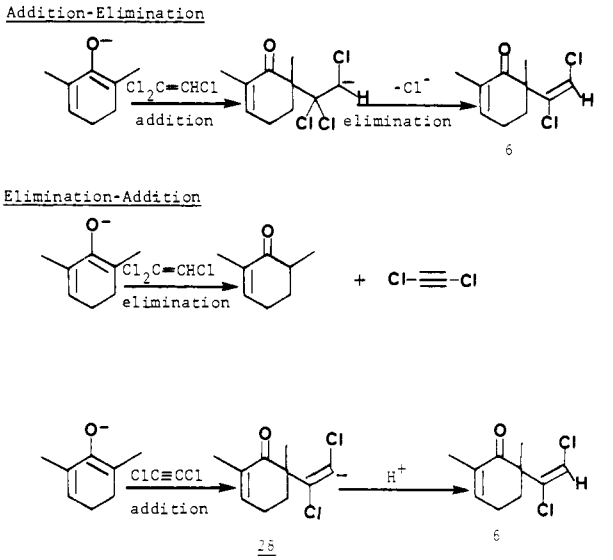
this acid toward decarboxylation even upon heating to 150 °C. Regioselective formation of lactones **24** and **25** is probably the result of γ-participation by the nearest ester group in the intramolecular solvation of the protonated triple bond.[16] Furthermore, the conversion of a terminal dichloromethylene unit to COOH (during formation of lactone **24**) has some analogy.[17]

The Mechanism of Enolate Condensation with Trichloroethylene.[18] At least four discrete mechanisms could be proposed to rationalize the initial results from alkylation of enolates with trichloroethylene, namely: (1) transfer alkylation;[13] (2) $S_{RN}1$ radical chain;[14,15] (3) addition–elimination;[19] and (4) elimination–addition.[20]

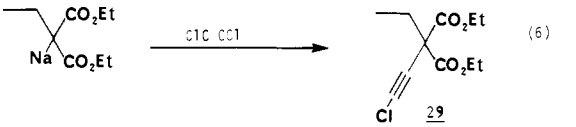
Several factors argued against transfer alkylation. First there was a complete absence of α-chloro ketones (a necessary intermediate) in the product mixture. Second, selective dechlorination of trichloroethylene in the first step to eventually yield a single regio- and stereochemical product was unlikely. Several factors also argued against an $S_{RN}1$ radical chain mechanism. Neither light nor t-Bu_2NO had any effect on product yield, making a radical chain mechanism untenable.[14]

Differentiation between the remaining two mechanisms, addition–elimination and elimination–addition, was less obvious (Scheme III). The observed formation of 1,2-dichlorovinyl rather than 2,2-dichlorovinyl products seems to argue against addi-

Scheme III. Addition–Elimination and Elimination–Addition Mechanisms for Enolate Dichlorovinylation



tion–elimination since the 2,2-regiochemistry would be anticipated. Indeed, Truce has shown that arylthiolate additions to vinylidene chlorides proceed in just such a regiochemical fashion.[21] Furthermore, Truce and others have shown that the reaction between trichloroethylene and arylthiolate or phenolate nucleophiles proceeds through initial formation of dichloroacetylene (ClC≡CCl).[22] On the other hand, our limited knowledge of the substitution chemistry of dichloroacetylene with carbon nucleophiles, based entirely on the work of Ott with sodium diethyl ethylmalonate to give chloroethynyl adduct **29** (eq 6), would predict



(6)

formation of α-chloroethynyl derivatives from a dichloroacetylene intermediate rather than the observed dichlorovinyl products.[23]

To determine the possible role of ClC≡CCl in our dichlorovinylations, we undertook to generate ClC≡CCl free of Cl_2C=CHCl and to examine its reactions with enolates. None of the published procedures were suitable in our hands for this purpose.[24] We ultimately found that addition of a solution of Cl_2C=CHCl in Et_2O at −78 °C to a suspension of $LiN(SiMe_3)_2$ in hexanes, followed by warming to room temperature over 3 h and then direct distillation at 30–36 °C through a 12-cm Vigreux column, reproducibly gave a distillate free of Cl_2C=CHCl that contained (GLC) 50% ClC≡CCl, 40% diethyl ether, and 10% hexanes.[25]

With a convenient preparation of dichloroacetylene in hand, we proceeded to test the possibility that the elimination–addition mechanism (Scheme III) might be operative for enolate dichlorovinylation. In particular, by treating the enolate of 2,6-dimethyl-2-cyclohexen-1-one with dichloroacetylene, we expected to observe the formation of dichlorovinyl adducts. Much to our surprise, when the kinetic C-6 lithium enolate of 2,6-dimethyl-2-cyclohexen-1-one was reacted with freshly distilled ClC≡

(16) (a) Castaner, J.; Pascual, J. *J. Chem. Soc.* **1958**, 3962. (b) Serrasota, F. *Tetrahedron* **1961**, *16*, 185. (c) Yamamoto, M. *J. Chem. Soc., Chem. Commun.* **1978**, 649. (d) Fuks, R.; Viehe, H. G. in "Chemistry of Acetylenes"; Viehe, H. G., Ed.; Marcel Dekker: New York, 1969; pp 520–532.

(17) (a) Nesmeyanov, A. N.; Friedlina, R. K.; Zakharkin, L. I.; Vasil'eva, E. I.; Kost, V. N.; Vasil'eva, T. T. *Zh. Obshch. Khim.* **1957**, *27*, 2418 (*Chem. Abstr.* **1960**, *52*, 7149c). (b) Hayashi, S.; Nakai, T.; Ishikawa, N. *Chem. Lett.* **1980**, 651.

(18) Kende, A. S.; Fludzinski, P. *Tetrahedron Lett.* **1982**, 2369.

(19) For a review on nucleophilic vinyl substitution, see: Rappoport, Z. *Acc. Chem. Res.* **1981**, *14*, 7.

(20) For a review of nucleophilic substitution on acetylenic carbon, see: (a) Viehe, H. G., "Chemistry of Acetylenes"; Marcel Dekker: New York, 1969. (b) Dickstein, J. I.; Miller, S. I. in "The Chemistry of the Carbon–Carbon Triple Bond"; Patai, S., Ed. of series: "Chemistry of Functional Groups"; Wiley: New York, 1978. (c) Miller, S. I.; Dickstein, J. I. *Acc. Chem. Res.* **1976**, *9*, 358.

(21) (a) Truce, W. E.; Boudakian, M. M. *J. Am. Chem. Soc.* **1956**, *78*, 2748. (b) Truce, W. E.; Boudakian, M. M. *Ibid.* **1956**, *78*, 2752. (c) Flynn, J., Jr.; Badiger, V. V.; Truce, W. E. *J. Org. Chem.* **1963**, *28*, 2298.

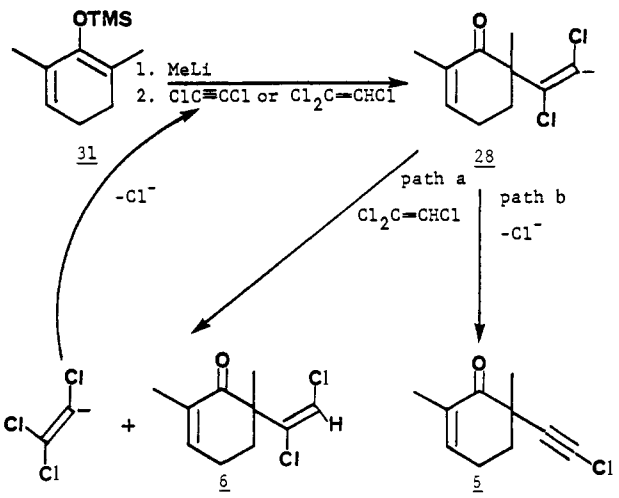
(22) (a) Truce, W. E.; Kassinger, R. *J. Am. Chem. Soc.* **1958**, *80*, 1916. (b) Backer, H. J.; Strating, J. *Recl. Trav. Chim. Pays-Bas* **1954**, *73*, 565. (c) Tanimoto, S.; Taniyasu, R.; Takahashi, T.; Miyake, T.; Okano, M. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 1931.

(23) Ott, E.; Dittus, G. *Chem. Ber.* **1943**, *76*, 80.

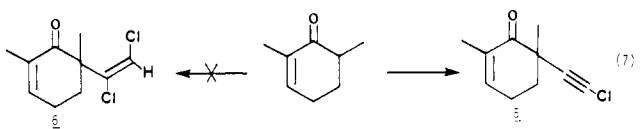
(24) (a) Wotiz, J. H.; Huba, F.; Vendley, R. *J. Org. Chem.* **1961**, *26*, 1626. (b) Riemschneider, R.; Brendel, K. *Liebigs Ann. Chem.* **1961**, *640*, 1. (c) Siegel, J.; Jones, R. A.; Kurlanski, L. *J. Org. Chem.* **1970**, *35*, 3199. (d) Kloster-Jensen, E. *Tetrahedron* **1971**, *27*, 33.

(25) Kende, A. S.; Fludzinski, P. *Synthesis* **1982**, 455.

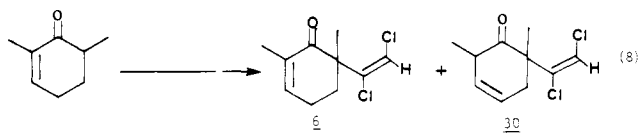
Scheme IV. Fate of Intermediate Vinyl Anion 28 Generated in Elimination–Addition Mechanism



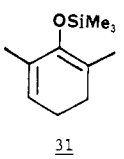
$CCl{\cdot}Et_2O$, no dichlorovinyl ketone **6** was formed. We obtained instead a 64% yield of α-chloroethynyl ketone **5** (eq 7). The



presence of excess ClC≡CCl or excess ketone gave a similar result. However, when the Li enolate was prepared by using $LiN(SiMe_3)_2$ instead of LDA, the major product was indeed **6** (40%), accompanied by a small amount of isomer **30** (eq 8).

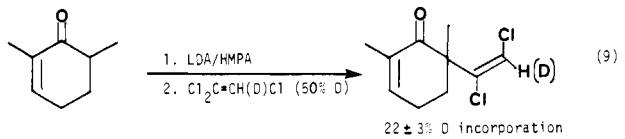


How could the choice of base have led to such distinctly different product types? As a working hypothesis, we considered the possibility that all of our data were consistent with the intermediacy of ClC≡CCl in enolate dichlorovinylation. The elimination–addition mechanism (Scheme III) could be operative, and the fate of the vinyl anion (**28**) first formed (Scheme IV) would depend on competition between Cl^- elimination (path b) to form **5** vs. proton abstraction from an in situ proton donor (path a) to yield **6**. On this basis, our data suggested that $Cl_2C{=}CHCl$ or $HN(SiMe_2)_2$ could serve as proton donors toward vinyl anion **28**, whereas the starting ketone or the less acidic amine $HN(i\text{-}Pr)_2$ could not. When $Cl_2C{=}CHCl$ served as the proton source, the trichlorovinyl anion generated could eliminate Cl^- and regenerate ClC≡CCl. Consistent with this hypothesis were the observations that the Me_3Si enol ether **31**, upon treatment with 1 equiv of MeLi,



followed by ClC≡CCl, gave only **5**, whereas **31** with MeLi and then $Cl_2C{=}CHCl$ gave only **6** (Scheme IV).

Our evidence indicated that the intermediacy of dichloroacetylene could indeed lead to dichlorovinyl adducts. However, we had not yet excluded the possibility of an addition–elimination mechanism. A reliable distinction between addition–elimination and elimination–addition was available from intermolecular competition in product formation using a mixture of $Cl_2C{=}CHCl$ and $Cl_2C{=}CDCl$. Addition–elimination would predict only a small secondary isotope effect, whereas the elimination–addition mechanism for enolate dichlorovinylation could lead to a potentially large primary isotope effect at the proton (deuteron) transfer step (path a, Scheme IV) to form the observed product **6**. A 10-fold excess of dry trichloroethylene containing 50 ± 2% $Cl_2C{=}CDCl$, prepared by partial deuteration of $Cl_2C{=}CHCl$ using $Ca(OD)_2$ in D_2O,[26] was reacted with the kinetic enolate in the usual manner. The resulting dichlorovinylation product **6** was analyzed by mass spectrometry and 400-MHz ^1H NMR. Careful integration of the vinyl proton against the β-proton of the enone (duplicate determination on two separate reaction products, after calibration using two separate reaction products obtained with 100% $Cl_2C{=}CHCl$) showed 0.78 ± 0.03 out of 1.0 vinyl proton corresponding to 22 ± 3% deuterium incorporation (eq 9). To



establish that loss of label did not occur after product formation, unlabeled dichlorovinyl adduct **6** was mixed with 5 equiv of 100% $Cl_2C{=}CDCl$ in THF and then treated with LDA/HMPA. No exchange of vinyl protons (<1%) could be detected under the usual reaction conditions.

Calculation of the path a isotope effect using the method of Melander and Saunders[27] gave $k_H/k_D = 3.7 \pm 0.5$, a primary isotope effect comparable to those reported for E_2 eliminations[28] and *clearly consistent with the elimination–addition mechanism for enolate dichlorovinylation.*

We concluded from our data that the reaction of the kinetic C-6 lithium enolate of 2,6-dimethylcyclohexenone with trichloroethylene to yield **6** does indeed proceed through a dichloroacetylene intermediate. The fate of the initial adduct between ClC≡CCl and an enolate, vinyl anion **28**, was determined by competition between unimolecular elimination of Cl^- and bimolecular proton abstraction. Hence, for the dichlorovinylation of enolates with trichloroethylene, an elimination–addition mechanism was operating, in which $Cl_2C{=}CHCl$ acted as proton source in quenching vinyl anion **28** and regenerated ClC≡CCl in a propagative fashion. These conclusions can be extrapolated to rationalize our results with other simple polyhalogenated ethylenes. Thus, by invoking chlorofluoroacetylene as an obligatory intermediate, we can rationalize the formation of a single regio- and stereochemically pure product from the enolate condensation with 1,2-dichloro-1-fluoroethylene (1/1 mixture of cis/trans) (eq 3). Similar arguments can be used to rationalize the results with tetrachloroethylene (eq 4). Here, the enolate nucleophile reacted at chlorine to give an α-chloro ketone (which eventually decomposed to the observed 2,6-dimethylphenol) and a trichlorovinyl anion, which decomposed to dichloroacetylene. Dichloroacetylene further reacted with enolate to yield the observed chloroethynyl adduct.

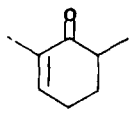
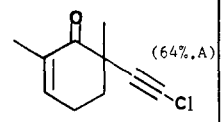
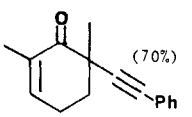
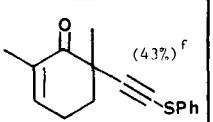
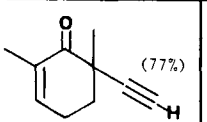
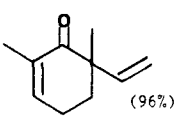
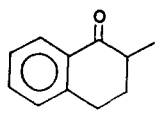
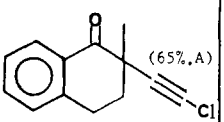
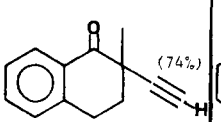
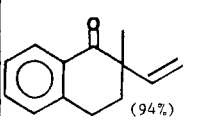
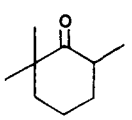
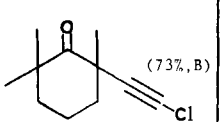
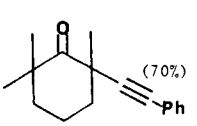
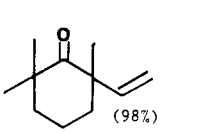
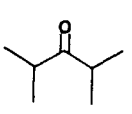
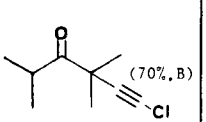
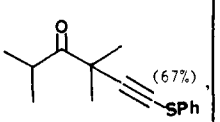
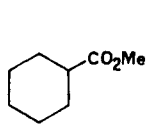
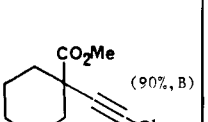
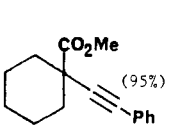
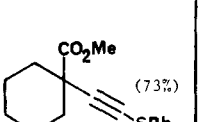
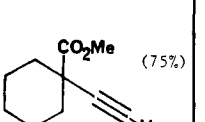
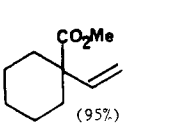
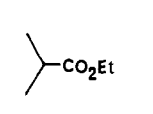
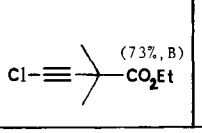
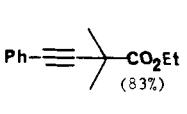
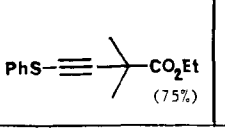
Chloroacetylenes as Michael Acceptors. We were delighted to find that dichloroacetylene underwent reaction with a variety of tertiary enolates to give chloroethynyl adducts in good to excellent yield (Table I, column 2). Method A, adding a dry ether solution of ClC≡CCl to the enolate at −78 °C and allowing the mixture to warm to room temperature over several hours, worked very well for enolates derived from conjugated ketones. However, this method led to little or no product when applied to tertiary enolates from saturated ketones or esters. Instead, method B, adding an enolate to a dry ether solution of ClC≡CCl at −20 °C and allowing the mixture to warm to room temperature over

(26) (a) Francis, J. E.; Leitch, L. C. *Can. J. Chem.* **1957**, *35*, 348. (b) The pK_a of trichloroethylene is 18. Butin, K. P.; Beletskaya, I. P.; Kashin, A. N.; Reutov, O. A. *J. Organomet. Chem.* **1967**, *10*, 197.

(27) Melander, L.; Saunders, W. H., Jr. "Reaction Rates of Isotopic Molecules"; Wiley: New York, 1980; p 95.

(28) (a) Miller, S. I.; Lee, W. G. *J. Am. Chem. Soc.* **1959**, *81*, 6313. (b) Landini, D.; Montanari, F.; Modena, G.; Nasa, F. *J. Chem. Soc. B* **1969**, 243. (c) Marchese, G.; Naso, F.; Modena, G. *Ibid.* **1968**, 958. (d) Marchese, G.; Naso, F.; Tangari, N.; Modera, G. *Ibid.* **1970**, 1196.

Table I

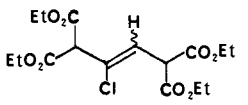
COLUMN 1 STARTING MATERIAL	COLUMN 2 CHLOROETHYNYL ADDUCT[a] (Yield[b], Method[c])	COLUMN 3 PHENYLETHYNYL ADDUCT[a] (Yield[b])	COLUMN 4 PHENYLTHIOETHYNYL ADDUCT[a] (Yield[b])	COLUMN 5 ETHYNYL DERIVATIVE[a] (Yield[d,e])	COLUMN 6 VINYL DERIVATIVE[a] (Yield[d])
	 (64%, A)	 (70%)	 (43%)[f]	 (77%)	 (96%)
	 (65%, A)			 (74%)	 (94%)
	 (73%, B)	 (70%)			 (98%)
	 (70%, B)		 (67%)		
	 (90%, B)	 (95%)	 (73%)	 (75%)	 (95%)
	 (73%, B)	 (83%)	 (75%)		

[a] All adducts gave a satisfactory elemental analysis and/or had ^{1}H NMR, MS, and IR consistent with proposed structures. [b] Yields are of purified products (chromatography or Kugelrohr distillation). [c] See Experimental Section. [d] Isolated yields, no purification necessary. [e] The less than quantitative yields represents a loss in mass balance; no starting materials were present by TLC or NMR. [f] Isolated with 30% recovered starting material.

several hours, worked very successfully (i.e., inverse addition, entries 3 through 6 in Table I, column 2). The failure of saturated ketone and ester enolates to react with dichloroacetylene under the conditions of method A is consistent with our earlier observation that they would not react with trichloroethylene (which involves a dichloroacetylene intermediate) under similar conditions.

In an attempt to simplify this chloroethynylation procedure, we tried to prepare dichloroacetylene in situ (adding trichloroethylene–ether to lithium hexamethyldisilazide at −78 °C and allowing the mixture to warm to 0 °C and cool to −20 °C and then adding enolate). Unfortunately, the hexamethyldisilazane present (after deprotonation of the ketone) served as a proton source and quenched the intermediate dichlorovinyl anion formed from enolate addition to dichloroacetylene, leading to mixtures of chloroethynyl and dichlorovinyl products.

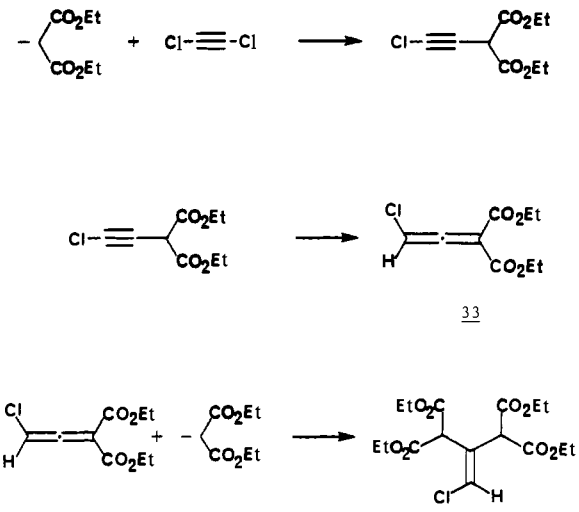
Attempts to react primary and secondary enolates with dichloroacetylene led to unidentifiable products. Presumably a proton exchange can occur between enolate and initially formed adduct, eventually leading to formation of byproducts. An exception was the reaction of sodium diethyl malonate with a dry ether solution of dichloroacetylene at room temperature for 16 h. This reaction was reported by Ott to give the presumed linear diadduct **32**.[23] Upon closer examination, we found this reaction



32

to involve presumptive formation of chloroallene **33**, which underwent a second Michael addition of malonate to give an 86% chromatographed yield of the "Ott diadduct", which was shown

Scheme V. Formation of the "Ott Diadduct"



33

34

by ^{1}H NMR to have chlorovinyl structure **34** (Scheme V).

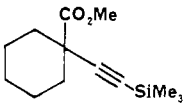
When tertiary enolates were treated with phenylchloroacetylene at −78 °C and allowed to warm to room temperature over several hours, phenylethynyl adducts were obtained in good to excellent yields.[29,30] Furthermore, this simple procedure was successful

(29) See ref 20b,c.

for a representative sampling of tertiary enolates (Table I, column 3). The reaction failed with diethyl ethylmalonate and a variety of primary or secondary enolates, including diethyl malonate.[31]

So far, we had been able to show that those chloroacetylenes where the β-substituent was chlorine or phenyl could serve as useful Michael acceptors. An attempt was made to use a chloroacetylene where the substituent was an alkyl group. Unfortunately, under our usual reaction conditions, 1-chloro-1-hexyne[32] did not react at all with enolates; only starting materials were recovered. Furthermore, 1-bromo-1-hexyne[30] reacted exclusively with bromine transfer; no desired products were detected. Thus, it appeared that mild stabilization of a carbanion intermediate β to the chlorinated carbon was necessary for the observed reactivity, in accord with an addition–elimination mechanism. Consistent with this was our finding that (phenylthio)chloroacetylene (PhSC≡CCl) was highly reactive toward tertiary enolates, leading to condensation products (Table I, column 4) in good yields under the same reaction conditions that were used for phenylchloroacetylene.

In keeping with this prerequisite of mild stabilization of a transient β carbanion, (trimethylsilyl)chloroacetylene[33] was subjected to our usual reaction conditions. With the enolate derived from 2,6-dimethyl-2-cyclohexen-1-one, a 44% yield of the silyl transfer product **31** was obtained, with 31% recovered starting material. When the enolate from methyl cyclohexanecarboxylate was used, a 38% yield of the desired (trimethylsilyl)ethynyl adduct **35** was obtained.



35

Synthetic Transformations of Michael Adducts. The chloroethynyl adducts (Table I, column 2) were cleanly converted by copper powder to the corresponding α-ethynyl adducts (no purification necessary) in good yield (Table I, column 5). Attempts to use other reagents to effect this transformation (*n*-Bu_3SnH, AIBN, refluxing benzene; *t*-BuLi; *n*-BuLi; or Zn dust in refluxing HOAc) led to recovered starting materials or decomposition products.

This two-step procedure (reaction with ClC≡CCl, and then dechlorination with Cu) for ethynylating tertiary ketone and ester enolates represents a facile approach to a previously difficult transformation. In contrast, ethynylation procedures for ketone enolates have been limited to the reaction between an acetylenic iodonium salt and a β-diketone enolate[34] or to multistep procedures.[35]

Semihydrogenation of the α-chloroethynyl carbonyl compounds (Table I, column 2) over Lindlar catalyst (H_2 (1 atm), 10/1 EtOAc/Et_3N, room temperature) gave the corresponding α-vinyl compounds in high yield (Table I, column 6), providing particularly direct access to these potential precursors for Cope and oxy-Cope rearrangements.[36] Indeed, the synthetic utility of α-vinyl ketones has generated a recent flurry of methods for their preparation.[37]

On the basis of the above experiments, it is established that the dichlorovinylation of tertiary enolates with trichloroethylene must proceed by way of a dichloroacetylene intermediate through a carbanion chain mechanism. This in turn has led to the discovery that dichloroacetylene and 1-chloroalkynes having a carbanion-stabilizing β-substituent are versatile Michael acceptors, providing a new route to ketones and esters having an ethynyl or vinyl group at a tertiary α-position.

Experimental Section

General Information. Trichloroethylene and hexachlorobutadiene were distilled from phosphorus pentoxide prior to use. All other simple polyhalogenated olefins were used as obtained without further purification. Unless otherwise noted, other materials obtained from commercial suppliers were used without further purification. In experiments requiring dry solvents, tetrahydrofuran (THF), diethyl ether, and hexamethylphosphoric triamide (HMPA) were distilled from sodium–benzophenone. Hexanes, diisopropylamine, and hexamethyldisilazane were distilled from calcium hydride. HMPA was stored over 4-Å sieves; diisopropylamine and hexamethyldisilazane were stored over potassium hydroxide.

The silica gel used for medium-pressure liquid chromatography (MPLC) was EC/B Manufacturing Chemists Inc., Silica Gel 60 (230–400 mesh). The solvent pump was supplied by Fluid Metering, Inc., Oyster Bay, NY. Preparative thin-layer chromatography was performed with silica gel plates purchased from Analtech, Inc., Newark, DE.

Lithium diisopropylamide was prepared in the following way: diisopropylamine (*n* mmol) was suspended in dry THF (5*n* mL) at 0 °C under nitrogen. A solution of 1.52 M *n*-butyllithium (*n* mmol) was added dropwise and the solution stirred at 0 °C for 10 min. The lithium diisopropylamide (LDA) thus formed was cooled to −78 °C and used immediately.

2,6-Dimethyl-2-cyclohexen-1-one (3). 2,6-Dimethylcyclohexanone (46 g, 370 mmol) was suspended in carbon tetrachloride (300 mL) in a 1-L 3-neck flask equipped with an overhead stirrer and reflux condenser. *N*-Bromosuccinimide (71.6 g, 400 mmol) and azobisisobutyronitrile (AIBN) (50 mg, catalytic) were added. The reaction was heated to reflux for 18 h, at which time an NMR of an aliquot showed the reaction to be complete. The reaction mixture was allowed to cool to room temperature, poured onto saturated sodium bicarbonate solution, and extracted three times with chloroform. The combined extracts were washed twice with water and filtered through sodium sulfate. Short-path distillation gave **3** as a colorless liquid: yield 30.3 g (66%); NMR (100 MHz, $CDCl_3$) δ 6.70 (br s, 1 H), 2.56–1.44 (m, 5 H), 1.78 (br s, 3 H), 1.14 (d, J = 8 Hz, 3 H).

Occasionally, an NMR of an aliquot after several hours would show only 2-bromo-2,6-dimethylcyclohexanone present. Under these circumstances, passage of small amounts of anhydrous gaseous hydrogen bromide through the reaction mixture would cause the reaction to go to completion.

General Procedure for Enolate Dichlorovinylation. LDA (1.0 mmol) was prepared as described and cooled to −78 °C. The ketone (1.0 mmol, neat) was added, followed immediately by the addition of HMPA (180 mg, 1.0 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min. Trichloroethylene (130 mg, 1.0 mmol, neat) was added and the reaction allowed to warm to room temperature slowly over 3–4 h. The reaction was poured onto water and extracted three times with diethyl ether. The combined ether extracts were washed four times with water and once with brine and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator gave the crude product as a dark oil.

3-Ethoxy-6-((*E*)-1,2-dichlorovinyl)-6-methyl-2-cyclohexen-1-one (2). Starting with 3-ethoxy-6-methyl-2-cyclohexen-1-one, the above procedure gave a crude product having an NMR showing a 70:30 mixture of product:starting material: NMR (product only, 100 MHz, $CDCl_3$) δ 6.36 (s, 1 H), 5.44 (s, 1 H), 3.96 (q, J = 6 Hz, 2 H), 2.7–1.8 (m, 4 H), 1.48 (s, 3 H), 1.38 (t, J = 6 Hz, 3 H); ^{13}C NMR (product only $CDCl_3$) δ

(30) Miller, S. I.; Ziegler, G. R.; Wieleseck, R. "Organic Syntheses"; Wiley: New York; Collect. Vol. 5, p 921. In our hands, NaOCl works well only with arylacetylenes; NaOBr works well for both aryl- and alkylacetylenes.

(31) Miller has reported that phenylchloroacetylene reacts with diethyl malonate in KOH/Me_2SO to give a 1:2 adduct in 27% yield. Izumi, T.; Miller, S. I. *J. Org. Chem.* **1978**, *43*, 871.

(32) Truchet, R. *Ann. Chim. (Paris)* **1931**, *16*, 309.

(33) West, R.; Quass, L. C. *J. Organomet. Chem.* **1969**, *18*, 55.

(34) Beringer, F. M.; Galton, S. A. *J. Org. Chem.* **1965**, *30*, 1930.

(35) (a) Negishi, E.; King, A. O.; Klima, W. L.; Patterson, W.; Silveira, A., Jr. *J. Org. Chem.* **1980**, *45*, 2526. (b) Klioze, S. S.; Darmory, F. P. *Ibid.* **1975**, *40*, 1588.

(36) (a) Kato, T.; Kondo, H.; Nishino, M.; Tanaka, M.; Hata, G.; Miyake, A. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 2958. (b) Still, W. C. *J. Am. Chem. Soc.* **1979**, *101*, 2493. (c) Holt, D. A. *Tetrahedron Lett.* **1981**, 2243. (d) Ziegler, F. E.; Piwinski, J. J. *J. Am. Chem. Soc.* **1981**, *102*, 880. (e) Still, W. C. *Ibid.* **1977**, *99*, 4186. (f) Williams, J. R.; Callahan, J. F. *J. Org. Chem.* **1980**, *45*, 4479. (g) Bruhn, J.; Heimgartner, J.; Schmid, H. *Helv. Chim. Acta* **1979**, *62*, 2630.

(37) (a) For examples of nickel-catalyzed vinylation and arylation of enolates by bromides and iodides, see: Millard, A. A.; Rathke, M. W. *J. Am. Chem. Soc.* **1977**, *99*, 4833. (b) For examples of nickel- and palladium-catalyzed arylation and vinylation of Reformatsky reagents, see: Fauvarque, V. F.; Jutand, A. *J. Organomet. Chem.* **1978**, *177*, 273. (c) For examples of iron-assisted vinylation of enolates, see: Chang, T. C.; Rosenblum, M.; Samuels, S. B. *J. Am. Chem. Soc.* **1980**, *102*, 5930. (d) Kowalski, C. J.; Dung, J.-S. *Ibid.* **1980**, *102*, 7951. (e) Clive, D. L. J.; Russell, C. G.; Suri, S. C. *J. Org. Chem.* **1982**, *47*, 1632. (f) Hudrlik, P. F.; Kulkarni, A. K. *J. Am. Chem. Soc.* **1981**, *103*, 6251. (g) Koppel, G. A.; Kinnick, M. D. *J. Chem. Soc., Chem. Commun.* **1975**, 473.

197.7, 175.3, 137.9, 115.0, 101.8, 64.1, 50.7, 32.0, 26.2, 22.2, 14.1.

A purified sample (bp 140–142 °C/1 torr) gave a satisfactory analysis. Anal. Calcd for $C_{11}H_{14}Cl_2O_2$: C, 53.02; H, 5.68. Found: C, 53.20; H, 5.43.

6-((*E*)-1,2-Dichlorovinyl)-2,6-dimethyl-2-cyclohexen-1-one (6). Starting with 2,6-dimethyl-2-cyclohexen-1-one, the above procedure gave a crude product with an NMR showing a 60:40 mixture of product: starting material. Purification by preparative thin-layer chromatography (5% ethyl acetate in hexanes as eluant) gave **6** as a colorless oil which crystallized upon refrigeration: mp 44–45 °C; yield 123 mg (56%); NMR (400 MHz, $CDCl_3$) δ 6.60 (br s, 1 H), 6.30 (s, 1 H), 2.66–1.70 (m, 4 H), 1.84 (br s, 3 H), 1.38 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 198.3, 142.5, 137.4, 134.7, 114.5, 51.4, 34.5, 22.9, 21.8, 16.6; MS, *m/e* 218 (M^+) (Cl_2 isotope pattern) (3), 183 (Cl) (10), 82 (100). With longer reaction times (e.g., 12 h), 6-(chloroethynyl)-2,6-dimethyl-2-cyclohexen-1-one (**5**) was formed as an unwanted byproduct. Complete spectroscopic data for **5** are given later.

Diethyl ((*E*)-1,2-Dichlorovinyl)ethylmalonate (7). Sodium hydride (7.30 g of 61% sodium hydride in oil, 186 mmol) was washed twice with pentanes and suspended in THF (150 mL) at room temperature under nitrogen. Diethyl ethylmalonate (36 g, 192 mmol, neat) was added dropwise, causing rapid evolution of hydrogen gas. Once the addition was complete, the suspension was stirred at room temperature for 20 min. Trichloroethylene (6.29 g, 48 mmol, neat) was added, followed by HMPA (20.6 g, 115 mmol, neat). A reflux condenser was attached and the reaction was refluxed under nitrogen for 17 h. The reaction mixture was allowed to cool to room temperature, poured into an equal volume of 10% hydrochloric acid, and extracted four times with diethyl ether. The combined extracts were washed twice with saturated sodium bicarbonate solution, four times with water, twice with brine, and dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by fractional distillation through a 16-cm Vigreux column gave **7** as a colorless oil: yield 8.55 g (64%, based on trichloroethylene); bp 120–125 °C/2.5 torr. The starting diethyl ethylmalonate (21.5 g) was recovered from the fractional distillation: bp 76–79 °C/2.5 torr; NMR (100 MHz, $CDCl_3$) δ 6.64 (s, 1 H), 4.34 (q, J = 8 Hz, 4 H), 2.30 (q, J = 8 Hz, 2 H), 1.32 (t, J = 8 Hz, 6 H), 1.08 (t, J = 8 Hz, 3 H); ^{13}C NMR ($CDCl_3$) δ 167.2, 131.2, 118.1, 63.4, 62.0, 27.8, 13.8, 9.3; IR (neat) 1720 cm^{-1}; MS, *m/e* no M^+, 209 (Cl_2 isotope pattern) (100), 181 (Cl_2) (80).

Anal. Calcd for $C_{11}H_{16}Cl_2O_4$: C, 46.66; H, 5.70. Found: C, 46.85; H, 5.86.

Ethyl 2-Acetyl-2-((*E*)-1,2-dichlorovinyl)propionate (8). Sodium hydride (400 mg of 61% sodium hydride in oil, 10 mmol) was washed twice with pentanes and suspended in dimethylformamide (15 mL, distilled from calcium hydride) at room temperature under nitrogen. Ethyl 2-acetylpropionate (1.53 g, 10 mmol, neat) was added dropwise, causing rapid evolution of hydrogen gas. Once the addition was complete, the suspension was stirred at room temperature for 20 min. Trichloroethylene (0.34 g, 2.6 mmol, neat) was added. A reflux condenser was attached and the reaction heated to 100 °C for 40 h. The reaction mixture was allowed to cool to room temperature, poured onto an equal volume of water, and extracted four times with diethyl ether. The combined extracts were washed four times with water and twice with brine and then dried over magnesium sulfate. Kugelrohr distillation gave a colorless oil: yield 0.27 g; bp 120–125 °C/15 torr. The NMR showed this oil to be a 2:1 mixture of product:starting material: NMR (product only, 100 MHz, $CDCl_3$) δ 6.60 (s, 1 H), 4.34 (q, J = 8 Hz, 2 H), 2.44 (s, 3 H), 1.68 (s, 3 H), 1.28 (t, J = 8 Hz, 3 H).

Diethyl Ethylethynylmalonate (9). Diethyl ((*E*)-1,2-dichlorovinyl)-ethylmalonate (**7**) (300 mg, 1.1 mmol) was suspended in THF (15 mL) at −78 °C under nitrogen. A solution of 1.8 M *tert*-butyllithium (1.2 mL, 2.2 mmol) was added and the reaction stirred at −78 °C for 90 min. The reaction mixture was poured onto rapidly stirring water, extracted four times with chloroform, and filtered through sodium sulfate. Removal of the solvent on a rotary evaporator followed by preparative thin-layer chromatography (20% diethyl ether in hexanes as eluant) gave **9** as a colorless oil: yield 142 mg (63%); NMR (100 MHz, $CDCl_3$) δ 4.38 (q, J = 7 Hz, 4 H), 2.56 (s, 1 H), 2.22 (q, J = 8 Hz, 2 H), 1.36 (t, J = 7 Hz, 6 H), 1.08 (t, J = 8 Hz, 3 H).

6-((*E*)-2-Chloro-1-fluorovinyl)-2,6-dimethyl-2-cyclohexen-1-one (11). The procedure used was identical with the general procedure for enolate dichlorovinylation, except that a 1:1 mixture of cis/trans 1,2-dichloro-1-fluoroethylene was used instead of trichloroethylene. The NMR of the crude reaction product showed a 2:1 mixture of starting material:product. Purification by preparative thin-layer chromatography (5% ethyl acetate in hexanes as eluant) gave **11** as a colorless oil: yield 54 mg (27%); NMR (100 MHz, $CDCl_3$) δ 6.71 (br s, 1 H), 6.04 (d, J_{HF} = 14 Hz, 1 H), 2.76–1.80 (m, 4 H), 1.92 (br s, 3 H), 1.48 (s, 3 H); MS, *m/e* 202 (M^+) (Cl isotope pattern), 183 (Cl), 167.

Enolate Reaction with Tetrachloroethylene (eq 4). The procedure used was identical with the general procedure for enolate dichlorovinylation, except that tetrachloroethylene was used instead of trichloroethylene. Purification by MPLC (5% ethyl acetate in hexanes as eluant) gave 6-(chloroethynyl)-2,6-dimethyl-2-cyclohexen-1-one (**5**) as a colorless oil (yield 38 mg (21%)) and 2,6-dimethylphenol as a colorless oil (yield 28 mg (23%)). Complete spectroscopic data for **5** are given later. Since 2,6-dimethylphenol was not present in the crude reaction product, aromatization of 6-chloro-2,6-dimethyl-2-cyclohexen-1-one (a presumed intermediate) probably occured upon MPLC.

Enolate Reaction with 1,1-Dichloro-2,2-difluoroethylene. The procedure used was identical with the general procedure for enolate dichlorovinylation, except that 1,1-dichloro-2,2-difluoroethylene was used instead of trichloroethylene. The NMR of the crude reaction product showed only 6-chloro-2,6-dimethyl-2-cyclohexen-1-one, with traces of starting material: NMR (100 MHz, $CDCl_3$) δ 6.64 (br s, 1 H), 2.80–1.60 (m, 4 H), 1.80 (br s, 3 H), 1.68 (s, 3 H); MS, *m/e* 158 (M^+) (Cl isotope pattern).

Ethyl 2,2-Dimethyl-5,6,6-trichlorohex-3-yn-5-enoate (13). LDA (100 mmol) was prepared as described and cooled to −78° C. Ethyl isobutyrate (9.0 g, 78 mmol) in THF (100 mL) was added, followed immediately by the addition of HMPA (13.9 g, 78 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min. Hexachlorobutadiene (9.5 g, 37 mmol, neat) was added, and the solution immediately became deep indigo blue in color. The reaction was allowed to warm to room temperature slowly over 6 h. The reaction was poured onto water and extracted four times with diethyl ether. The combined ether extracts were washed four times with water and twice with brine and then dried over magnesium sulfate. Removal of the solvent by distillation through a 12-cm Vigreux column gave the crude product as a dark oil. Kugelrohr distillation of the crude product, after removal of a forerun containing ethyl α-chloroisobutyrate, gave **13** as a colorless oil: yield 6.16 g (63%); bp 87–90 °C/0.1 torr; NMR (100 MHz, $CDCl_3$) δ 4.15 (q, J = 7 Hz, 2 H), 1.55 (s, 6 H), 1.28 (5, J = 7 Hz, 3 H); ^{13}C NMR ($CDCl_3$) δ 172.2, 126.7, 112.7, 102.0, 75.7, 61.6, 39.0, 26.5, 14.0; IR (neat) 1740, 1560 cm^{-1}; MS, *m/e* 268 (M^+) (Cl_3 isotope pattern) (14), 233 (Cl_2) (14), 195 (Cl_3) (100); UV (MeOH) 245 (ϵ 13 500), 251 nm (ϵ 13 800).

Anal. Calcd for $C_{10}H_{11}Cl_3O_2$: C, 44.55; H, 4.11; Cl, 39.46. Found: C, 44.46; H, 4.09; Cl, 39.40.

Diethyl (Pentachlorobutadienyl)methylmalonate (14). Sodium hydride (0.43 g of 50% sodium hydride in oil, 9.0 mmol) was washed twice with pentanes and suspended in THF (8 mL) at room temperature under nitrogen. Diethyl methylmalonate (1.52 g, 8.7 mmol, neat) was added dropwise, causing rapid evolution of hydrogen gas. Once the addition was complete, the suspension was stirred at room temperature for 20 min. Hexachlorobutadiene (0.52 g, 2.0 mmol, neat) was added, followed by HMPA (1.44 g, 8.1 mmol). A reflux condenser was attached and the reaction was refluxed under nitrogen for 35 h. The reaction mixture was allowed to cool to room temperature, poured onto 0.5 M hydrochloric acid, and extracted four times with diethyl ether. The combined extracts were washed twice with saturated sodium bicarbonate solution, four times with water and twice with brine and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by purification by preparative thin-layer chromatography (5% diethyl ether in hexanes as eluant) gave **14** as a colorless oil: yield 483 mg (61%); NMR (100 MHz, $CDCl_3$) δ 4.24 (q, J = 7 Hz, 4 H), 1.82 (s, 3 H), 1.32 (t, J = 7 Hz, 6 H); ^{13}C NMR ($CDCl_3$) δ 167.5, 134.3, 125.5, 125.1, 124.4, 62.6, 60.9, 21.4, 13.3; IR (neat) 1745 cm^{-1}; MS, *m/e* 396 (M^+) (Cl_5 isotope pattern) (0.7), 361 (Cl_4) (65), 326 (Cl_3) (29), 215 (Cl_4) (100); UV (MeOH) 220 nm (ϵ 12 900).

Kugelrohr distillation (bp 135–140 °C/0.1 torr) gave an analytically pure sample. Anal. Calcd for $C_{12}H_{13}Cl_5O_4$: C, 36.16; H, 3.29; Cl, 44.49. Found: C, 36.29; H, 3.39; Cl, 44.25.

Catalytic hydrogenation (5% Pd/C, atmospheric pressure, 4:1 EtOH:Et_3N) gave diethyl *n*-butylmethylmalonate: NMR (100 MHz, $CDCl_3$) δ 4.20 (q, J = 7 Hz, 4 H), 2.15–1.20 (m, 9 H), 1.24 (s, 3 H), 1.22 (t, J = 7 Hz, 6 H); MS, *m/e* 230 (M^+) (0.6), 112 (21), 105 (100).

Ethyl 2,2-Dimethyl-4-oxo-5,6,6-trichlorohex-5-enoate (15). Ethyl 2,2-dimethyl-5,6,6-trichlorohex-3-yn-5-enoate (**13**) (0.91 g, 3.4 mmol) was dissolved in 99% ethanol (10 mL). A freshly prepared saturated solution of mercuric sulfate in 1% sulfuric acid (5 mL) was added. A reflux condenser was attached and the reaction was heated to 75 °C for 21 h. The reaction mixture was allowed to cool to room temperature, poured onto diethyl ether, washed twice with saturated sodium bicarbonate solution, once with water and once with brine, and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by purification by preparative thin-layer chromatography gave **15** as a colorless oil: yield 0.60 g (63%); NMR (100 MHz, $CDCl_3$) δ 4.10 (q, J = 7 Hz, 2 H), 3.06 (s, 2 H), 1.24 (s, 6 H), 1.16 (5, J = 7 Hz, 3

H); ^{13}C NMR ($CDCl_3$) δ 191.7, 176.1, 127.4, 126.6, 60.5, 50.5, 40.2, 25.3, 14.0; IR (neat) 1735, 1720 cm^{-1}; MS, *m/e* 286 (M^+) (Cl_3 isotope pattern) (1), 251 (Cl_2) (18), 241 (Cl_3) (8), 213 (Cl_3) (7), 157 (Cl_3) (100); UV (MeOH) 260 nm (ϵ 5500).

Kulgerohr distillation (bp 85–90 °C/0.1 torr) gave an analytically pure sample. Anal. Calcd for $C_{10}H_{13}Cl_3O_3$: C, 41.76; H, 4.56; Cl, 36.99. Found: C, 41.65; H, 4.48; Cl, 36.87.

Catalytic hydrogenation (5% Pd/C, atmospheric pressure, 4:1 EtOH:Et_3N) gave ethyl 2,2-dimethyl-4-oxohexanoate: NMR (100 MHz, $CDCl_3$) δ 4.10 (q, J = 7 Hz, 2 H), 2.68 (s, 2 H), 2.40 (q, J = 7 Hz, 2 H), 1.26 (t, J = 7 Hz, 3 H), 1.24 (s, 6 H), 1.04 (t, J = 7 Hz, 3 H); MS *m/e* 186 (M^+) (6), 157 (41), 141 (27), 129 (45), 113 (18), 87 (100).

Ethyl 2,2-Dimethyl-4-oxo-5-chloro-6,6-bis(dimethylamino)hex-5-enoate (16). Ethyl 2,2-dimethyl-4-oxo-5,6,6-trichlorohex-5-enoate (220 mg, 0.77 mmol) was dissolved in 99% ethanol (5 mL) at 0 °C. Anhydrous dimethylamine (2 mL) was added and the reaction stirred at 0 °C for 1 h. The reaction was poured onto diethyl ether, washed twice with water, and dried over magnesium sulfate. Removal of the solvent on a rotary evaporator gave a pale yellow oil: yield 201 mg (86%); NMR (100 MHz, $CDCl_3$) δ 4.12 (q, J = 7 Hz, 2 H), 2.86 (s, 12 H), 2.84 (s, 2 H), 1.26 (s, 6 H), 1.22 (t, J = 7 Hz, 3 H); IR (CCl_4) 1730 (strong), 1660 (medium), 1610 (strong) cm^{-1}; MS, *m/e* 304 (M^+) (Cl isotope pattern) (19), 269 (82), 259 (Cl) (100).

Ethyl 2,2-Dimethyl-4-oxo-5,6,6-tris(phenylthio)hex-5-enoate (17). Sodium hydride (290 mg of 61% sodium hydride in oil, 7.4 mmol) was washed twice with pentanes and suspended in THF (10 mL) at room temperature under nitrogen. Thiophenol (980 mg, 9.0 mmol, neat) was added dropwise, forming a voluminous white precipitate. The suspension was stirred at room temperature for 20 min, followed by the addition of ethyl 2,2-dimethyl-4-oxo-5,6,6-trichlorohex-2-enoate (**15**) (200 mg, 0.70 mmol) in THF (5 mL). The reaction was stirred at room temperature for 5 h, poured onto diethyl ether, washed twice with 5% potassium hydroxide solution, once with water and once with brine, and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by purification by preparative thin-layer chromatography gave **17** as a yellow oil: yield 230 mg (65%); NMR (100 MHz, $CDCl_3$) δ 7.60–6.88 (m, 15 H), 3.98 (q, J = 7 Hz, 2 H), 3.00 (s, 2 H), 1.08 (s, J = 7 Hz, 3 H), 1.00 (s, 6 H); IR (CCl_4) 1740 (strong), 1710 (medium) cm^{-1}; MS, *m/e* 508 (M^+) (100).

2,6-Dimethyl-6-(trichlorobut-3-en-1-ynyl)-2-cyclohexen-1-one (18). LDA (10 mmol) was prepared as described and cooled to −78 °C. 2,6-Dimethyl-2-cyclohexen-1-one (1.20 g, 9.7 mmol) in THF (10 mL) was added, followed immediately by the addition of HMPA (1.75 g, 9.8 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min. Hexachlorobutadiene (1.17 g, 4.5 mmol, neat) was added, and the solution immediately became deep indigo blue in color. The reaction was allowed to warm to room temperature slowly over $4^1/_2$ h. The reaction was poured onto water and extracted four times with diethyl ether. The combined extracts were washed four times with water and twice with brine and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by preparative thin-layer chromatography (20% diethyl ether in hexanes as eluant) gave **18** as a colorless oil: yield 0.70 g (56%); NMR (100 MHz, $CDCl_3$) δ 6.72 (br s, 1 H), 2.80–1.68 (m, 4 H), 1.84 (br s, 3 H), 1.48 (s, 3 H); CMR ($CDCl_3$) δ 194.8, 144.9, 133.5, 126.9, 112.7, 100.8, 76.4, 42.7, 36.3, 23.8, 22.9, 16.6; IR (neat) 1685 cm^{-1}; MS, *m/e* 276 (M^+) (Cl_3 isotope pattern) (14), 261 (Cl_3) (50), 241 (Cl_2) (100), 206 (Cl) (14); UV (MeOH) 245 (ϵ 19 000), 323 nm (ϵ 500).

Kugelrohr distillation (bp 120–125 °C/0.1 torr) gave an analytically pure sample. Anal. Calcd for $C_{12}H_{11}Cl_3O$: C, 51.92; H, 3.99; Cl, 38.32. Found: C, 52.08; H, 3.98; Cl, 38.40.

Perchlorobutenyne (21).[12] Hexachlorobutadiene (25.7 g, 100 mmol) was suspended in hexanes (200 mL) at 0 °C under nitrogen. A solution of 1.53 M *n*-butyllithium (65 mL, 100 mmol) was added dropwise. After addition was complete, a brown precipitate formed. The reaction was stirred at 0 °C for 90 min and filtered through Florisil. Removal of the solvent on a rotary evaporatory gave the crude product as an orange-red oil. Fractional distillation of the crude product through a 15-cm Vigreux column gave **21** as a colorless oil, which yellowed upon standing: yield 4.95 g (26%); bp 40–50 °C/0.1 torr; MS, *m/e* 188 (M^+) (Cl_4 isotope pattern) (53), 153 (Cl_3) (63), 118 (Cl_2) (100).

The lithium enolate of ethyl isobutyrate was reacted with perchlorobutenyne under identical reaction conditions used for the reaction with hexachlorobutadiene, except a 1:1 stoichiometry was used instead of a 2:1 stoichiometry. Ethyl 2,2-dimethyl-5,6,6-trichlorohex-3-yn-5-enoate (**13**) was obtained in 76% yield, identical in all respects with the sample obtained from hexachlorobutadiene.

Diethyl 5,6-Dichloro-2,2,7,7-tetramethyloct-3-yn-5-ene-1,8-dicarboxylate (22). Mixture of *E*/*Z* Isomers. Method A. LDA (34.5 mmol, in 50 mL of THF) was prepared as described and cooled to −78 °C. Ethyl isobutyrate (4.08 g, 35.2 mmol) in THF (20 mL) was added, followed immediately by the addition of HMPA (6.18 g, 34.5 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min. Hexachlorobutadiene (2.51 g, 9.7 mmol, neat) was added, and the solution immediately became deep indigo blue in color. The reaction was allowed to warm to room temperature slowly over 6 h. The reaction was poured onto water and extracted four times with diethyl ether. The combined extracts were washed four times with water and twice with brine and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by purification by column chromatography on silica gel (250 g, 40–140 mesh) (20% diethyl ether in hexanes as eluant) gave **22** as a colorless oil; yield 2.69 g (80%, based on hexachlorobutadiene).

Method B. LDA (1.43 mmol) was prepared as described and cooled to −78 °C. Ethyl isobutyrate (0.17 g, 1.47 mmol) in THF (5 mL) was added, and the reaction was stirred at −78 °C for 30 min. Ethyl 2,2-dimethyl-5,6,6-trichlorohex-3-yn-5-enoate (**13**) (0.37 g, 1.38 mmol) in THF (5 mL) was added, followed by the addition of HMPA (0.26 g, 1.45 mmol, neat). The reaction was allowed to warm to room temperature slowly over 4 h. The reaction was worked up by the workup procedure described in method A. Purification by preparative thin-layer chromatography (20% diethyl ether in hexanes as eluant) gave **22** as a colorless oil: yield 0.33 g (69%); NMR (both isomers, 100 MHz, $CDCl_3$) δ 4.18 (overlapping q, J = 7 Hz, 4 H), 1.52, 1.48, 1.46, 1.44 (overlapping s, 12 H), 1.26 (overlapping t, J = 7 Hz, 6 H); ^{13}C NMR (both isomers, $CDCl_3$) δ 174.1, 172.8, 141.8, 110.5, 101.7, 98.9, 61.5, 48.9, 39.0, 26.7 (isomer A), 26.3 (isomer B), 25.8 (isomer B), 25.2 (isomer A), 14.0; IR (neat) 1740 cm^{-1}; MS, *m/e* 348 (M^+) (Cl_2 isotope pattern) (7), 313 (Cl) (27), 168 (Cl) (100); UV (MeOH) 244 (ϵ 9650) 248 nm (ϵ 9650).

Kugelrohr distillation (bp 105–108 °C/0.1 torr) gave an analytically pure sample. Anal. Calcd for $C_{16}H_{22}Cl_2O_4$: C, 55.02; H, 6.35; Cl, 20.30. Found: C, 55.04; H, 6.29; Cl, 20.25.

Catalytic hydrogenation (5% Pd/C, atmospheric pressure, 4:1 EtOH:Et_3N) gave diethyl 2,2,7,7-tetramethyloctane-1,8-dicarboxylate (**23**): NMR (100 MHz, $CDCl_3$) δ 4.06 (q, J = 7 Hz, 4 H), 1.80–1.40 (m, , H), 1.22 (5, J = 7 Hz, 6 H), 1.12 (s, 12 H).

4-[((*Z*)-2-Chloro-2-carboxy)methylene]-2,2-dimethylbutyrylactone (24). Ethyl 2,2-dimethyl-5,6,6-trichlorohex-3-yn-5-enoate (**13**) (1.04 g, 3.88 mmol) was suspended in concentrated sulfuric acid (10 mL) at room temperature. The reaction was stirred at room temperature for 24 h, poured onto ice, and extracted four times with diethyl ether. The combined extracts were washed once with brine and dried over magnesium sulfate. Removal of the solvent on a rotary evaporator gave the crude product as an oil. Recrystallization from 20% hexanes in benzene gave **24** as colorless needles: yield 0.39 g (49%); mp 180.5–181.5 °C; NMR (100 MHz, acetone-d_6) δ 3.24 (s, 2 H), 1.38 (s, 6 H); ^{13}C NMR (acetone-d_6) δ 179.7, 164.1, 161.4, 101.7, 43.3, 40.0, 25.3; IR ($CHCl_3$) 1830, 1695, 1635 cm^{-1}; MS, *m/e* 204 (M^+) (Cl isotope pattern) (50), 175 (Cl) (50), 161 (Cl) (100); UV (MeOH) 234 nm (ϵ 11 700).

Anal. Calcd for $C_8H_9ClO_4$: C, 46.96; H, 4.43; Cl, 17.33. Found: C, 47.09; H, 4.35; Cl, 17.32.

6,7-Dichloro-3,3,8,8-tetramethyl-2,9-dioxo-1,10-dioxaspiro[4.5]dec-6-ene (25). Diethyl 5,6-dichloro-2,2,7,7-tetramethyloct-3-yn-5-ene-1,8-dicarboxylate (**22**), a mixture of *E*/*Z* isomers (1.19 g, 3.42 mmol), was suspended in concentrated sulfuric acid (15 mL) at room temperature. The reaction was stirred at room temperature for 51 h, poured onto ice, and extracted four times with diethyl ether. The combined extracts were dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by recrystallization of the crude product in hot hexanes gave **25** as colorless prisms: yield 0.52 g (53%); mp 81–82 °C; NMR (400 MHz, $CDCl_3$) δ 2.97 (d, J = 14 Hz, 1 H), 2.40 (d, J = 14 Hz, 1 H), 1.60 (s, 3 H), 1.59 (s, 3 H), 1.52 (s, 3 H), 1.40 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 180.0, 169.2, 139.2, 123.0, 103.9, 46.7, 45.3, 39.8, 26.7, 26.3 (degenerate), 25.8; IR (CCl_4) 1815, 1780 cm^{-1}; MS, *m/e* 292 (M^+) (Cl_2 isotope pattern) (10), 257 (Cl) (5), 248 (Cl_2) (87), 233 (Cl_2) (100).

Anal. Calcd for $C_{12}H_{14}Cl_2O_4$: C, 49.16; H, 4.81; Cl, 24.19. Found: C, 49.36; H, 4.87; Cl, 24.35.

Methyl 7-Carboxy-3,4-dichloro-2,2,7-trimethyl-5-oxooct-3-enoate (26), *Z* Isomer. 6,7-Dichloro-3,3,8,8-tetramethyl-2,9-dioxo-1,10-dioxaspiro[4.5]dec-6-ene (**25**) (96 mg, 0.33 mmol) was suspended in methanol (5 mL). Hydrochloric acid (10%, five drops) was added, and the reaction was stirred at room temperature for 9 h. The reaction was poured onto diethyl ether, washed once with water and once with brine, and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by recrystallization of the crude product from 1:1 diethyl ether:hexanes gave **26** as colorless prisms: yield 98 mg (90%); mp 137–139 °C; NMR (100 MHz, $CDCl_3$) δ 8.16 (br s, 1 H), 3.66 (s, 3 H), 3.14 (s, 2 H), 1.50 (s, 6 H), 1.27 (s, 6 H); ^{13}C NMR ($CDCl_3$) δ 194.7, 182.9, 174.1, 147.8, 128.3, 52.5, 51.4, 50.4, 39.9, 26.5, 25.3; IR (CCl_4) 2950 (broad), 1735, 1715, 1705 cm^{-1}; MS, *m/e* no M^+, 288 (Cl

isotope pattern) (100), 247 (Cl_2) (38), 233 (Cl_2) (28), 205 (Cl_2) (38), 195 (Cl_2) (28); UV (MeOH) 261 nm (3700), 211 (3100).

Anal. Calcd for $C_{13}H_{18}Cl_2O_5$: C, 48.01; H, 5.58; Cl, 21.80. Found: C, 48.11; H, 5.69; Cl, 21.74.

Reaction of 1-(Trimethylsiloxy)-2,6-dimethylcyclohexa-1,5-diene (31) with Methyllithium and Trichloroethylene (Scheme IV). 1-Trimethylsiloxy-2,6-dimethylcyclohexa-1,5-diene (**31**) (325 mg, 1.66 mmol) was suspended in THF (6 mL) at 0 °C under nitrogen. A solution of 1.5 M methyllithium (1.1 mL, 1.7 mmol) was added, followed immediately by HMPA (310 mg, 1.7 mmol, neat). The solution was stirred at 0 °C for 40 min and then cooled to −78 °C. Trichloroethylene (220 mg, 1.7 mmol, neat) was added and the solution allowed to warm to room temperature slowly over 4 h. The reaction was poured onto water and extracted three times with diethyl ether. The combined extracts were washed four times with water, once with brine, and dried over magnesium sulfate. Removal of the solvent on a rotary evaporator, followed by purification by MPLC (10% ethyl acetate in hexanes as eluant) gave 6-((*E*)-1,2-dichlorovinyl)-2,6-dimethyl-2-cyclohexen-1-one (**6**) as a colorless oil; yield 200 mg (54%). Complete spectral characterization of **6** is given elsewhere in this section.

Reaction of 1-(Trimethylsiloxy)-2,6-dimethylcyclohexa-1,5-diene (31) with Methyllithium and Dichloroacetylene (Scheme IV). The procedure used was identical with the procedure just described, except that dichloroacetylene (2–3 equiv, based on enolate) was used instead of trichloroethylene. 6-(Chloroethynyl)-2,6-dimethyl-2-cyclohexen-1-one (**5**) was obtained in 70% yield. Complete spectral characterization of (**5**) is given elsewhere in this section.

Trichloroethylene-d_1.[26] Calcium metal (2.0 g, 50 mmol) was dissolved in deuterium oxide (D_2O, 30 mL). Trichloroethylene (36.5 g, 280 mmol, neat) was added. A reflux condenser was attached, and the solution was heated to reflux and refluxed for 36 h. The reaction was allowed to cool, followed by distillation through a 12-cm Vigreux column to give the product, bp 85–90 °C/760 torr.

The deuterium content was analyzed by NMR as follows: A standard solution of triphenylmethane (1.01 g, 4.1 mmol) in chloroform-d_1 (3.0 mL) was prepared. A carefully measured amount (100 μL) was placed into each of two NMR tubes. In the first tube, trichloroethylene 100% H (50 μL) was added. In the second tube, trichloroethylene-d_1 (prepared above) (50 μL) was added. Careful integration of the NMR spectra, after normalization with the internal triphenylmethane standard, indicated 90 ± 2% deuterium content in the trichloroethylene-d_1 prepared. This trichloroethylene-d_1 was diluted with trichloroethylene 100% ^1H to 50 ± 2% deuterium content. The dilution was checked by repeating the NMR standardization with triphenylmethane.

Diethyl 2,4-Dicarbethoxy-3-(2-chloromethylene)pentane-1,5-dicarboxylate (34). Sodium hydride (52 mg of 60% sodium hydride in oil, 1.3 mmol) was washed twice with pentanes and suspended in THF (10 mL) at room temperature under nitrogen. Diethyl malonate (160 mg, 1.0 mmol, neat) was added dropwise, causing rapid evolution of hydrogen gas. Once the addition was complete, the suspension was stirred at room temperature for 20 min. Dichloroacetylene–ether solution (1 mL, ~5 mmol) was added, and the reaction mixture was stirred at room temperature for 16 h. The reaction was poured onto saturated ammonium chloride and extracted three times with diethyl ether. The combined ether extracts were washed twice with saturated sodium bicarbonate solution and once with brine and then dried over magnesium sulfate. Purification by MPLC (10% ethyl acetate in hexanes as eluant) gave **34** as a colorless oil: yield 163 mg (86%); NMR (100 MHz, $CDCl_3$) δ 6.58 (s, 1 H), 4.88 (s, 1 H), 4.48 (s, 1 H), 4.14 (q, J = 7 Hz, 8 H), 1.26 (t, J = 7 Hz, 12 H); IR (neat) 1760, 1730 cm^{-1}; MS, m/e 378 (M^+) (Cl isotope pattern).

Anal. Calcd for $C_{16}H_{23}ClO_8$: C, 50.73; H, 6.12. Found: C, 50.70; H, 6.15.

General Procedure for Enolate Reaction with Dichloroacetylene. Method A. LDA (1.0 mmol) was prepared as described and cooled to −78 °C. The ketone (1.0 mmol, neat) was added, followed immediately by the addition of HMPA (180 mg, 1.0 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min. Dichloroacetylene–ether solution (1 mL, ≈5 mmol) was added and the reaction allowed to warm to room temperature over 3–4 h. The reaction was poured onto water and extracted three times with diethyl ether. The combined extracts were washed four times with water and once with brine and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator gave the crude product as a dark oil. Purification was done by MPLC (10% ethyl acetate in hexanes as eluant) to give products as colorless oils.

General Procedure for Enolate Reaction with Dichloroacetylene. Method B. LDA (1.0 mmol) was prepared as described and cooled to −78 °C. The ketone (1.0 mmol, neat) was added, followed immediately by the addition of HMPA (180 mg, 1.0 mmol, neat). The enolate thus formed was stirred at 0 °C for 20 min, followed by transfer by cannula to a flask containing dichloroacetylene–ether solution (1 mL, ≈5 mmol) precooled to −20 °C. The reaction was allowed to warm to room temperature slowly over 2–3 h. Workup was identical with the procedure described in method A. Purification was done by MPLC (10% ethyl acetate in hexanes as eluant) to give products as colorless oils.

6-(Chloroethynyl)-2,6-dimethyl-2-cyclohexen-1-one (5). Method A was used, starting with 2,6-dimethyl-2-cyclohexen-1-one: yield 64%; NMR (90 MHz, $CDCl_3$) δ 6.71 (br s, 1 H), 2.88–1.60 (m, 4 H), 1.80 (br s, 3 H), 1.37 (s, 3 H); ^{13}C NMR ($CDCl_3$) δ 195.8; 144.8, 133.1, 69.6, 60.1, 41.8, 34.3, 21.5, 21.3, 16.3; IR (neat) 1685 cm^{-1}; MS, m/e 182 (M^+) (Cl isotope pattern).

Anal. Calcd for $C_{10}H_{11}ClO$: C, 65.76; H, 6.07. Found: C, 65.65; H, 6.08.

2-Chloroethynyl-2-methyl-1-tetralone. Method A was used, starting with 2-methyl-1-tetralone: yield 65%; NMR (100 MHz, $CDCl_3$) δ 8.01 (dd, J = 7, 2 Hz, 1 H), 7.54–7.12 (m, 3 H), 3.46–3.16 (m, 1 H), 3.00–2.70 (m, 1 H), 2.40–1.78 (m, 2 H), 1.51 (s, 3 H); IR (neat) 1695, 1600 cm^{-1}; MS, m/e 218 (M^+) (Cl isotope pattern) (100).

Anal. Calcd for $C_{13}H_{11}ClO$: C, 71.40; H, 5.07. Found: C, 71.10; H, 5.11.

Ethyl 4-Chloro-2,2-dimethylbut-3-ynoate. Method B was used, starting with ethyl isobutyrate: yield 73%; NMR (100 MHz, $CDCl_3$) δ 4.18 (q, J = 7 Hz, 2 H), 1.48 (s, 6 H), 1.28 (t, J = 7 Hz, 3 H); IR (neat) 1730 cm^{-1}.

Anal. Calcd for $C_8H_{11}ClO_2$: C, 55.02; H, 6.35. Found: C, 54.72; H, 6.51.

2-(Chloroethynyl)-2,6,6-trimethylcyclohexanone. Method B was used, starting with 2,2,6-trimethylcyclohexanone: yield 73%; NMR (100 MHz, $CDCl_3$) δ 2.20–1.22 (m, 6 H), 1.40 (s, 3 H), 1.34 (s, 3 H), 1.08 (s, 3 H); MS, m/e 198 (M^+) (Cl isotope pattern).

Anal. Calcd for $C_{11}H_{15}ClO$: C, 66.49; H, 7.61. Found: C, 66.54; H, 7.57.

1-Chloro-3,3,5-trimethylhex-1-yn-4-one. Method B was used, starting with 2,4-dimethyi-3-pentanone. Purification by Kugelrohr distillation gave a colorless oil: bp 70–80 °C/15 torr; yield 70%; NMR (100 MHz, $CDCl_3$) δ 3.36 (m, 1 H), 1.40 (s, 6 H), 1.16 (d, J = 7 Hz, 6 H); MS, m/e 172 (M^+) (Cl isotope pattern).

Anal. Calcd for $C_9H_{13}ClO$: C, 62.61; H, 7.59. Found: C, 62.65; H, 7.80.

Methyl 1-(Chloroethynyl)cyclohexanecarboxylate. Method B was used, starting with methyl cyclohexanecarboxylate: yield 90%; NMR (100 MHz, $CDCl_3$) δ 3.66 (s, 3 H), 2.12–1.08 (m, 10 H); IR (neat) 1730 cm^{-1}; MS, m/e 200 (M^+) (Cl isotope pattern) (70), 165 (40), 141 (Cl) (100).

Anal. Calcd for $C_{10}H_{13}ClO_2$: C, 59.85; H, 6.53. Found: C, 59.68; H, 6.47.

General Procedure for Enolate Reaction with Phenylchloroacetylene. LDA (1.0 mmol) was prepared as described and cooled to −78 °C. The ketone (1.0 mmol, neat) was added, followed immediately by the addition of HMPA (180 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min. Phenylchloroacetylene (136 mg, 1.0 mmol, neat) was added and the reaction allowed to warm to room temperature and stir overnight. The reaction was poured onto water and extracted three times with diethyl ether. The combined extracts were washed four times with water and once with brine and then dried over magnesium sulfate. The solvent was removed on a rotary evaporator.

2,6-Dimethyl-6-(phenylethynyl)-2-cyclohexen-1-one. Starting with 2,6-dimethyl-2-cyclohexen-1-one, the above procedure, followed by preparative thin-layer chromatography (20% diethyl ether in hexanes as eluant), gave the product as a colorless oil: yield 70%; NMR (100 MHz, $CDCl_3$) δ 7.64–7.32 (m, 5 H), 6.84 (br s, 1 H), 2.96–1.78 (m, 4 H), 1.88 (br s, 3 H), 1.52 (s, 3 H); IR (neat) 1680 cm^{-1}; MS, m/e 224 (M^+).

Anal. Calcd for $C_{16}H_{16}O$: C, 85.68; H, 7.19. Found: C, 85.75; H, 7.46.

2,6,6-Trimethyl-2-(phenylethynyl)cyclohexanone. Starting with 2,2,6-trimethylcyclohexanone, the above procedure, followed by preparative thin-layer chromatography (5% diethyl ether in hexanes as eluant, eluted twice), gave the product as a colorless oil: yield 70%; NMR (100 MHz, $CDCl_3$) δ 7.68–7.40 (m, 5 H), 2.62–1.50 (m, 6 H), 1.51 (s, 3 H), 1.44 (s, 3 H), 1.13 (s, 3 H).

Anal. Calcd for $C_{17}H_{20}O$: C, 84.95; H, 8.39. Found: C, 85.40; H, 8.92.

Methyl 1-(Phenylethynyl)cyclohexanecarboxylate. Starting with methyl cyclohexanecarboxylate, the above procedure, followed by preparative thin-layer chromatography (2% ethyl acetate in hexanes as eluant), gave the product as a colorless oil: yield 95%; NMR (100 MHz, $CDCl_3$) δ 7.71–7.28 (m, 5 H), 3.82 (s, 3 H), 2.20–1.12 (m, 10 H); IR (neat) 1735 cm^{-1}; MS, m/e 242 (M^+) (52), 183 (100).

Anal. Calcd for $C_{16}H_{18}O_2$: C, 79.31; H, 7.49. Found: C, 79.14; H, 7.65.

Ethyl 2,2-Dimethyl-4-phenylbut-3-ynoate. Starting with ethyl isobutyrate, the above procedure gave the product as a colorless oil. No purification was necessary (excess starting materials removed on rotary evaporator): yield 83%; NMR (100 MHz, $CDCl_3$) δ 7.60–7.24 (m, 5 H), 4.28 (q, J = 7 Hz, 2 H), 1.62 (s, 6 H), 1.32 (t, J = 7 Hz, 3 H); IR (neat) 1730 cm^{-1}; MS, m/e 216 (M^+) (13), 143 (100), 128 (28).

Kugelrohr distillation (bp 100–110 °C/0.1 torr) gave an analytically pure sample. Anal. Calcd for $C_{14}H_{16}O_2$: C, 77.75; H, 7.46. Found: C, 77.58; H, 7.68.

(Phenylthio)chloroacetylene. Hexamethyldisilazane (2.23 g, 13.9 mmol) was suspended in THF (20 mL) at 0 °C under nitrogen. A solution of 1.55 M *n*-butyllithium (9.0 mL, 14.0 mmol) was added and the solution stirred at 0 °C for 10 min. The lithium hexamethyldisilazide (LHMDS) thus formed was cooled to −78 °C. 1,1-Dichloro-2-(phenylthio)ethylene[38] (2.33 g, 11.4 mmol) in THF (15 mL) was added and the reaction allowed to warm to room temperature slowly over 5 h. The reaction was poured onto hexanes, washed twice with 0.5 M hydrochloric acid, twice with saturated sodium bicarbonate solution, once with water, and once with brine, and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator followed by Kugelrohr distillation gave the product as a red oil: yield 0.85 g (45%); bp 70–80 °C/0.1 torr; NMR (100 MHz, $CDCl_3$) 7.52–6.96 (m); MS, m/e 168 (M^+).

General Procedure for Enolate Reaction with (Phenylthio)chloroacetylene. This general procedure is identical with the general procedure described for enolate reaction with phenylchloroacetylene, except that (phenylthio)chloroacetylene (1.2 mmol) in THF (3 mL) was added to the enolate (1.0 mmol in 5 mL of THF). Crude products were purified by preparative thin-layer chromatography (20% ethyl acetate in hexanes as eluant) to give the adducts as colorless oils.

2,6-Dimethyl-6-((phenylthio)ethynyl)-2-cyclohexen-1-one. Starting with 2,6-dimethyl-2-cyclohexen-1-one, the above procedure was used: yield 43% (isolated with 30% recovered 2,6-dimethyl-2-cyclohexen-1-one; i.e., not separable by preparative TLC); NMR (product only, 100 MHz, $CDCl_3$) δ 7.40–6.96 (m, 5 H), 6.54 (br s, 1 H), 2.40–1.68 (m, 4 H), 2.80 (br s, 3 H), 1.44 (s, 3 H); IR (neat) 1680, 1580 cm^{-1}; MS, m/e 256 (M^+) (100).

3,3,5-Trimethyl-1-(phenylthio)hex-1-yn-4-one. Starting with 2,4-dimethyl-3-pentanone, the above procedure was used: yield 67%; NMR (100 MHz, $CDCl_3$) δ 7.56–7.08 (m, 5 H), 3.36 (m, 1 H), 1.44 (s, 6 H), 1.12 (d, J = 7 Hz, 6 H); IR (neat) 1715, 1580 cm^{-1}; MS, m/e 246 (M^+).

Kugelrohr distillation (bp 120–130 °C/0.1 torr) gave an analytically pure sample. Anal. Calcd for $C_{15}H_{18}OS$: C, 73.12; H, 7.36. Found: C, 73.33; H, 7.39.

Methyl 1-((Phenylthio)ethynyl)cyclohexanecarboxylate. Starting with methyl cyclohexanecarboxylate, the above procedure was used: yield 73%; NMR (100 MHz, $CDCl_3$) δ 7.40–7.04 (m, 5 H), 3.73 (s, 3 H), 2.08–1.12 (m, 10 H); IR (neat) 1735, 1580 cm^{-1}; MS m/e 274 (M^+) (45), 215 (100).

Ethyl 2,2-Dimethyl-4-(phenylthio)but-3-ynoate. Starting with ethyl isobutyrate, the above procedure was used: yield 75%; NMR (100 MHz, $CDCl_3$) δ 7.40–7.04 (m, 5 H), 4.16 (q, J = 7 Hz, 2 H), 1.56 (s, 6 H), 1.28 (t, J = 7 Hz, 3 H); IR (neat) 1735, 1580 cm^{-1}; MS, m/e 248 (M^+) (100).

General Procedure for Preparing Ethynyl Derivatives from Chloroethynyl Adducts. The chloroethynyl adduct (0.6 mmol) and copper powder (3.0 mmol) were suspended in THF (10 mL). Acetic acid (3 mL) was added and the reaction heated to 70 °C for 1 to 2 h. (The reaction was conveniently monitored by thin-layer chromatography.) During the course of the reaction, the reaction went from a copper–bronze color to a blue color. At completion (by TLC), the reaction was poured onto water and extracted three times with diethyl ether. The combined extracts were washed three times with saturated ammonium chloride solution, twice with saturated sodium bicarbonate solution, twice with water, once with brine, and dried over magnesium sulfate. Removal of the solvent on a rotary evaporator gave the products as colorless oils. No purification was necessary (products were clean by NMR and single spot on TLC). The less than quantitative yields represented mechanical loss of this reaction scale.

6-Ethynyl-2,6-dimethyl-2-cyclohexen-1-one. Starting with 6-(chloroethynyl)-2,6-dimethyl-2-cyclohexen-1-one, the above procedure was used: yield 77%; NMR (100 MHz, $CDCl_3$) δ 6.70 (br s, 1 H), 2.88–1.80 (m, 4 H), 2.18 (s, 1 H), 1.82 (br s, 3 H), 1.42 (s, 3 H); MS, m/e 148 (M^+).

2-Ethynyl-2-methyl-1-tetralone. Starting with 2-(chloroethynyl)-2-methyl-1-tetralone, the above procedure was used: yield 74%; NMR (100 MHz, $CDCl_3$) δ 8.00 (dd, J = 7,2 Hz, 1 H), 7.50–7.08 (m, 3 H), 3.52–3.16 (m, 1 H), 3.00–2.68 (m, 1 H), 2.36–1.96 (m, 2 H), 2.16 (s, 1 H), 1.53 (s, 3 H); IR (neat) 3300, 1695, 1600 cm^{-1}; MS, m/e 184 (M^+).

Methyl 1-Ethynylcyclohexanecarboxylate. Starting with methyl 1-(chloroethynyl)cyclohexanecarboxylate, the above procedure was used: yield 75%; NMR (100 MHz, $CDCl_3$) δ 3.73 (s, 3 H), 2.28 (s, 1 H), 2.08–1.14 (m, 10 H); IR (neat) 3300, 1735 cm^{-1}; MS, m/e 166 (M^+) (24), 165 (18), 106 (100).

General Procedure for Preparing Vinyl Derivatives from Chloroethynyl Adducts. The chloroethynyl adduct (1.0 mmol) was suspended in ethyl acetate (5 mL). Triethylamine (0.5 mL) and Lindlar catalyst (20 mg, purchased from Aldrich) were added. The reaction flask was attached to an atmospheric pressure hydrogenation apparatus at room temperature. When the theoretical amount of hydrogen gas was taken up, the reaction was diluted with pentanes and filtered through Celite. Removal of the solvent on a rotary evaporator gave the products as colorless oils. No purification was necessary.

2,6-Dimethyl-6-vinyl-2-cyclohexen-1-one. Starting with 6-(chloroethynyl)-2,6-dimethyl-2-cyclohexen-1-one, the above procedure was used: yield 96%; NMR (100 MHz, $CDCl_3$) δ 6.48 (br s, 1 H), 5.78 (dd, J = 17,10 Hz, 1 H), 4.92 (d, J = 10 Hz, 1 H), 4.80 (d, J = 17 Hz, 1 H), 2.40–1.80 (m, 4 H), 1.76 (br s, 3 H), 1.20 (s, 3 H).

2-Methyl-2-vinyl-1-tetralone. Starting with 2-(chloroethynyl)-2,6,6-trimethylcyclohexanone, the above procedure was used: yield 94%; NMR (100 MHz, $CDCl_3$) δ 7.94 (dd, J = 7,2 Hz, 1 H), 7.44–7.00 (m, 3 H), 5.90 (dd, J = 16,10 Hz, 1 H), 5.00 (d, J = 10 Hz, 1 H), 4.88 (d, J = 16 Hz, 1 H), 3.10–1.90 (m, 4 H), 1.28 (s, 3 H).

2,6,6-Trimethyl-2-vinylcyclohexanone. Starting with 2-(chloroethynyl)-2,6,6-trimethyl-2-cyclohexanone, the above procedure was used: yield 98%; NMR (100 MHz, $CDCl_3$) δ 5.86 (dd, J = 17,10 Hz, 1 H), 5.04 (d, J = 17 Hz, 1 H), 5.02 (d, J = 10 Hz, 1 H), 2.24–1.44 (m, 6 H), 1.14 (s, 3 H), 1.10 (s, 3 H), 1.08 (s, 3 H).

Methyl 1-Vinylcyclohexanecarboxylate. Starting with methyl 1-(chloroethynyl)cyclohexanecarboxylate, the above procedure was used: yield 95%; NMR (100 MHz, $CDCl_3$) δ 5.77 (dd, J = 18,10 Hz, 1 H), 5.08 (d, J = 10 Hz, 1 H), 5.03 (d, J = 18 Hz, 1 H), 3.68 (s, 3 H), 2.23–1.20 (m, 10 H).

Attempted Reaction between Diethyl (Pentachlorobutadienyl)methylmalonate (14) and the Lithium Enolate of Ethyl Isobutyrate (Eq 5). A stock solution of lithium diisopropylamide (LDA) was prepared as follows. Diisopropylamine (0.25 g, 2.5 mmol) was suspended in THF (3 mL) at 0 °C under nitrogen. A solution of 1.53 M *n*-butyllithium (1.6 mL, 2.5 mmol) was added and the solution stirred at 0 °C for 10 min, to give an approximately 0.5 M solution of LDA. An aliquot of this LDA solution (0.6 mL, 0.30 mmol) was cooled to −78 °C. Ethyl isobutyrate (35 mg, 0.30 mmol, neat) was added, followed immediately by the addition of HMPA (54 mg, 0.30 mmol, neat). The enolate thus formed was stirred at −78 °C for 30 min and then transferred via cannula to a solution of (119 mg, 0.30 mmol) diethyl (pentachlorobutadienyl)-methylmalonate (**14**) in THF (3 mL), precooled to −78 °C. The reaction mixture was allowed to warm to room temperature slowly over 4 h, poured onto water, and extracted four times with diethyl ether. The combined extracts were washed four times with water and twice with brine and then dried over magnesium sulfate. Removal of the solvent on a rotary evaporator gave an oil which was shown to be recovered starting materials by NMR and TLC.

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Registry No. 1, 62952-33-4; (*E*)-**2**, 89509-67-1; **3**, 40790-56-5; **4**, 77958-40-8; **5**, 73843-29-5; (*E*)-**6**, 73843-28-4; (*E*)-**7**, 89509-68-2; (*E*)-**8**, 89509-69-3; **9**, 73843-31-9; (*E*)-**11**, 89509-70-6; **13**, 77958-39-5; **14**, 77958-43-1; **15**, 77958-40-8; **16**, 89509-71-7; **17**, 89509-72-8; **18**, 77958-42-0; **21**, 5658-91-3; (*E*)-**22**, 77958-44-2; (*Z*)-**22**, 77958-46-4; **23**, 77958-45-3; (*Z*)-**24**, 89509-73-9; **25**, 89509-74-0; (*Z*)-**26**, 89509-75-1; **31**, 83022-81-5; **34**, 83188-33-4; HCBD, 87-68-3; $CH_3CH_2CH(CO_2Et)_2$, 133-13-1; $CH_3COCH(CH_3)CO_2Et$, 609-14-3; $CH_3CH(CO_2Et)_2$, 609-08-5; $CH_3(CH_2)_3C(CH_3)(CO_2Et)_2$, 5514-29-9; $CH_3CH_2COCH_2C(CH_3)_2CO_2Et$, 89509-76-2; $CH_2(CO_2Et)_2$, 105-53-3; $(CH_3)_2CHCOCH(CH_3)_2$, 565-80-0; $(CH_3)_2CHCOC(CH_3)_2C{\equiv}CCl$, 83188-23-2; $(CH_3)_2CHCOC(CH_3)_2C{\equiv}CSPh$, 83188-28-7; $(CH_3)_2CHCO_2Et$, 97-62-1; $ClC{\equiv}CC(CH_3)_2CO_2Et$, 83188-30-1; $PhC{\equiv}CC(CH_3)_2CO_2Et$, 83188-31-2; $PhSC{\equiv}CC(CH_3)_2CO_2Et$, 83188-32-3; $Cl_2C{=}CHCl$, 79-01-6; *cis*-ClFC=CHCl, 13245-53-9; *trans*-ClFC=CHCl, 13245-54-0; C_2Cl_4, 127-18-4; $Cl_2C{=}CF_2$, 79-35-6; Me_2NH, 124-40-3; PhSH, 108-98-5; C_2Cl_2, 7572-29-4; $Cl_2C{=}CDCl$, 13291-68-4; $PhC{\equiv}CCl$, 1483-82-5; $PhSC{\equiv}CCl$, 79894-52-3; $PhSCH{=}CCl_2$, 83790-99-2; 2,6-di-

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methylcyclohexanone, 2816-57-1; 2-bromo-2,6-dimethylcyclohexanone, 55234-03-2; 6-chloro-2,6-dimethyl-2-cyclohexen-1-one, 89529-60-2; 2,6-dimethyl-6-(phenylethynyl)-2-cyclohexen-1-one, 83188-15-2; 2,6-dimethyl-6-[(phenylthio)ethynyl]-2-cyclohexen-1-one, 83188-18-5; 6-ethynyl-2,6-dimethyl-2-cyclohexen-1-one, 83188-16-3; 2,6-dimethyl-6-vinyl-2-cyclohexen-1-one, 83188-17-4; 2-methyl-1-tetralone, 1590-08-5; 2-(chloroethynyl)-2-methyl-1-tetralone, 83188-19-6; 2-ethynyl-2-methyl-1-tetralone, 83188-20-9; 2-methyl-2-vinyl-1-tetralone, 83188-35-6; 2,2,6-trimethylcyclohexanone, 2408-37-9; 2-(chloroethynyl)-2,6,6-trimethylcyclohexanone, 83188-21-0; 2,6,6-trimethyl-2-(phenylethynyl)cyclohexanone, 83188-22-1; 2,6,6-trimethyl-2-vinylcyclohexanone, 78828-56-5; methyl cyclohexanecarboxylate, 4030-82-4; methyl 1-(chloroethynyl)cyclohexanecarboxylate, 83188-24-3; methyl 1-(phenylethynyl)cyclohexanecarboxylate, 83188-25-4; methyl 1-[(phenylthio)ethynyl]cyclohexanecarboxylate, 83188-29-8; methyl 1-ethynylcyclohexanecarboxylate, 83188-26-5; methyl 1-vinylcyclohexanecarboxylate, 83188-27-6; 2,6-dimethylphenol, 576-26-1.

Supplementary Material Available: Calculation of the isotope effect by using the method of Melander and Saunders, ^{13}C NMR data in tabular form, and tables of crystallographic data (10 pages). Ordering information is given on any current masthead page.

On the Mechanism of the Photochemical Reaction between 1,4-Naphthalenedicarbonitrile and Methylbenzenes

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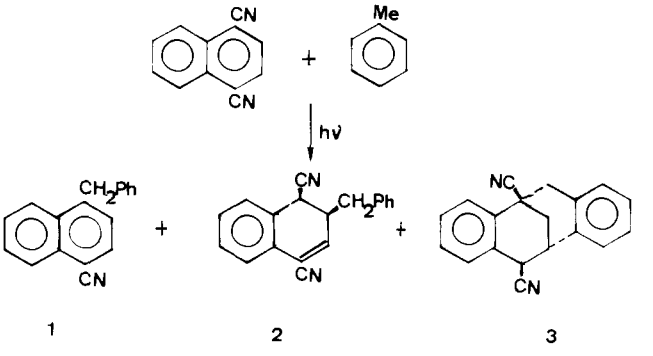
Abstract: On the basis of the correlation between fluorescence quenching and reaction quantum yield and of deuteration studies, it is shown that the photochemical reaction between 1,4-naphthalenedicarbonitrile (NDN) and methylbenzenes involves (i) water-mediated proton transfer within the charge-transfer exciplex, (ii) in-cage reaction of the two radicals to form 2-benzyl-1,2-dihydro-1,4-naphthalenedicarbonitrile (**2**) and 6,11-dicyano-5,11-methano-5,6,11,12-tetrahydrodibenzo[*a,e*]cyclooctene (**3**), the formation of the latter product requiring a further water-mediated hydrogen transfer, and (iii) escape of the benzylic radical, which is trapped by NDN, to give 4-benzyl-1-naphthalenecarbonitrile (**1**), a product formed also when benzylic radicals are generated from other sources.

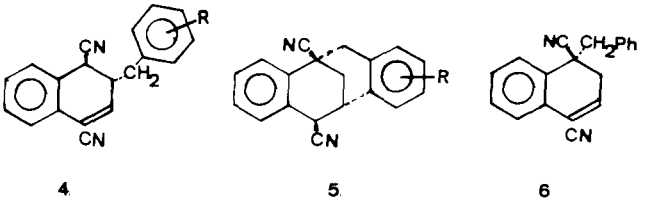
Aromatic molecules in their excited states differ from their ground-state counterpart mainly in their tendency to form complexes with other molecules containing n or π electrons.[1] This is a relevant change in the chemical properties, and the formation of an excited complex is, in some cases, revealed by the appearance of a new emission or by a chemical reaction. The latter possibility is of great interest because of the regio- and stereoselectivity often observed in the reaction, which can be attributed to the existence of preferred conformation in the excited complex. However, establishing a correlation between the photophysics of the exciplex and the chemical pathway to the products is usually not straightforward.

A large number of theoretical[2] and experimental[3-7] studies have been devoted to the photochemical reaction between aromatic molecules and alkenes or polyenes, to the elucidation of the role of exciplexes, and to the exploitation of the synthetic potential,[8] whereas mechanistic knowledge about photochemical reaction between aromatics is limited, being mainly confined to the 4 + 4 photodimerization of anthracenes and derivatives.[9]

We recently reported a new reaction with methyl aromatics. Thus, 1,4-naphthalenedicarbonitrile (NDN) and toluene photochemically react in polar media to yield products **1-3** (Scheme I), whereas in apolar solvents exciplex emission but no photochemical reaction is observed.[10] With 1,3,5-trimethyl- and 1,2,4,5-tetramethylbenzene the reaction is similar except that minor amounts of the stereoisomers **4** and **5** are formed.

Scheme I





The reaction is of interest in its stereochemical control, particularly in regard to the formation of the tetracyclic compound **3**, which appears to be a primary photoproduct (e.g., it does not arise from further photoreaction from **6**).[10] Different mechanistic pathways can be considered. Does the reaction proceed via hydrogen abstraction and direct coupling of the radicals or by

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