drops whereupon it turned deep brown. Aliquots (2 mL) were quenched with 0.1 mol dm$^{-3}$ aqueous HCl and then back titrated with 0.1 mol dm$^{-3}$ aqueous NaOH, activity ca. 95%. A 25-mL aliquot was treated with $ClSiMe_3$ and after 12 h the THF was removed in vacuo. GC/MS analysis of a hexane extract showed that 1,8-bis[(trimethylsilyl)methyl]naphthalene was the exclusive product. The remainder of the original reaction mixture was left for 3 days during which a deep red/brown precipitate formed. This was collected and washed with THF (2 × 10 mL), and 0.1 mol dm$^{-3}$ aqueous HCl was then added to a slurry of this material in THF (10 mL) yielding a white precipitate. This was collected and recrystallized from diethyl ether as fine white needles as one of the isomers of the conjugate acid of compound **27** possessing $C_2$ symmetry, 1.1 g, 43% yield, mp 230–231 °C. Anal. Found: C, 83.85; H, 7.45. Calcd for $C_{46}H_{48}Si_2$: C, 84.09; H, 7.36. $^1$H NMR (80 MHz, chloroform-*d*): $\delta$ 0.30 (s, 18 H, Si*Me*), 3.95 (m, 8 H, *CH*Si, *CHCH$_2$*), 6.2–7.9 (m, 22 H, $CH_{aromatic}$); $^{13}$C NMR (20.1 MHz, chloroform-*d*, $^1$H decoupled): $\delta$ 0.2 (Si*Me*), 40.2 ($CHCH_2$), 47.3 (CHSi) 47.9 ($CH_2$), 124.3, 125.8, 127.3, 129.1, 129.4, 132.4 ($CH_{aromatic}$), 131.2, 135.2, 135.7, 136.2, 138.4 ($C_{aromatic}$). MS: *m/e* 657 ($M^+$).

Data of new silicon compounds derived from quenching Grignard reagents **9** and **17** with $ClSiMe_3$ (and prepared by the in situ trapping of the Grignard reagents generated by using magnesium metal in THF in ca. 80% yield) are as follows. 4-*tert*-Butyl-2,6-dimethyl-1-[(trimethylsilyl)methyl]benzene, distilled as a colorless liquid, 135–136 °C, at 10$^{-2}$ mmHg. Anal. Found: C, 77.50; H, 11.10. Calcd for $C_{16}H_{28}Si$: C, 77.34; H, 11.36. $^1$H NMR (80 MHz, chloroform-*d*): $\delta$ 0.21 (s, 9 H, Si*Me*), 1.47 (s, 9 H, C*Me*$_3$), 2.29 (s, 2 H, $CH_2$), 2.40 (s, 6 H, C*Me*) 7.16 (s, 2 H, $C_6H_2$). $^{13}$C NMR (20.1 MHz, chloroform-*d*, $^1$H decoupled): $\delta$ –0.2 (si*Me*), 19.6 ($CH_2$), 21.3 (C*Me*), 31.4 (C*Me*$_3$), 124.8 ($(CH)_2C_4$), 134.1, 134.8, 146.2 ($(CH)_2C_4$). MS: *m/e* 248 ($M^+$). 1-(Trimethylsilyl)-1-phenylpropane, distilled as a colorless liquid, 47–48 °C, at 5 mmHg. Anal. Found: C, 74.75; H, 10.35. Calcd for $C_{12}H_{20}Si$: C, 74.95, H, 10.47. $^1$H NMR (300 MHz, chloroform-*d*): $\delta$ 0.17 (s, 9 H, Si*Me*), 0.95 (t, 3 H, $J$ = 7.1 Hz, C*Me*), 1.90 (m, 3 H, *CH$_2$,CH*), 7.20 (m, 5 H, $C_6H_5$). $^{13}$C NMR (75.4 MHz, chloroform-*d*, $^1$H decoupled) $\delta$ 2.9 (Si*Me*), 14.3 (C*Me*), 22.5 ($CH_2$), 39.3 (CH), 124.2, 127.7, 128.0 ($(CH)_5C$) 143.7 ($(CH)_5C$). MS: *m/e* 192 ($M^+$).

**Reaction of 4 with (±)-1-Chloro-1-phenylethane in Toluene.** To a stirred slurry of **4** (1.3 g, 3 mmol) in toluene (15 mL) was added 1-chloro-1-phenylethane (0.43 g, 3 mmol) in toluene (15 mL). A yellow precipitate remained after 12 h and an acid-quenched aliquot indicated 85% formation of the Grignard reagent. The mixture was then transferred by cannula into a toluene/dry ice slurry and after 12 h the solvent was removed in vacuo and 2 mol dm$^{-1}$ of NaOH added. The mixture was washed with hexane and then acidified and extracted with diethyl ether. Concentration and distillation in vacuo gave 2-phenylpropionic acid. Yield 0.3 g, 70%; $[\alpha]_D$ +6.6° (EtOH); cf. +81° for resolved material.[55]

**Acknowledgement** is made to the Australian Research Grants Scheme for support of this research, to C. Eaborn for a sample of tris(trimethylsilyl)methyl chloride, and to M. V. Sargent for many helpful discussions.

**Registry No.** **1**, 86901-19-1; **2**, 114679-04-8; **3**, 109889-35-2; **4**, 109906-74-3; **5**, 100908-25-6; **6**, 114679-05-9; **7**, 100908-24-5; **9**, 114693-85-5; **10** (X = Cl), 96693-22-0; **10** (X = Br), 114693-86-6; **13**, 114693-87-7; **14** (X = Cl), 114693-88-8; **14** (X = Br), 114693-89-9; **15** (X = Cl), 114693-90-2; **16** (X = Cl), 34324-92-0; **17a** (X = Br), 41745-02-2; **17b** (X = Cl), 114693-91-3; **17b** (X = Br), 114693-92-4; **18**, 57482-85-6; **19a** (X = Cl), 78499-87-3; **19a** (X = Br), 114693-93-5; **19b** (X = Br, isomer 1), 114693-94-6; **19b** (X = Br, isomer 2), 114693-95-7; **20a** (X = Cl), 114693-96-8; **20a** (X = Br), 114693-97-9; **20b** (X = Cl), 114693-98-0; **21**, 96693-26-4; **22** (X = Cl), 84609-48-3; **22** (X = Br), 96693-23-1; **23** (X = Cl), 96693-24-2; **23** (X = Br), 96693-25-3; **24** (X = Cl), 114693-99-1; **24** (X = Br), 114694-00-7; **25** (X = Cl), 114694-01-8; **26** (X = Cl), 114694-02-9; **27** (conjugate acid), 114694-03-0; *o*-TMSCH(Br)$C_6H_4$CH(Br)TMS (isomer 1), 114694-04-1; *o*-TMSCH(Br)$C_6H_4$CH(Br)TMS (isomer 2), 114694-05-2; PhCH(Me)CH(Me)Ph, 5789-35-5; PhCH(Et)CH(Et)Ph, 5789-31-1; *p*-$ClMgCH_2C_6H_4(CH_2)_2C_6H_4CH_2MgCl$-*p*, 114694-06-3; $(Me_3Si)_3CMgCl$, 114694-07-4; 2,6-dimethyl-4-*tert*-butylbenzyl chloride, 19387-83-8; 9-anthrylmethyl chloride, 24463-19-2; 8-(chloromethyl)quinoline, 94127-04-5; phenyl(trimethylsilyl)methyl bromide, 17903-41-2; bis(2-chloromethyl)-1,1′-binaphthalene, 96693-27-5; 9-anthrylmethyl bromide, 2417-77-8; bis(2-bromomethyl)-1,1′-binaphthalene, 54130-90-4; 1,2-bis[(trimethylsilyl)methyl]benzene, 18412-14-1; 9-[(trimethylsilyl)methyl]anthracene, 88920-42-7; 8-[(trimethylsilyl)methyl]quinoline, 105212-20-2; 1,8-bis[(trimethylsilyl)methyl]naphthalene, 57754-03-7; 4-*tert*-butyl-2,6-dimethyl-1-[(trimethylsilyl)methyl]benzene, 114694-08-5; (±)-1-chloro-1-phenylethane, 38661-82-4; 1-(trimethylsilyl)-1-phenylpropane, 18027-67-3.

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(55) Raper, H. S. *J. Chem. Soc.* **1923**, *123*, 2557.

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# Nickel(0)-Catalyzed Cycloaddition of Diynes and Carbon Dioxide to Bicyclic α-Pyrones

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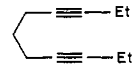
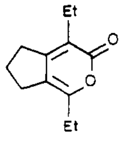
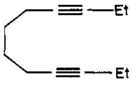
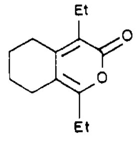
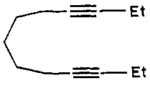
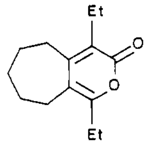
$Ni(COD)_2$–trialkylphosphine catalysts effected the cycloaddition of $CO_2$ and terminally dialkyl-substituted diynes $RC{\equiv}CCH_2{-}Z{-}CH_2C{\equiv}CR$ (**1**) (**1a**, Z = $CH_2$, R = Et; **1b**, Z = $CH_2CH_2$, R = Et; **1c**, Z = $CH_2CH_2CH_2$, R = Et; **1d**, Z = $CH_2CH_2$, R = Me; **1e**, Z = $CH_2CH_2$, R = *n*-Bu; **1f**, Z = $CH_2CH_2$, R = *sec*-Bu; **1g**, Z = O, R = Et; **1h**, Z = N-*n*-Pr, R = Et) to afford 3,6-dialkyl-4,5-cycloalkano-α-pyrones (**2**) in one step. Trialkylphosphines such as tri-*n*-alkyl- and tri-*sec*-alkylphosphines were the effective ligands. The structure of **1** had an influence upon the formation of **2**: each diyne **1** required its own suitable trialkylphosphine ligand. By the proper use of the phosphine ligand, the bicyclic α-pyrones **2** were obtained in 50–90% yields from diynes **1a–h** except **1c**. The diyne dimerization product **3** was formed as a byproduct in the formation reaction of **2d** from **1d**. This finding suggests that the bicyclic α-pyrone formation competes with the diyne oligomerization. Under the condition where the diynes **1a** and **1b** produced bicyclic α-pyrones **2a** and **2b** efficiently, the cycloaddition of the monoyne, e.g., 4-octyne, with $CO_2$ failed.

Utilization of carbon dioxide in a transition metal catalyzed synthesis of complex organic molecules is an interesting problem and has received considerable attention in recent years.[1] Transition metal catalyzed $CO_2$ fixation

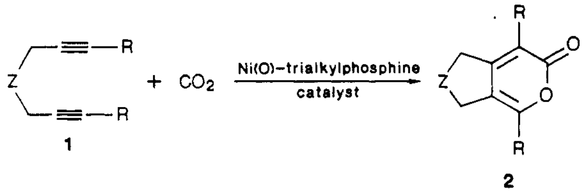
**Table I. Nickel(0)-Catalyzed Bicyclic α-Pyrone Synthesis from Diethyl-Substituted Diynes and $CO_2$**[a]

| diyne (1) | $Ni(COD)_2/1$ | ligand (L) | $L/Ni(COD)_2$ | temp, °C | bicyclic α-pyrone (2),[b] % | |
|---|---|---|---|---|---|---|
| <br>**1a** | 0.10 | $PCy_3$ | 1<br>2 | room temp | <br>**2a** | 65<br>88 [59][c] |
| | | | 4 | | | 83 |
| | | P-*sec*-$Bu_3$ | 2 | | | 86 |
| | | $PEt_3$ | | | | 19 |
| | | P-*n*-$Bu_3$ | | | | 25 |
| | | $PPh_3$ | | | | 8 |
| | 0.050 | $PCy_3$ | | 120 | | 90 |
| <br>**1b** | 0.10<br>0.050 | | | room temp<br>120 | <br>**2b** | 85 [64][c]<br>84 |
| <br>**1c** | 0.10 | | | room temp | <br>**2c** | 19 |

[a] 1, 0.90 mmol; $CO_2$ (initial pressure at room temperature), 50 kg/cm$^2$; solvent, THF (10 mL); time, 20 h. [b] Yield was determined by GC using an internal standard. [c] The value in brackets is the isolated yield (percent) by PLC in the reaction employing 0.90 mmol of 1.

into unsaturated hydrocarbons such as butadiene[2] and acetylenes[3] is an active research field in $CO_2$ chemistry. Synthesis of α-pyrones by the cycloaddition of acetylenes and $CO_2$ is interesting because mono- and bicyclic α-pyrones are useful intermediates in organic synthesis.[4] Monocyclic and annulated α-pyrone ring systems also are found in several biologically active natural products.[4a-c] New approaches to mono- and bicyclic α-pyrones have appeared recently, but these methods need multistep manipulations.[4c,5]

Nickel(0)-catalyzed monocyclic α-pyrone formation from internal monoacetylenic compounds (monoynes) and $CO_2$ has been reported.[3] In this reaction, a bidentate 1,4-bis(diphenylphosphino)butane (dppb) ligand is effective while a monodentate $PPh_3$ ligand is ineffective. The yield and the selectivity of the monocyclic α-pyrone formation, however, are moderate. Recently we reported bicyclic α-pyrone formation from diacetylenic compounds (diynes) and $CO_2$ by the use of a stoichiometric amount of the Ni(0)–phosphine complex in which a monodentate tricyclohexylphosphine ($PCy_3$) ligand is simlarly effective to dppb.[6] In this paper, we report a nickel(0)-catalyzed one-step bicyclic α-pyrone 2 synthesis by the cycloaddition of the diyne 1 and $CO_2$ using the monodentate trialkylphosphine ligand (eq 1). This reaction also offers a novel example using a carbonyl group as another component in the transition metal catalyzed cycloaddition of the diyne, which has received considerable attention recently as a useful methodology in organic synthesis.[7]



(1)

**a**, Z=$CH_2$, R=Et; **b**, Z=$CH_2CH_2$, R=Et; **c**, Z=$CH_2CH_2CH_2$, R=Et; **d**, Z=$CH_2CH_2$, R=Me; **e**, Z=$CH_2CH_2$, R=*n*-Bu; **f**, Z=$CH_2CH_2$, R=*sec*-Bu; **g**, Z=O, R=Et; **h**, Z=N-*n*-Pr, R=Et; **i**, Z=$CH_2CH_2$, R=H

When 3,8-undecadiyne (**1a**) was treated with $CO_2$ under pressure in the presence of a $Ni(COD)_2$–$2PCy_3$ catalyst (10 mol %) in THF at room temperature for 20 h, the bicyclic α-pyrone **2a** was obtained in 88% yield. The greater part of the formation of **2a** was acomplished in 5 h, but its completion required the reaction time of 20 h; 67% (5 h), 73%, (10 h), 88% (20 h), and 77% (40 h). Reactions carried out at reaction temperature between room temperature and 120 °C gave **2a** in good yields, but a higher reaction temperature of 130 °C decreased the yield of **2a**. Even at 0 °C, **2a** was obtained in moderate yield. Ether, 1,2-dimethoxyethane, and benzene were other suitable solvents. Pyridine, however, inhibited the reaction completely. The reaction using the decreased Ni(0) catalyst amount of 5.0 mol % produced **2a** only in low yield at room

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(1) (a) Sneeden, R. P. A. In *Comprehensive Organometallic Chemistry*; Wilkinson, G., Ed.; Pergamon: New York, 1982; Vol. 8, 225.

(2) For recent studies, see: (a) Behr, A.; He, R.; Juseak, K.-D.; Krüger, C.; Tsay, Y.-H. *Chem. Ber.* **1986**, *119*, 991 and references therein. (b) Hoberg, H.; Gross, S.; Milchereit, A. *Angew, Chem., Int. Ed. Engl.* 1987, *26*, 571 and references therein.

(3) Inoue, T.; Itoh, Y.; Kazama, H.; Hashimoto, H. *Bull. Chem. Soc. Jpn.* **1980**, *53*, 3329 and references therein.

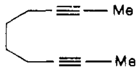
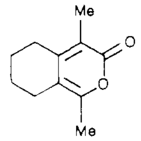
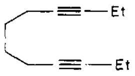
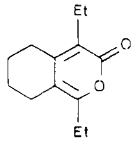
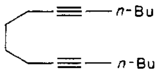
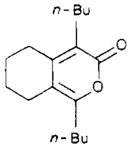
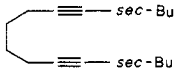
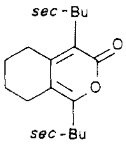
(4) (a) Staunton, J. In *Comprehensive Organic Chemistry*; Sammes, P. G., Ed.; Pergamon: Oxford, England, 1979; Vol. 4, 629. (b) Ellis, G. P. In *Comprehensive Heterocyclic Chemistry*; Boulton, A. J.; McKillop, A., Ed.; Pergamon: Oxford, England, 1984; Vol. 3, 675. (c) Dieter, R. K.; Fishpaugh, J. R. *J. Org. Chem.* **1983**, *48*, 4439 and references therein. (d) Jung, M. E.; Lowe, J. A.; Lyster, M. A.; Node, M.; Pfluger, R. W.; Brown, R. W. *Tetrahedron* **1984**, *40*, 4751.

(5) (a) Dieter, R. K.; Fishpaugh, J. R. *Tetrahedron Lett.* **1986**, *27*, 3823. (b) Stetter, H.; Kogelnik, H.-J. *Synthesis* **1986**, 140.

(6) Tsuda, T.; Sumiya, R.; Saegusa, T. *Synth. Commun.* **1987**, *17*, 147.

(7) See, for example: (a) Vollhardt, K. P. C. *Angew, Chem., Int. Ed. Engl.* **1984**, *23*, 539. (b) Negishi, E.; Cederbaum, F. E.; Takahashi, T. *Tetrahedron Lett.* **1986**, *27*, 2829. (c) Nugent, W. A.; Thorn, D. L.; Harlow, R. L. *J. Am. Chem. Soc.* **1987**, *109*, 2788.

**Table II. Nickel(0)-Catalyzed Bicyclic α-Pyrone Synthesis from Dialkyl-Substituted 1,7-Octadiynes and $CO_2$[a]**

| diyne (1) | ligand (L) | solvent (mL) | temp, °C | bicyclic α-pyrone (2),[b] % | |
|---|---|---|---|---|---|
|  <br>**1d** | $PMe_3$ | THF (5) | 80 |  <br>**2d** | 19 |
| | $PEt_3$ | | | | 43 |
| | P-*n*-$Bu_3$ | | room temp | | 21 |
| | | | 65 | | 46 |
| | | | 80 | | 45 |
| | | | 110 | | 44 |
| | P(*n*-$C_6H_{13})_3$ | | 80 | | 50 |
| | P(*n*-$C_8H_{17})_3$ | | | | 50 |
| | | THF (20) | | | 69 [65][c] |
| | | THF (20) | | | 75[d] |
| | P-*i*-$Bu_3$ | THF (10) | | | 41 |
| | P-*i*-$Pr_3$ | | | | 39 |
| | P-*sec*-$Bu_3$ | | | | 30 |
| | $PCy_3$ | | | | 33 |
| | P-*t*-$Bu_3$ | | | | 35 |
|  <br>**1b** | $PCy_3$ | | room temp |  <br>**2b** | 85 [64][c] |
|  <br>**1e** | $PEt_3$ | | 80 |  <br>**2e** | 42 |
| | $PCy_3$ | | | | 53 |
| | | THF (20) | room temp | | 70 |
| | | $CH_3C_6H_5$ (20) | | | 76 [68][c] |
|  <br>**1f** | P(*n*-$C_8H_{17})_3$ | THF (20) | 80 |  <br>**2f** | 50[e,f] |
| | | | 120 | | 31[f] |
| | $PCy_3$ | | 80 | | 16[e,g] |

[a] **1**, 0.50 mmol; $Ni(COD)_2/\mathbf{1} = 0.10$; $L/Ni(COD)_2 = 2$; $CO_2$ (initial pressure at room temperature), 50 kg/cm$^2$; time, 20 h. [b] Yield was determined by GC using an internal standard. [c] The value in brackets is the isolated yield (percent) by PLC in the reaction employing 0.50–0.90 mmol of **1**. [d] **1d**, 0.25 mmol. [e] Time, 50 h. [f] Conversion of **1f** was ca. 85%. [g] Conversion of **1f** was 61%.

temperature but afforded **2a** in excellent yield at 120 °C.

The formation of **2a** was highly dependent on the structure of the trialkylphosphine ligand used (Table I). Bulky and electron-donating tri-*sec*-alkylphosphines such as $PCy_3$ and P-*sec*-$Bu_3$ afforded **2a** efficiently. In contrast, tri-*n*-alkylphosphines such as P-*n*-$Bu_3$ and $PEt_3$ were less effective. Other phosphorus ligands such as tri-*o*-tolylphosphine, diisopropyl phenylphosphonite, trimethylolpropane phosphite, 1,4-bis(dicyclohexylphosphino)butane, and dppb together with nitrogen ligands such as 2,2′-dipyridyl and *N,N,N′,N′*-tetramethylethylenediamine were ineffective. Even at 100 °C, the dppb ligand, which is effective for the monoyne reaction,[3] produced **2a** only in 15% yield. It is noteworthy that the diyne exhibited a different ligand effect from the monoyne in the nickel(0)-catalyzed cycloaddtion with $CO_2$. The bicyclic α-pyrone with a fused six-membered ring, **2b**, was similarly obtained in high yield, but the one having a seven-membered ring, **2c**, was produced in low yield. These results are summarized in Table I.

Influence of the terminal alkyl substituent of the diyne upon the bicyclic α-pyrone formation was examined by using 1,7-octadiyne. Under the reaction conditions ($Ni(COD)_2$–$2PCy_3$ (10 mol %), THF, room temperature, and 20 h) where **2b** was produced effectively, the dimethyl-substituted 1,7-octadiyne **1d** gave **2d** only in 18% yield. The ligand effect was investigated at 80 °C to improve the yield of **2d**, and the results are summarized in Table II. It is noticeable that the methyl substituent exhibited a different ligand effect from the ethyl substituent. For the formation of **2d**, the tri-*n*-alkylphosphine ligand was preferable to the tri-*sec*-alkylphosphine ligand. For example, a $Ni(COD)_2$–$2P(n\text{-}C_8H_{17})_3$ catalyst (10 mol %) afforded **2d** in 50% yield in the reaction using 0.50 mmol of **1d** and 5 mL of THF at 80 °C for 20 h. In this reaction, the amount of solvent also influenced the formation of **2d**. Increasing the amount of THF raised the yield of **2d**: 33% (2 mL), 50% (5 mL), 69% (20 mL), and 75% (40 mL).[8] This may be related to the suppression of the diyne oligomerization (vide post). By the appropriate choice of ligand and solvent, **2e** and **2f** were obtained in 50–80% yield from the di-*n*-butyl- and di-*sec*-butyl-substituted 1,7-octadiynes, respectively. The reaction of **1f** proceeded relatively slowly to leave the starting diyne **1f** partly unreacted. The diyne with a heteroatom such as oxygen or nitrogen introduced into its methylene chain could also be used for the bicyclic α-pyrone synthesis (Table III). Reaction of unsubstituted diyne **1i** with $CO_2$ using $PEt_3$, $PCy_3$, P(*o*-tolyl)$_3$, PPh(O-*i*-Pr)$_2$, and dppb in THF at room

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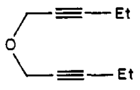
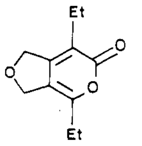
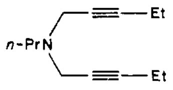
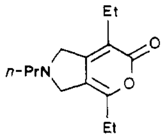
[8] See footnote *d* in Table II.

**Table III. Nickel(0)-Catalyzed Bicyclic α-Pyrone Synthesis from Diethyl-Substituted Diynes Having a Heteroatom in the Methylene Chain[a]**

| diyne (1) | ligand (L) | solvent | temp, °C | bicyclic α-pyrone,[b] % | |
|---|---|---|---|---|---|
|  <br>**1g** | $PEt_3$ | THF | 80 |  <br>**2g** | 33 |
| | $P(n\text{-}C_8H_{17})_3$ | | | | 49 |
|  <br>**1h** | $PCy_3$ | $C_6H_6$ | room temp |  <br>**2h** | 56 |
| | | THF | | | 32 |
| | | $CH_3C_6H_5$ | | | 43 |
| | $PEt_3$ | THF | 80 | | 67 |
| | $P(n\text{-}C_8H_{17})_3$ | $C_6H_6$ | | | 78 |
| | | THF | | | 71 [68][c] |
| | $PCy_3$ | | | | 45 |

[a] 1, 0.50 mmol; $Ni(COD)_2/1 = 0.10$; $L/Ni(COD)_2 = 2$; $CO_2$ (initial pressure at room temperature), 50 kg/cm$^2$; solvent, 20 mL; time, 20 h. [b] Yield was determined by GC using an internal standard. [c] The value in brackets is the isolated yield (percent) by PLC.

temperature to 120 °C did not produce the bicyclic α-pyrone **2i** although the starting diyne was almost or completely consumed. Use of a stoichiometric amount of the $Ni(COD)_2$–$2PEt_3$ complex, however, produced **2i** in ca. 15% yield in pyridine–toluene at room temperature. α,ω-Bis(trimethylsilyl)-1,7-octadiyne did not undergo the nickel(0)-catalyzed cycloaddition with $CO_2$.

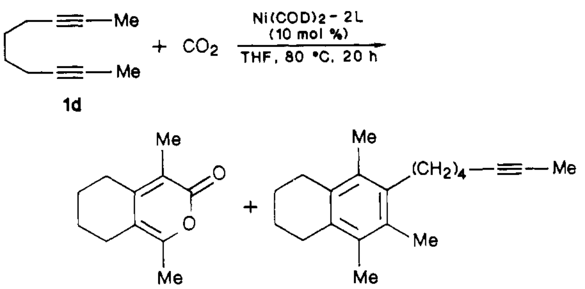
Thus the Ni(0)-catalyzed cycloaddition of the terminally dialkyl-substituted diyne and $CO_2$ provides a convenient method of preparing a variety of 3,6-dialkyl-4,5-cycloalkano-α-pyrones **2** (R = Me, Et, *n*-Bu, and *sec*-Bu; Z = $CH_2$, $CH_2CH_2$, O, and N-*n*-Pr) in one step. Each diyne substrate required its own suitable phosphine ligand; by the proper use of the tri-*n*-alkyl- and tri-*sec*-alkylphosphine ligands, **2** could be obtained in 50–90% yields. There are many reports on the transition metal promoted $CO_2$ fixation into unsaturated hydrocarbons.[1-3,6,9] Examples of the transition metal catalyzed $CO_2$ fixation with high efficiency, however, are limited. To our knowledge, two efficient reactions can be cited:[10] the $(\eta^3\text{-allyl})(\eta^5\text{-Cp})Pd$–$4PPh_3$-catalyzed reaction of methylenecyclopropane and $CO_2$ in DMF at 165 °C gives an unsaturated γ-lactone in 80% yield,[11] and the $Pd(acac)_2$–$3P\text{-}i\text{-}Pr_3$-catalyzed $CO_2$ fixation into butadiene in $CH_3CN$ at 90 °C produces an unsaturated δ-lactone selelctively (ca. 90%) although conversion of butadiene (ca. 45%) is not high.[2a] The present reaction affording **2a** and **2b** in ca. 90% yield adds another entry into the transition metal catalyzed efficient $CO_2$ fixation into unsaturated hydrocarbons.

**Table IV. Dimer 3 Formation in the Synthesis of Bicyclic α-Pyrone 2d from Diyne 1d (Eq 2)[a]**

| ligand (L) | **2d**,[b] % | **3**,[b] % |
|---|---|---|
| $PMe_3$ | 19 | 4 |
| $P\text{-}n\text{-}Bu_3$ | 45 | 0 |
| $P\text{-}t\text{-}Bu_3$ | 35 | 11 |
| $PCy_3$ | 33 | 0 |
| $P(n\text{-}C_8H_{17})_3$ | 50 | 15 |
| | 46[c] | 44[c] |

[a] **1d**, 0.50 mmol; $CO_2$ (initial pressure at room temperature), 50 kg/cm$^2$; solvent, THF (5 mL). [b] Yield was determined by GC. [c] Temperature, 120 °C; time, 5 h.

Diyne oligomers are possible side reaction products in the bicyclic α-pyrone synthesis. The formation of a dimer **3** was demonstrated in the reaction of **1d** (eq 2) and was



(2)

**2d** **3**

found to be dependent upon the phosphine ligand used (Table IV). Other oligomers[12] besides **3** may be formed because the starting diyne **1d** was completely consumed. The formation of **2d** and **3** satisfied the material balance of the reaction carried out at 120 °C for 5 h using $P(n\text{-}C_8H_{17})_3$. Coupled with the result that the starting diynes **1a**–**h** except the sterically congested **1f** were completely consumed in the reactions shown in Tables I–III, the formation of **3** suggests that the bicyclic α-pyrone is formed in competition with the diyne oligomerization.

The monoyne exhibited a remarkably different reactivity from that of the diyne. The Ni(0)-catalyzed cycloaddition of 4-octyne with $CO_2$ was carried out under the reaction

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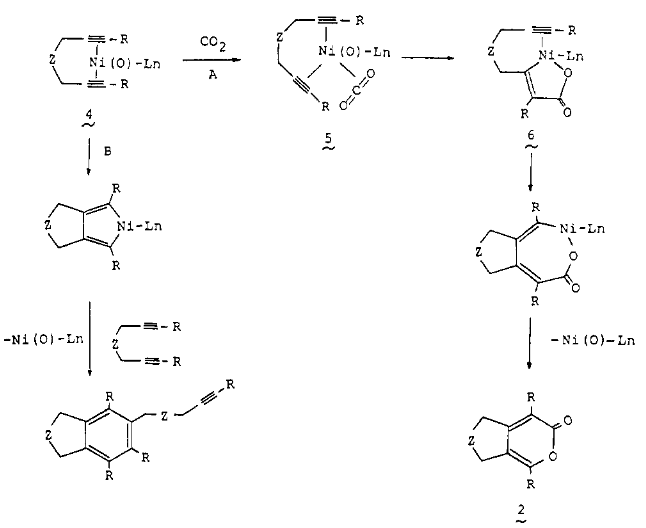
(9) For the reaction of ethylene and $CO_2$, see: (a) Alvarez, R.; Carmona, E.; C.-Hamilton, D. J.; Galindo, A.; G.-Puebla, E.; Monge, A.; Poveda, M. L.; Ruiz, C. *J. Am. Chem. Soc.* **1985**, *107*, 5529. (b) Hoberg, H.; Peres, Y.; Krüger, C.; Tsay, Y.-H. *Angew. Chem., Int. Ed. Engl.* **1987**, *26*, 771 and references therein. For the vinyl carbamate synthesis from acetylenes, amines, and $CO_2$, see: (c) Sasaki, Y.; Dixneuf, P. H. *J. Org. Chem.* **1987**, *52*, 314 and references therein. (d) Mitsudo, T.; Yamakawa, T.; Watanabe, Y. *Tetrahedron Lett.* **1987**, *28*, 4417.

(10) After completion of the present study, the quantitative monocyclic α-pyrone formation from 3-hexyne and $CO_2$ using the catalytic system $PEt_3/CH_3CN/Ni(COD)_2$ was reported; the catalytic system $PCy_3/CH_3CN/Ni(COD)_2$ was much less effective: Walther, D.; Schönberg, H.; Sieler, J. *J. Organomet. Chem.* **1987**, *334*, 377. Our preliminary experiments show that the catalytic system $PEt_3/CH_3CN/Ni(COD)_2$ was not highly effective for the synthesis of the bicyclic α-pyrone **2b**: $Ni(COD)_2$ (10 mol %)–$2PEt_3$ effected the reactions of **1b** (0.90 and 0.50 mmol) in THF (5 mL)–$CH_3CN$ (5 mL) at room temperature and 110 °C for 20 h to give **2b** in 46% (conversion of **1b**, 98%) and 55% (conversion of **1b**, 94%) yields, respectively.

(11) Binger, P.; Weintz, H.-J. *Chem. Ber.* **1984**, *117*, 654. See also: Inoue, Y.; Hibi, T.; Satake, M.; Hashimoto, H. *J. Chem. Soc., Chem. Commun.* **1979**, 982.

(12) (a) Chiusoli, G. P.; Pallini, L.; Terenghi, G. *Transition Met. Chem.* **1983**, *8*, 189. (b) Chiusoli, G. P.; Pallini, L.; Terenghi, M. G. *Transition Met. Chem.* **1985**, *10*, 350.

**Scheme I**



conditions ($Ni(COD)_2$ (5.0 mol %)-$2PCy_3$, THF, room temperature or 120 °C, 20 h) that produced **2a** and **2b** efficiently, but no corresponding monocyclic $\alpha$-pyrone was produced and the starting monoyne remained almost unreacted.[10] Thus it is preferable to discriminate the diyne as a novel substrate from the monoyne in the transition metal catalyzed $CO_2$ fixation into unsaturated hydrocarbons.

On the basis of the recent study[13] on the stoichiometric reaction of the Ni(0) complex, the monoyne, and $CO_2$, the probable reaction path for the Ni(0)-catalyzed bicyclic $\alpha$-pyrone formation is depicted in Scheme I.[14] The electron-donating trialkylphosphine ligand may be indispensable for tight $CO_2$ coordination[15] in **5** to generate the five-membered metallacycle **6**. The different reactivity between the diyne and the monoyne may be partly ascribed to an enhanced coordinating ability of the diyne toward the nickel atom in **4**–**6** owing to its intramolecular coordination. The pronounced effect of the structures of both the trialkylphosphine ligand and the alkyl substituent upon the bicyclic $\alpha$-pyrone formation suggests that these two factors control the subtle balance between the bicyclic $\alpha$-pyrone formation (route A) and the diyne oligomerization (route B).

## Experimental Section

IR spectra were determined on a Hitachi 260-50 grating spectrophotometer. $^1H$ NMR (400 MHz) and $^{13}C$ NMR (100 MHz) spectra were taken in $CDCl_3$ on a JEOL JNM-JX-400 instrument. All chemical shifts are reported in $\delta$ downfield from internal tetramethylsilane. Coupling constants ($J$) are reported in hertz. Mass spectra were obtained on a JEOL DX-300 instrument. Gas chromatographic analyses (GC) were made on a Shimadzu 4CPT instrument. GC quantitative analyses of reaction products were made with internal standards with calibration based upon authentic samples employing a 20% silicone DC 550 on Celite 545 column. Preparative layer chromatography (PLC) was carried out by using 20 × 20 × 0.2 cm plates prepared with Merck silica gel 60PF-254.

Tetrahydrofuran (THF) was distilled from $LiAlH_4$ under nitrogen. Benzene and toluene were distilled from $CaH_2$ under nitrogen. 1,7-Octadiyne (**1i**) was a commercial reagent and was distilled under nitrogen after drying over anhydrous $CaSO_4$ (Drierite). The terminally dialkyl-substituted diynes **1a**–**e** were prepared by alkylation of **1i** with alkyl iodides according to the published method.[16] Diyne **1f** was obtained by alkylation of **1i** using tri-*sec*-butylborane.[17] Diyne **1g** was prepared by the reaction of sodium 2-pentyl oxide and 1-bromo-2-pentyne.[18] Diyne **1h** was prepared by the ethylation[16] of *N*-*n*-propyl-di-2-propynylamine.[19] 4-Octyne was a commercial reagent and was distilled under nitrogen after drying over Drierite. Bis(1,5-cyclooctadiene)nickel(0) ($Ni(COD)_2$) was purchased from Kanto Kagaku, Inc. Phosphorus ligands were commercial reagents and were used without further puirification. Carbon dioxide was a commercial reagent (assay: minimum 99.99 vol %) supplied by Seitetsu Kagaku, Inc., and was used without further purification.

**Nickel(0)-Catalyzed Cycloaddition of 3,9-Dodecadiyne (1b) with Carbon Dioxide to the Bicyclic $\alpha$-Pyrone 2b.** The reaction was carried out under nitrogen. In a 50-mL stainless steel autoclave were placed a THF solution (1.8 mL) of $Ni(COD)_2$ (0.090 mmol), a toluene solution (0.17 mL) of tricyclohexylphosphine ($PCy_3$) (0.18 mmol), and THF (8.2 mL). After the mixture was stirred for several minutes, **1b** (0.19 mL, 0.90 mmol) was added and then $CO_2$ gas was compressed up to 50 kg/cm$^2$ at room temperature. The reaction mixture was magnetically stirred for 20 h at room temperature. The remaining $CO_2$ gas was purged off, and the reaction mixture was transferred to a flask using ether (20 mL). The solution was concentrated to give a residue that was purified by PLC (hexane:ether = 2:1 (v/v)) to give the product **2b** (0.12 g, 64%): IR (neat, cm$^{-1}$) 1695, 1625, 1540; $^1H$ NMR 1.01 (t, $J$ = 7.5, 3 H), 1.13 (t, $J$ = 7.5, 3 H), 1.58–1.68 (m, 4 H), 2.35–2.45 (m, 6H), 2.50–2.57 (m, 2 H); $^{13}C$ NMR 11.3, 12.1, 19.6, 22.0, 22.2, 23.7, 23.8, 26.8, 111.4, 123.4, 151.2, 158.7, 163.6; MS (*m*/*e*) (relative intensity) 206 (M$^+$, 42), 178 (36), 163 (100); HRMS (*m*/*e*) 206.1306, calcd for $C_{13}H_{18}O_2$ 206.1307.

The reactions of **2a** and **2c**–**h** were carried out as described above and the corresponding products were identified as follows. **2a** (PLC, hexane:ether = 2:1 (v/v)): IR (neat, cm$^{-1}$) 1695, 1625, 1540; $^1H$ NMR 1.01 (t, $J$ = 7.5, 3 H), 1.20 (t, $J$ = 7.6, 3 H), 2.00 (quint, $J$ = 7.4, 2 H), 2.42 (q, $J$ = 7.5, 2 H), 2.45 (q, $J$ = 7.6, 2 H), 2.62 (t, $J$ = 7.4, 2 H), 2.70 (t, $J$ = 7.5, 2 H); $^{13}C$ NMR 11.4, 12.5, 21.2, 25.08, 25.11, 27.45, 31.0, 118.7, 120.9, 156.0, 159.5, 164.6; MS (*m*/*e*) (relative intensity) 192 (M$^+$, 88), 177 (28), 164 (20), 149 (100); HRMS (*m*/*e*) 192.1141, calcd for $C_{12}O_{16}O_2$ 192.1150. **2c** (PLC, hexane:ether = 8:5 (v/v)): IR ($CDCl_3$, cm$^{-1}$) 1705, 1635, 1550; $^1H$ NMR 1.00 (t, $J$ = 7.4, 3 H), 1.12 (t, $J$ = 7.6, 3 H), 1.38–1.72 (m, 6 H), 2.38–2.53 (m, 6 H), 2.53–2.64 (m, 2 H); $^{13}C$ NMR 12.7, 13.7, 20.1, 24.5, 27.2, 27.8, 29.0, 30.1, 30.9, 117.4, 123.4, 156.7, 157.5, 164.0; MS (*m*/*e*) (relative intensity) 220 (M$^+$, 31), 192 (36), 177 (100); HRMS (*m*/*e*) 220.1439, calcd for $C_{14}H_{20}O_2$ 220.1463. **2d** (PLC, hexane:ether = 2:1 (v/v)): IR (neat, cm$^{-1}$) 1700, 1625, 1540; $^1H$ NMR 1.68–1.70 (m, 4 H), 1.98 (s, 3 H), 2.16 (s, 3 H), 2.37–2.40 (m, 2 H), 2.40–2.58 (m, 2 H); $^{13}C$ NMR 11.7, 16.7, 22.0, 22.2, 24.3, 27.7, 112.1, 117.6, 151.7, 153.9, 163.9; MS (*m*/*e*) (relative intensity) 178 (M$^+$, 58), 150 (100), 135 (23), 122 (36), 43 (54); HRMS (*m*/*e*) 178.0994, calcd for $C_{11}H_{14}O_2$ 178.0993. **2e** (PLC, hexane:ether = 2:1 (v/v)): IR (neat, cm$^{-1}$) 1710, 1630, 1550; $^1H$ NMR 0.92 (t, $J$ = 7.3, 6 H), 1.31–1.49 (m, 8 H), 1.66–1.73 (m, 4 H), 2.41–2.48 (m, 6 H), 2.59 (t, $J$ = 6.4, 2 H); MS (*m*/*e*) (relative intensity) 262 (M$^+$, 42), 234 (16), 191 (100); HRMS (*m*/*e*) 262.1939, calcd for $C_{17}H_{26}O_2$ 262.1933. **2f** (PLC, hexane:ether = 2:1 (v/v)): IR (neat, cm$^{-1}$) 1700, 1625, 1535; $^1H$ NMR 0.82 (dt, $J$ = 2.6, 7.5, 3 H), 0.84 (dt, $J$ = 3.5, 7.4, 3 H), 1.18 (dd, $J$ = 0.6, 6.9, 3 H), 1.25 (dd, $J$ = 1.2, 6.9, 3 H), 1.47–1.97 (m, 8 H), 2.41–2.49 (m, 2 H), 2.59–2.65 (m, 2 H), 2.67–2.83 (m, 2 H); MS (*m*/*e*) (relative intensity) 262 (M$^+$, 30), 233 (50), 205 (100); HRMS (*m*/*e*) 262.1916, calcd for $C_{17}H_{26}O_2$ 262.1932. **2g** (PLC, hexane:ether = 2:1 (v/v)): IR (neat, cm$^{-1}$) 1710, 1675, 1610, 1055; $^1H$ NMR 1.13 (t, $J$ = 7.6, 3 H), 1.23 (t, $J$ = 7.6, 3 H), 2.38 (q, $J$ = 7.6, 2 H), 2.43 (q, $J$ = 7.6, 2 H), 4.806 (s, 2 H), 4.811 (s, 2 H); MS (*m*/*e*) (relative intensity) 194 (M$^+$, 100), 151 (42), 57 (62); HRMS (*m*/*e*) 194.0943, calcd for $C_{11}H_{14}O_3$ 194.0943. **2h** (PLC, hexane:ether = 1:1 (v/v)): IR (neat, cm$^{-1}$)

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(14) For the reaction of $Ni(COD)_2$ and trialkylphosphines, see: Jolly, P. W.; Wilke, G. In *The Organic Chemistry of Nickel*; Academic: New York, 1974; Vol. 1, p 290.

(15) Aresta, M.; Nobile, C. F. *J. Chem. Soc., Dalton Trans.* **1977**, 708.

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(17) Suzuki, A.; Miyaura, N.; Abiko, S.; Itoh, M.; Brown, H. C.; Sinclair, J. A.; Midland, M. M. *J. Am. Chem. Soc.* **1973**, *95*, 3080.

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(19) Ben-Efraim, D. A. *Tetrahedron* **1973**, *29*, 4111.

*J. Org. Chem.* **1988**, *53*, 3145–3147 **3145**

1715, 1680, 1620; $^{1}$H NMR 0.99 (t, $J$ = 7.3, 3 H), 1.12 (t, $J$ = 7.5, 3 H), 1.22 (t, $J$ = 7.6, 3 H), 1.66 (sext, $J$ = 7.4, 2 H), 2.40 (q, $J$ = 7.4, 2 H), 2.43 (q, $J$ = 7.5, 2 H), 2.72 (t, $J$ = 7.3, 2 H), 3.75 (s, 2 H), 3.80 (s, 2 H); MS ($m/e$) (relative intensity) 235 (M$^+$, 22), 206 (100), 192 (32), 57 (16); HRMS ($m/e$) 235.1557, calcd for $C_{14}H_{21}NO_2$ 235.1572.

The stoichiometric reaction using **1i** (0.50 mmol), Ni(COD)$_2$ (0.50 mmol), and PEt$_3$ (1.00 mmol) under CO$_2$ pressure (initial pressure, 50 kg/cm$^2$) in pyridine (10 mL)–toluene (10 mL) at room temperature for 20 h produced **2i** in 22% yield as determined by GC. PLC (hexane:ether = 1:1 (v/v)) of the combined reaction products of the several reactions permitted isolation and identification of **2i**: IR (neat, cm$^{-1}$) 1720, 1635, 1535; $^{1}$H NMR (quint, $J$ = 3.4, 4 H), 2.46 (m, 2 H), 2.63 (m, 2 H), 6.07 (s, 1 H), 7.24 (s, 1 H); MS ($m/e$) (relative intensity) 150 (M$^+$, 100), 122 (81), 94 (33), 79 (38); HRMS ($m/e$) 150.0689, calcd for $C_9H_{10}O_2$ 150.0680.

**Nickel(0)-Catalyzed Cycloaddition of 2,8-Decadiyne (1d) with Carbon Dioxide to the Bicyclic α-Pyrone 2d and the Dimerization Product 3.** The reaction was carried out under nitrogen. In a 50-mL stainless steel autoclave were placed a THF solution (0.9 mL) of Ni(COD)$_2$ (0.050 mmol), tri-*n*-octylphosphine (0.046 mL, 0.10 mmol), and THF (4.1 mL). After the mixture was stirred for several minutes, **1d** (0.076 mL, 0.50 mmol) was added and then CO$_2$ gas was compressed up to 50 kg/cm$^2$ at room temperature. The reaction mixture was magnetically stirred for 5 h at 120 °C. The remaining CO$_2$ gas was purged off and then a THF solution (0.50 mL) of *n*-docosane (0.25 mmol) was added as a GC internal standard. GC analysis (a 1-m column of 20% silicone DC 550 on Celite 545) exhibited the formation of **2d** and **3** in 46% and 44% yields, respectively. PLC (hexane:ether = 7:1 (v/v)) of the combined reaction products of the several reactions permitted isolation and characterization of **3**: IR (neat, cm$^{-1}$) 1460, 1020; $^{1}$H NMR 1.51–1.67 (m, 4 H), 1.73–1.82 (m, 4 H), 1.77 (t, $J$ = 2.6, 3 H), 2.15 (s, 3 H), 2.18 (s, 3 H), 2.18–2.23 (m, 2 H), 2.25 (s, 3 H), 2.61–2.69 (m, 6 H); $^{13}$C NMR 3.4, 15.0, 15.4, 16.0, 18.5, 23.3, 28.3, 28.4, 29.0, 29.4, 29.9, 75.7, 79.1, 131.5, 131.7, 132.5, 133.1, 133.2, 136.3; MS ($m/e$) (relative intensity) 268 (M$^+$, 100), 253 (25), 187 (69), 173 (16); HRMS ($m/e$) 268.2178, calcd for $C_{20}H_{28}$ 268.2191.

**Registry No.** **1a**, 106449-82-5; **1b**, 61827-89-2; **1c**, 51566-74-6; **1d**, 4116-93-2; **1e**, 3779-15-5; **1f**, 114764-02-2; **1g**, 114764-03-3; **1h**, 114764-04-4; **1i**, 871-84-1; **2a**, 111395-95-0; **2b**, 111395-92-7; **2c**, 111395-96-1; **2d**, 111395-94-9; **2e**, 114764-05-5; **2f**, 114764-06-6; **2g**, 114764-07-7; **2h**, 114764-08-8; **2i**, 6249-20-3; **3**, 114764-09-9; Ni(COD)$_2$, 1295-35-8; PCy$_3$, 2622-14-2; P-*sec*-Bu$_3$, 17586-49-1; PEt$_3$, 554-70-1; P-*n*-Bu$_3$, 998-40-3; PPh$_3$, 603-35-0; PMe$_3$, 594-09-2; P($n$-C$_6$H$_{13}$)$_3$, 4168-73-4; P($n$-C$_8$H$_{17}$)$_3$, 4731-53-7; P-*i*-Bu$_3$, 4125-25-1; P-*i*-Pr$_3$, 6476-36-4; P-*t*-Bu$_3$, 13716-12-6; CO$_2$, 124-38-9; α,ω-bis(trimethylsilyl)-1,7-octadiyne, 63873-32-5.

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# Unexpected Regioselectivity in the Lithiation of Fluoroanisoles

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The regioselectivity of lithiation of a series of fluoroanisoles and fluoroveratroles has been studied by determining the ratio of isomeric aldehydes produced by dimethylformamide quenching. The position of lithiation is influenced by such factors as temperature and time of the reaction. Contrary to published reports, fluorine competes significantly with the methoxy group as an ortho director in lithiation reactions. Lithiation of dimethyl-*tert*-butylsilyl ethers of fluorophenols proceeds exclusively ortho to fluorine.

Electrophilic attack on aryllithium intermediates represents a versatile method for the functionalization of aromatic compounds.[1] Accordingly, factors controlling regioselectivity and efficiency of lithiation of aromatic substrates have been the subject of considerable research.[2] Of particular utility is the fact that certain functional groups on aromatic rings are effective in directing lithiation to the ortho position. The studies of Slocum[2b] and others[2] have resulted in a rank order in ortho-directing groups of CONR$_2$ > SO$_2$NR$_2$ > 2-oxazoline > CH$_2$NR$_2$ > OMe > F.

In the course of our research on fluorinated catecholamines we have used aryllithium intermediates extensively to prepare variously substituted fluorobenzaldehydes as convenient starting materials for side-chain elaboration. During this work we have noted unexpected behavior of fluorinated aromatic compounds. We have developed new procedures for regioselective introduction of electrophiles which exploit the ortho-directing influence of fluorine. These results are summarized in this report.

In an extensive investigation of aromatic lithiation, Slocum[2b] reported that lithiation of 4-fluoroanisole occurred exclusively ortho to the methoxyl group, while attempted lithiation of 2-fluoroanisole resulted in formation of a phenolic product, presumably through cleavage of the methyl ether, along with recovered starting material. On the other hand, Weinstock and Ladd[3] reported efficient lithiation of 3-fluoroanisole in the doubly activated 2-position under very mild conditions. In a later study, Adejare and Miller[4] cautioned that temperature-dependent benzyne formation can become a major competing pathway during lithiation of fluoroanisoles. Thus, at −35 °C benzyne formation is extensive during lithiation of 3-fluoroanisole, while at −78 °C benzyne-produced dimeric product can be minimized.

These previous studies were particularly relevant to our own work since we wished to use readily available fluoroanisoles and fluoroveratroles to prepare isomeric fluoroanisaldehydes and fluoroveratraldehydes by reaction of aryllithium intermediates with DMF. We also planned to introduce hydroxyl groups through oxidation of boronic

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