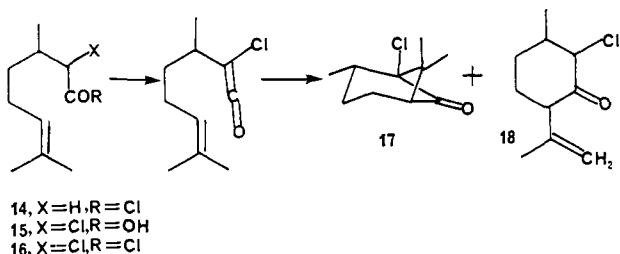er–Villiger oxidation of **1** and **7** proceeds in 90% yield to give **12** and **13**, respectively. This approach is therefore useful for the synthesis of the furofuran moiety of aflatoxins and neoclerodane insect antifeedants.

The preparation of **10** (entry 11) suggests that intramolecular ketene cycloadditions can provide a simple route to the pinane skeleton. Unfortunately, treatment of acyl chloride **14** with $NEt_3$ in benzene at reflux gave no cyclobutanone. Since (chloroalkyl)ketenes are known to give higher yields of cyclobutanones from alkenes than simple alkylketenes, we prepared the corresponding chloro acid **15** in 81% yield by treatment of the dianion of the acid with carbon tetrachloride.[8] Conversion of **15** to the acid chloride **16** with oxalyl chloride, followed by treatment with $NEt_3$ in benzene at reflux, gave a 55% yield of the desired bridged cyclobutanone **17** (from **15**) and an 18% yield of the Friedel–Crafts adduct **18**. As expected,[7a] the keteniminium salt reacts to give



14, X=H, R=Cl
15, X=Cl, R=OH
16, X=Cl, R=Cl

only the Friedel–Crafts adduct isopulegone in low yield.

These results clearly indicate the power of intramolecular [2 + 2] cycloadditions of ketenes to alkenes to generate complex polycyclic systems efficiently. This reaction provides a remarkably simple route to the pinane skeleton. We are continuing our exploration of the scope of the intramolecular cycloaddition which should find widespread use in organic synthesis.

**Registry No. 1**, 95123-29-8; **2**, 95123-30-1; **2** (semicarbazone), 95123-31-2; **3** (isomer 1), 95123-32-3; **3** (isomer 2), 95191-00-7; **4** (isomer 1), 95123-33-4; **4** (isomer 2), 95191-01-8; **4** (semicarbazone), 95123-34-5; **5** (isomer 1), 95123-35-6; **5** (isomer 2), 95191-02-9; **6**, 95123-36-7; **6** (semicarbazone), 18749-72-9; **7**, 95123-37-8; **8** (isomer 1), 95123-38-9; **8** (isomer 2), 95191-03-0; **9**, 95123-39-0; **10**, 95123-40-3; **11** (isomer 1), 95123-41-4; **11** (isomer 2), 95191-04-1; **12**, 95123-42-5; **13**, 95123-43-6; **14**, 36392-06-0; **16**, 95123-44-7; **17**, 95123-45-8; **18**, 95123-46-9; $CH_3C(=CH_2)(CH_2)_2OH$, 763-32-6; $CH_3(=CH_2)(CH_2)_3$-OH, 22508-64-1; $CH_3C(=CH_2)CH_2CH(CH_3)OH$, 2004-67-3; $CH_3C$-$(=CH_2)(CH_2)_2CH(CH_3)OH$, 50551-88-7; $CH_3C(=CH_2)CH(CH_3)C$-$H_3OH$, 1708-93-6; $CH_2=CH(CH_2)_2OH$, 627-27-0; (Z)-$CH_3CH_2CH=$$CH(CH_2)_2OH$, 928-96-1; $(CH_3)_2C=CH(CH_2)_2OH$, 763-89-3; $(CH_3)_2$-$C=CH(CH_2)_2CH(CH_3)OH$, 1569-60-4; $CH_3C(=CH_2)(CH_2)_2OCH_2C$-$O_2H$, 95123-48-1; $CH_3C(=CH_2)(CH_2)_3OCH_2CO_2H$, 95123-49-2; $CH_3C(=CH_2)CH_2CH(CH_3)OCH_2CO_2H$, 95123-50-5; $CH_3C(=CH_2)$-$CH_2)_2CH(CH_3)OCH_2CO_2H$, 95123-51-6; $CH_3C(=CH_2)CH(CH_3)C$-$H_2OCH_2CO_2H$, 95123-52-7; $CH_2=CH(CH_2)_2OCH_2CO_2H$, 95123-53-8; $CH_2=CH(CH_2)_2OCH_2CONMe_2$, 95123-54-9; $o$-$CH_2=$$CHC_6H_4OCH_2CO_2H$, 95123-55-0; (Z)-$CH_3CH_2CH=CH$-$(CH_2)_2OCH_2CO_2H$, 95273-92-0; (Z)-$CH_3CH_2CH=CH$-$(CH_2)_2OCH_2CONMe_2$, 95123-56-1; $(CH_3)_2C=CH(CH_2)_2OCH_2CO_2H$, 95123-57-2; $(CH_3)_2C=CH(CH_2)_2CH(CH_3)OCH_2CO_2H$, 95123-58-3; $(CH_3)_2C=CH(CH_2)_2CH(CH_3)CHCO_2^{-2}$, 95123-59-4; tetrahydro-4-propylidine-3-pyranone, 95123-60-7; 2-vinylphenol, 695-84-1; bromoacetic acid, 79-08-3; N,N-dimethyl-2-bromoacetamide, 39221-60-8.

**Supplementary Material Available:** $^1H$ and $^{13}C$ NMR and IR for **1–11** and **17** (3 pages). Ordering information is given on any current masthead page.

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[8] This efficient approach to α-chloro acids will be described separately.

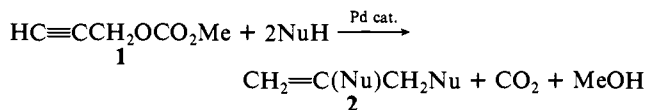## Novel Palladium-Catalyzed Reactions of Propargyl Carbonates with Carbonucleophiles under Neutral Conditions

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The palladium-catalyzed reactions of various allylic compounds with carbonucleophiles are well-established and useful synthetic methods.[1] We have shown that the allylation of carbonucleophiles can be carried out under neutral conditions by using allylic carbonates.[2–4] In contrast to the extensive studies on the palladium-catalyzed reactions of allylic compounds, very few studies have been carried out on the palladium-catalyzed reactions of propargyl compounds. The conversion of propargyl acetates or halides to 1,2-dienes by the reaction with hard carbonucleophiles such as alkyl magnesium or zinc compounds in the presence of palladium catalysts has been reported.[5] We wish to report here a new palladium-catalyzed reaction of propargyl carbonates with soft carbonucleophiles to give 2,3-disubstituted propenes **2** under neutral conditions as shown below.

$$HC≡CCH_2OCO_2Me + 2NuH \xrightarrow{\text{Pd cat.}}$$
$$\mathbf{1}$$

$$CH_2=C(Nu)CH_2Nu + CO_2 + MeOH$$
$$\mathbf{2}$$

Reaction of methyl propargyl carbonate (**1**) with 2 equiv of methyl 2-methyl-3-oxopentanoate in boiling THF for 2 h in the presence of $Pd_2(dba)_3CHCl_3$ and 1,2-bis(diphenylphosphino)-ethane (dppe) (Pd/dppe = $^1/_2$, 5 mol %) gave the adduct **3**[6] in 69% yield. Reaction of dimethyl malonate with **1** in boiling THF for 2 h afforded a 1:1 mixture of the adducts **4** and **5** in 49% yield. In boiling dioxane for 9 h, the exo olefin of **4** isomerized almost completely to the stable conjugated olefin to give **5**[6] in 69% yield (Scheme I).

β-Keto esters and β-diketones bearing two active hydrogens react with propargyl carbonates in a 1:1 ratio. In other words, both C- and O-alkylations take place with these compounds to give 4-methylene-4,5-dihydrofurans and 4-methylfurans (Table I). Reaction of **1** with methyl acetoacetate in THF at room temperature for 2 h in the presence of Pd/dppe catalyst (5 mol %) gave 3-(methoxycarbonyl)-2-methyl-4-methylene-4,5-dihydrofuran (**6a**)[8] in 88% yield after chromatographic purification on alumina.[9] This smooth cyclization proceeded under completely neutral conditions. On the other hand, the addition of a base was

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(1) For reviews, see: (a) Tsuji, J. "Organic Synthesis with Palladium Compounds"; Springer Verlag: Berlin, 1980. (b) Tsuji, J. *Pure Appl. Chem.* **1982**, *54*, 197–206. (c) Trost, B. M. *Tetrahedron* **1977**, *33*, 2615–2649. (d) Trost, B. M. *Acc. Chem. Res.* **1980**, *13*, 385–393.

(2) Tsuji, J.; Shimizu, I.; Minami, I.; Ohashi, Y. *Tetrahedron Lett.* **1982**, *23*, 4809–4812.

(3) Palladium-catalyzed neutral allylation using diene monoxides, see: (a) Tsuji, J.; Kataoka, H.; Kobayashi, Y. *Tetrahedron Lett.* **1986**, 2675–2578. (b) Trost, B. M.; Molander, G. A. *J. Am. Chem. Soc.* **1981**, *103*, 5969–5972. (c) Takahashi, T.; Kataoka, H.; Tsuji, J. *J. Am. Chem. Soc.* **1983**, *105*, 147–149.
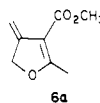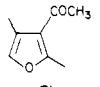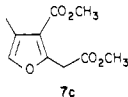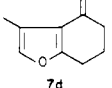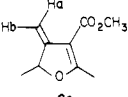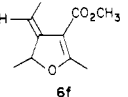
(4) Palladium-catalyzed neutral allylation by desilylation–allylation, see: (a) Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1979**, *101*, 6432–6433; **1980**, *102*, 6359–6361; **1981**, *103*, 5972–5974; **1983**, *105*, 2326–2335. (b) Trost, B. M.; Self, C. R. *J. Am. Chem. Soc.* **1983**, *105*, 5942–5944.

(5) (a) Jeffery-Juong, T.; Linstrumelle, G. *Tetrahedron Lett.* **1980**, *21*, 5019–5020. (b) Ruitenberg, K.; Kleijn, H.; Elsevier, C. J.; Meijer, J.; Vermeer, P. *Tetrahedron Lett.* **1981**, *22*, 1451–1452. (c) Elsevier, C. J.; Stehouwer, P. M.; Westmijze, H.; Vermeer, P. *J. Org. Chem.* **1983**, *48*, 1103–1105.
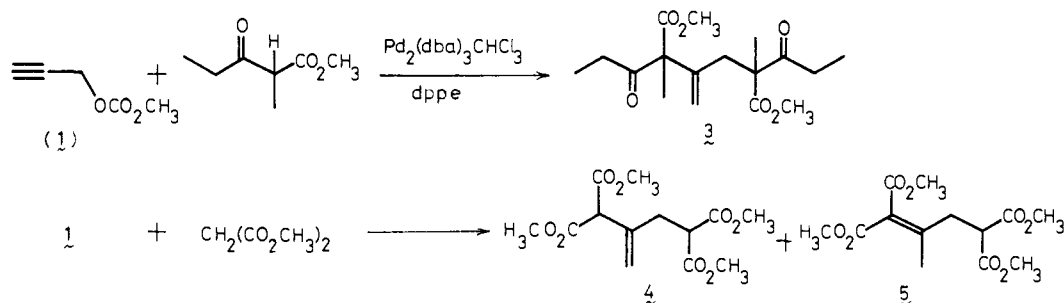
(6) Satisfactory spectral data were obtained for these materials and satisfactory elemental analyses were obtained as well.

(7) Batty, J. W.; Howes, P. D.; Stirling, C. J. M. *J. Chem. Soc., Perkin Trans. 1* **1973**, 65–68.

*Communications to the Editor*

*J. Am. Chem. Soc., Vol. 107, No. 7, 1985* 2197

**Table I.** Palladium-Catalyzed Synthesis of 4-Methylene-4,5-dihydrofurans **6**, 4-Methylfurans **7**, and Related Furan[a]

| entry | propargyl compd | nucleophile | temp, °C | time, h | prod[b] | yield, %[c] |
|---|---|---|---|---|---|---|
| 1 | HC≡CCH₂OCO₂Me (**1**) | CH₃COCH₂CO₂Me | rt | 4 | **6a** | 88 |
| 2[d,e] | HC≡CCH₂OAc | CH₃COCH₂CO₂Me | 80 | 2 | **6a** | 76 |
| 3[d,e] | HC≡CCH₂Br | CH₃COCH₂CO₂Me | 80 | 4 | **6a** | 20[f] |
| 4 | **1** | CH₃COCH₂COCH₃ | 60 | 1 | **7b** | 77[g] |
| 5[e] | **1** | MeO₂CCH₂COCH₂CO₂Me | 80 | 2 | **7c** | 86[g] |
| 6[e] | **1** | (cyclohexane-1,3-dione) | 80 | 4 | **7d** | 39[g] |
| 7 | CH₃C≡CCH₂OCO₂Me (**8**) | CH₃COCH₂CO₂Me | 60 | 1 | **6e** | 97 |
| 8 | HC≡CCH(CH₃)OCO₂Me (**9**) | CH₃COCH₂CO₂Me | 60 | 1 | **6f** | 79 |
| 9 | CH₃C≡CCH(CH₃)OCO₂Me (**10**) | CH₃COCH₂CO₂Me | 60 | 0.5 | **6f** | 94 |

[a] Reactions were carried out using propargyl compound (2 mmol) and nucleophile (2 mmol) in THF using Pd₂(dba)₃CHCl₃ (0.05 mmol) and dppe (0.2 mmol). [b] All products were identified by ¹H NMR and ¹³C NMR spectra. Alkylidenefurans **6a**, **6b**, **6e**, and **6f** were isomerized to the corresponding furans **7** under acidic conditions, which were identical with authentic samples prepared by the known procedure.[7] [c] Isolated yields after chromatographic purification. [d] NaH (2 mmol) was used. [e] Dioxane was used instead of THF. [f] CH₃COC(CH₂C≡CH)₂CO₂CH₃ (44%) was obtained as a major product by base-induced alkylation. [g] Isolated after treatment with acid.

**Scheme I**

necessary with propargyl acetate (76%) and bromide (20%). The methylenefurans **6** were unstable and isomerized to the stable furans **7** quantitatively under acidic conditions (3 N HCl, room temperature 10 min). Acetylacetone, dimethyl 3-oxoglutarate, and 1,3-cyclohexanedione reacted similarly with **1** to give the corresponding furans **7b** (77%), **7c** (86%), and **7d** (39%).

Reactions of both methyl 2-butynyl carbonate (**8**) and methyl 1-methylpropargyl carbonate (**9**) with methyl acetoacetate gave the same methylidenefuran **6e** selectively without forming the ethylidenefuran. Reaction of methyl 1-methyl-2-butynyl carbonate (**10**) gave (*E*)-2,5-dimethyl-3-ethylidenefuran (**6f**)[10] in 94% yield.

(8) Olefinic protons of **6e** appear at δ 4.59 (Hb) and 5.38 (Ha). The proton Ha lying cis in the plane of the ester carbonyl group resonates downfield from the trans proton Hb. For examples of deshielding of cis-γ-protons with carbonyl function, see: (a) Williams, D. H.; Bhacca, N. S.; Djerrassi, C. *J. Am. Chem. Soc.* **1963**, *85*, 2810–2817. (b) Jackman, L. M.; Wiley, R. H. *J. Chem. Soc.* **1960**, 2886–2890. (c) Martin, R. H.; Defay, N.; Geerts-Evrard, F. *Tetrahedron* **1964**, *20*, 1505–1518. (d) Elvidge, J. A.; Ralph, P. D. *J. Chem. Soc. C* **1966**, 387–389.

(9) Pd(PPh₃)₄ also catalyzed the reaction of **1** with methyl acetoacetate to give **6a** (83%), but Pd(OAc)₂(dppe) and PdCl₂(PhCN)₂ did not.

In order to elucidate the mechanism of the reaction, the furan formation was carried out using methyl α,α-dideuterioacetoacetate (**11**). The reaction of **8** with **11** gave the 5-deuteriofuran **12a** (97%) as a sole product, but the reaction of **9** afforded the furan **12b** deuterated at the methylene carbon (1:1 *E*/*Z* mixture, 67%). One deuterium from **11** was transferred to **8** or **9** at a different carbon.

In order to explain these results, we wish to propose the following mechanism for the furan formation (Scheme II). At first, S_N2′-type reaction of the propargyl carbonate with the palladium phosphine complex takes place to give 1,2-propadienylpalladium carbonate **13**. Then the palladium carbonate **13** undergoes de-
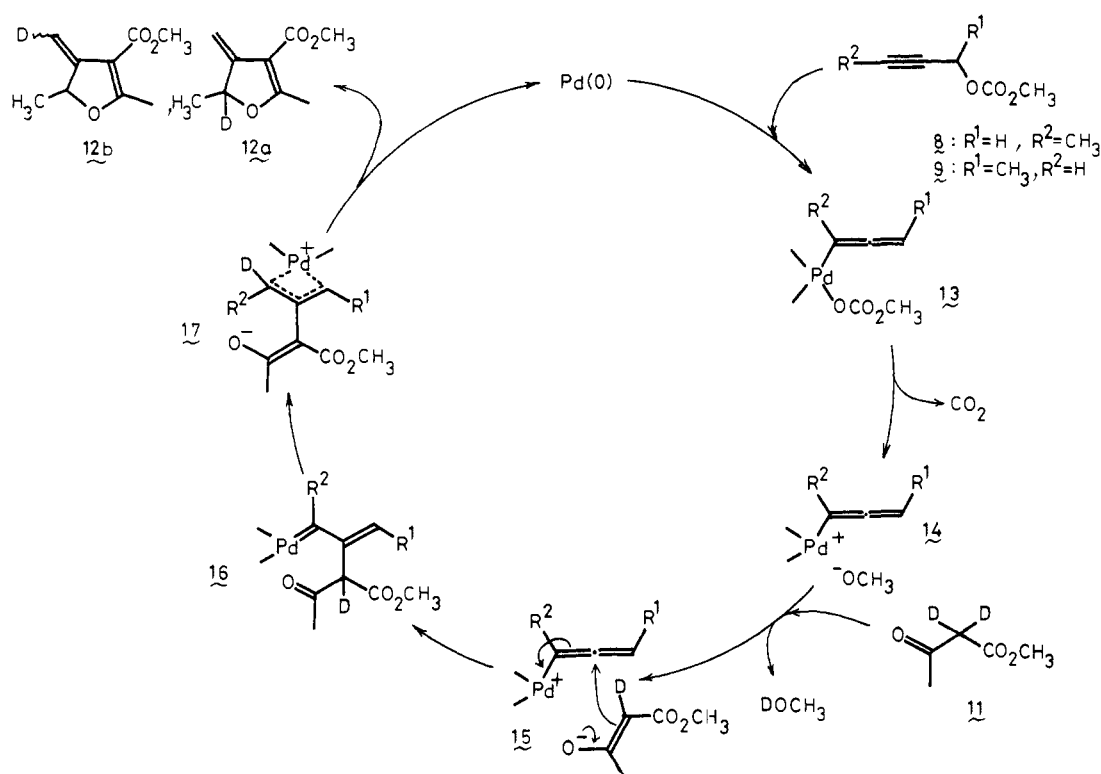
(10) Olefinic proton of **6f** appears at δ 5.02. Appearance of vinylic proton of **6f** 0.43 ppm downfield from Hb in **6a** indicates that the double bond in **6f** is *E* form.[11] This conclusion is also in agreement with the mechanistic consideration that the *E* double bond should be formed from the more stable syn-(π-allyl)palladium intermediate rather than anti form.

(11) Jackman, L. M.; Sternhell, S. "Application of Nuclear Magnetic Resonance Spectroscopy in Organic Synthesis", 2nd D.; Pergamon Press: Elmsford, NY, 1969; pp 159–267.

**Scheme II**

carboxylation to give a methoxide anion, which picks up an acidic hydrogen (or deuterium) from the active methylene compound to give the enolate complex **15**. Then the enolate anion attacks the sp carbon of the 1,2-propadienyl moiety to form the palladium carbene complex **16**, which isomerizes to ($\pi$-allyl)palladium complex **17** by intramolecular proton (or deuterium) transfer. Finally, the $\pi$-allyl complex **17** undergoes the intramolecular O-alkylation with the carbonyl oxygen at the more substituted side of the $\pi$-allyl system to give the *exo*-methylenefurans. Recently, the formation of palladium carbene complexes by desilylation of ($\pi$-[1-(trimethylsilyl)allyl])palladium complexes and subsequent reaction with carbonucleophiles has been reported.[4b] It is known that the palladium-catalyzed reaction of propargyl acetate with hard carbonucleophiles such as alkylzinc or magnesium compounds gives alkyl-1,2-propadienylpalladium complexes, which undergo reductive elimination to afford alkylated 1,2-dienyl compounds.[5] On the other hand, in the reaction of soft carbonucleophiles reported here, at first the nucleophile attacks the central sp carbon of the 1,2-ropadiene complex selectively. No example of such a reaction of alkenylpalladium complexes is known.

No other synthetic method for formation of unstable 4-alkylidene-4,5-dihydrofurans is known.[12] Also 4-methylfurans abound in naturally occurring terpenoids.[13,14] Thus the palla-

dium-catalyzed reactions of propargyl carbonates with soft carbonucleophiles under mild conditions are useful. Further synthetic applications and mechanistic investigation are in progress.

**Supplementary Material Available:** Experimental section including reaction of **1a** with methyl acetoacetate and characterization of **3, 5**, and **4** and table of spectral characterization of the furans in Table I (6 pages). Ordering information is given on any current masthead page.

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(12) Cf.: Trahanovsky, W. S.; Cassady, T. J.; Woods, T. L. *J. Am. Chem. Soc.* **1981**, *103*, 6691–6695.

(13) Devon, T. K.; Scott, A. I. "Handbook of Naturally Occurring Compounds"; Academic Press: New York, 1972; Vol. II.

(14) For recent works of the syntheses of 4-methylfurans, see: (a) Garst, M. E.; Spencer, T. A. *J. Org. Chem.* **1983**, *48*, 2442–2443. (b) Meier, L.; Runsink, J.; Scharf, H.-D. *Liebigs Ann. Chem.* **1982**, *45*, 2163–2171. (c) Tsuboi, S.; Shimazawa, K.; Takeda, A. *J. Org. Chem.* **1980**, *45*, 1517–1520. (d) Miyashita, M.; Kumazawa, T.; Yoshikoshi, A. *Chem. Lett.* **1979**, 163–166; *J. Org. Chem.* **1980**, *45*, 2945–2950. (e) Gopalan, A.; Magnus, P. *J. Org. Chem.* **1984**, *49*, 2317–2321 and references cited therein.