NaCl and dried ($MgSO_4$). The product was purified by flash chromatography on a 2 × 20 cm SiO_2 column by first separating nonpolar material with 30% ethyl acetate in petroleum ether (300 mL) and then eluting the carbamate with 5% methanol in chloroform. The product, **18**, was obtained as an amorphous blue solid which was dissolved in 3 mL of CH_2Cl_2 and added dropwise to 30 mL of petroleum ether. A fine blue solid was obtained (80 mg, 63%): mp 96–98 °C; ^1H NMR (py-d_5) δ 1.90 (s, 3 H, CH_3), 3.07 (s, 3 H, OCH_3), 3.4–3.55 (m, 2 H), 3.8–4.05 (m, 3 H), 4.6–4.9 (m, 4 H), 5.35–5.70 (m, 4 H), 6.8–7.7 (m, 7 H, ArH), 8.35 (d, J = 6.3 Hz, 1 H, ArH); IR (KBr) ν 3400, 1692, 1600, 1552 cm^{-1}; UV/vis (CH_3OH) λ_{max} 365 nm (log ϵ 4.32); HRMS m/e 610.1467 (calcd 610.1431). Anal. Calcd for $C_{28}H_{27}N_5O_7S_2 \cdot H_2O \cdot {}^1/_2EtOAc$: C, 53.60; H, 4.96; N, 10.43. Found: C, 53.76; H, 4.76; N, 10.00.

4-Nitrophenylcarbamic acid [4-[(3-nitrophenyl)dithio]-phenyl]methyl ester (12): yield 41%; yellow solid; mp 158–160 °C; ^1H NMR ($CDCl_3$) δ 1.60 (s, 1 H, NH), 5.25 (s, 2 H, CH_2OH), 7.2–8.4 (m, 12 H, ArH); UV/vis λ_{max} 313 nm (log ϵ 4.18); HRMS m/e 457.0408 (calcd 457.0402).

Benzyl MMC-1a-carboxylate (17): yield 55% blue powder; mp 100–101 °C (lit.[11] mp 102–103 °C).

3-(2-Pyridinyldithio)benzyl MMC-1a-carboxylate (19): yield 98%; blue powder; mp 90–92 °C; ^1H NMR (py-d_5) δ 1.90 (s, 3 H, CH_3), 3.05 (s, 3 H, OCH_3), 3.3–3.5 (m, 2 H), 3.7 (m, 2 H), 3.9–4.0 (m, 2 H), 4.5–4.8 (m, 4 H), 5.0–5.1 (m, 2 H), 5.50 (dd, J = 5.0, 6.5 Hz, 1 H), 6.8–7.7 (m, 7 H, ArH), 8.3–8.4 (m, 1 H, ArH); IR (KBr) ν 3400, 2920, 1690, 1550 cm^{-1}; UV/vis (CH_3OH) λ_{max} 357 nm (log ϵ 4.31); HRMS m/e 610.1414 (calcd 610.1431). Anal. Calcd for $C_{28}H_{27}N_5O_7S_2 \cdot H_2O \cdot {}^1/_2EtOAc$: C, 53.60; H, 4.96; N, 10.43. Found: C, 53.88; H, 4.66; N, 10.31.

4-(2-Pyridinyldithio)benzyl MMC-1a-carboxylate (20): yield 92%; blue powder; mp 99 °C dec; ^1H NMR (py-d_5) δ 1.95 (s, 3 H, CH_3), 3.15 (s, 3 H, OCH_3), 3.4–4.2 (m, 6 H), 4.6–5.0 (m, 4 H), 5.20 (s, 2 H, $ArCH_2$), 5.6 (dd, J = 4.6, 6.3 Hz, 1 H), 6.9–7.8 (m, 7 H, ArH), 8.35–8.5 (m, 1 H, ArH); IR (KBr) ν 3400, 2929, 1690, 1552 cm^{-1}; UV/vis (CH_3OH) λ_{max} 356 nm (log ϵ 4.31); HRMS m/e 610.1382 (calcd 610.1431). Anal. Calcd for $C_{28}H_{27}N_5O_7S_2 \cdot {}^1/_2H_2O \cdot {}^1/_2EtOAc$: C, 54.36; H, 4.88; N, 10.57. Found: C, 54.20; H, 4.55; N, 10.68.

4-[(3-Nitrophenyl)dithio]benzyl MMC-1a-carboxylate (21): prepared from MMC and chloroformate **8** according to the previously described methods; yield 70%; blue powder; mp 97–98 °C; ^1H NMR (py-d_5) δ 1.85 (s, 3 H, CH_3), 3.03 (s, 3 H, OCH_3), 3.35–3.42 (m, 2 H), 3.65 (d, J = 4.5 Hz, 1 H), 3.85–3.95 (m, 2 H), 4.55 (d, J = 13.2 Hz, 1 H), 4.70 (t, J = 8.0 Hz, 1 H), 4.75–4.85 (m, 3 H), 5.0–5.1 (m, 2 H, $ArCH_2$), 5.5 (dd, J = 4.5, 6.1 Hz, 1 H), 7.2–7.9 (m, 7 H), 8.30 (m, 1 H, ArH); IR (KBr) ν 3400, 2920, 1690, 1600, 1560, 1350 cm^{-1}; UV/vis (CH_3OH) λ_{max} (log ϵ) 356 (4.32), 242 (4.50); HRMS m/e 654.1322 (calcd 654.1328).

Reaction of 12 with Dithiothreitol. To a 4:1 CH_3OH/H_2O solution at room temperature containing **12** (0.08 mM) in tris(hydroxymethyl)aminomethane buffer (17 mM) and ethylenediamine tetraacetic acid (0.08 mM) at a final pH of 6.0, 7.2, or 8.0, was added excess dithiothreitol. p-Nitroaniline release (λ_{max} 371 nm, log ϵ 4.34) was measured by UV/vis spectroscopy and confirmed by HPLC analysis (Waters-μ-Bondapak column, 20% CH_3OH in 10 mM CH_3COOH (pH 4), monitored at 254 nm).

Reaction of MMC Benzyl Carbamate Disulfides 18–20 with Dithiothreitol. To a 4:1 CH_3OH/H_2O solution at 30 °C containing **18**, **19**, or **20** (0.81 mM) in tris(hydroxymethyl)-aminomethane buffer (17 mM) and ethylenediamine tetraacetic acid (0.08 mM) at pH 7.2 was added dithiothreitol (final concentration 2 mM). The release of MMC was measured by HPLC using a 10-cm Whatman Partasil 5 ODS-3 reverse phase (C-18) column and the following gradient system: 30% CH_3OH in 0.1% acetate (pH 6) to 95% CH_3OH in 6 min; continued for 8 min; flow rate 2 mL/min; monitored at 340 nm.

Cytotoxicity Studies. In vitro experiments were done using HSB2 (human T cell leukemia) and Namalwa (Burkitts lymphoma) cells obtained from American Type Culture Collection (Rockville, MD). The cells were grown in RPMI 1640 medium supplemented with 10% fetal bovine serum, penicillin, and streptomycin at 37 °C in 5% CO_2 humid atmosphere. Serial dilutions (in triplicate) of drugs were made in phosphate buffered saline (pH 7.2) and 100 μL of each dilution was added to 96-well microtiter plates. To each well was added a suspension of 10^5 cells in 100 μL of phosphate buffered saline (pH 7.2). The cells were incubated for 1 h at 37 °C, washed twice, and resuspended in 200 μL of culture medium. After incubation at 37 °C for 19 h, 50 μL of 1 μCi [6-^3H]thymidine (New England Nuclear, 15 Ci/mmol) was added to each well, and incubation was continued for 4 h at 37 °C. The cells were transferred to Millititer sv plates (Millipore) and precipitated with 25% cold trichloroacetic acid (TCA). The precipitates were washed 10 times with 5% cold TCA. Filters were dried, punched, and counted in Econofluor liquid scintillation fluid (New England Nuclear). All counts were corrected by subtraction of background counts. Cytotoxicity was expressed as the percent of [^3H]thymidine incorporated into DNA relative to untreated controls.

Acknowledgment. We wish to thank Drs. Terry Doyle and Dinesh Vyas for their helpful discussions and encouragement throughout the course of this research and Ana Wieman and Virginia LaMar for preparation of the manuscript.

Supplementary Material Available: ^1H NMR spectra for **4**, **12**, and **18–21** (3 pages). Ordering information is given on any current masthead page.

Nickel(0)-Catalyzed Cycloaddition of Silyl Diynes with Carbon Dioxide to Silyl Bicyclic α-Pyrones

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Mono- and bicyclic α-pyrones are useful intermediates in organic synthesis.[1] Furthermore monocyclic and annulated α-pyrone ring systems are found in several biologically active natural products.[1a-c] Thus it is interesting to develop a convenient synthetic method for functionalized α-pyrones. A silyl-substituted α-pyrone is attractive because the silyl substituent attached to an sp^2-carbon atom is known to be easily converted into a variety of functional groups,[2] i.e., halogen, acyl, and hydroxy groups[3] along with a hydrogen atom. Examples of the synthesis of silyl α-pyrones, however, are few. Formation of 3- and 5-(trimethylsilyl)-substituted 6-ethoxy-4-methyl-α-pyrones by the rhodium-catalyzed carbonylation of 1-carbethoxy-3-methyl-2-(trimethylsilyl)cyclopropene has been described.[4]

Recently we have reported the Ni(0)–trialkylphosphine complex-catalyzed one-step bicyclic α-pyrone synthesis from diynes and CO_2. A remarkable effect of the phosphine ligand on this reaction was observed: monodentate trialkylphosphine ligands such as $P(n\text{-}C_8H_{17})_3$ and tricyclohexylphosphine (PCy_3) are effective for the reaction of terminally dialkyl-substituted diynes[5] while the reaction of unsubstituted diynes requires the use of a functionalized

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

(2) Colvin, E. W. *Silicon in Organic Synthesis*; Butterworths: London, 1981; Chapter 7.

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(4) Cho, S. H.; Liebeskind, L. S. *J. Org. Chem.* **1987**, *52*, 2631.

(5) Tsuda, T.; Morikawa, S.; Saegusa, T. *J. Org. Chem.* **1988**, *53*, 3140. See also: Tsuda, T.; Sumiya, R.; Saegusa, T. *Synth. Commun.* **1987**, *17*, 147.

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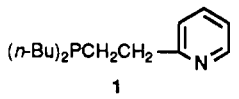
phosphine ligand, i.e., 1-(2′-pyridyl)-2-(di-*n*-butylphophino)ethane (1).[6] Here we investigated synthesis of



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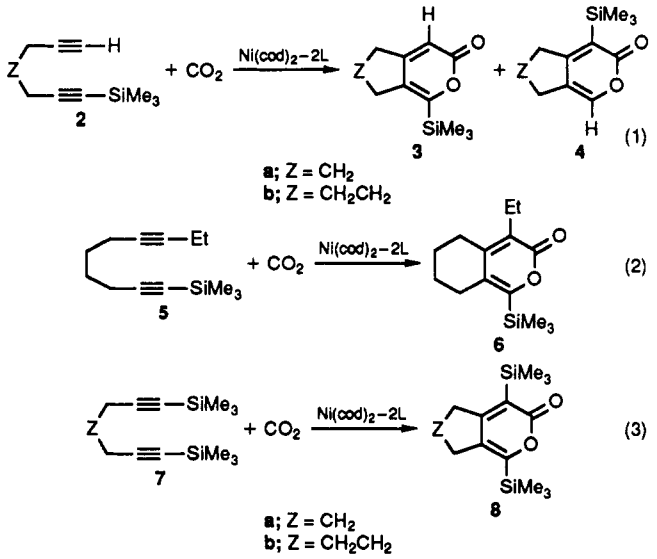
silyl-substituted bicyclic α-pyrones by the Ni(0)–trialkylphosphine complex-catalyzed cycloaddition of terminally silyl-substituted diynes with CO_2 (eqs 1–3). The reaction is also interesting for the reason that the Ni(0)-catalyzed cycloaddition of functionalized alkynes with CO_2 has not been known until our recent report on the reaction of ethoxyethyne and CO_2 forming 4,6-diethoxy-α-pyrone.[7]



a; Z = CH_2
b; Z = CH_2CH_2

The reactions were ordinally carried out in tetrahydrofuran (THF), using a Ni(0) catalyst (10 mol %) generated from $Ni(cod)_2$ and 2 equiv of the trialkylphosphine ligand (L). Table I summarizes the results of reactions of unsymmetrically silyl-substituted diynes **2a**, **2b**, and **5**. 6-(Trimethylsilyl)-substituted bicyclic α-pyrones **3b** and **6** containing a fused cyclohexane ring were produced regiospecifically from **2b** and **5**, respectively, without formation of the corresponding 3-(trimethylsilyl)-substituted isomers. In these two reactions, the bidentate phosphine ligand **1** containing a pyridyl functional group is the most effective catalyst while bis(diphenylphosphino)butane (dppb) was less effective. The monodentate trialkylphosphine ligands such as $P(n\text{-}C_8H_{17})_3$ and PCy_3, which give good results in the reaction of terminally dialkyl-substituted diynes,[5] were less efficient or ineffective.

By contrast, formation of the silyl bicyclic α-pyrone containing a fused cyclopentane ring from **2a** using the ligand **1** did not proceed regiospecifically; two regioisomeric bicyclic α-pyrones **3a** and **4a** were produced although the formation of **3a** was favored. Regioselectivity was increased as the reaction temperature was lowered. The bidentate dppb ligand also produced **3a** preferentially. The regioselectivity of the reaction of **2a**, however, was dependent upon the structure of the phosphine ligand used; tri-*n*-alkylphosphine ligands such as $P(n\text{-}Bu)_3$ and $P(n\text{-}C_8H_{17})_3$ gave **4a** exclusively.

Table II summarizes the results of reactions of bis(silyl)-substituted diynes **7a** and **7b**, where the ligand **1** was also effective. In comparison with the monosilyl-substituted diynes **2a**, **2b** and **5**, however, **7a** and **7b** showed a decreased reactivity toward CO_2. Under the reaction conditions using 10 mol % of $Ni(cod)_2$ and 2 equiv of **1**, conversion of **7a** and **7b** was low to moderate and the products **8a** and **8b** were obtained in low yields. Extension of the reaction time and elevation of the reaction temperature did not improve the results. This finding suggests that deactivation of the Ni(0) catalyst takes place during the reaction. An increase in the amount of the Ni(0) catalyst raised the yields of **8a** and **8b**; the effect was more pronounced in the formation of **8b** than **8a**. Thus the trimethylsilyl group acts as a deactivating substituent in the Ni(0)-catalyzed cycloaddition of diynes with CO_2 to bicyclic α-pyrones.[8]

Table I. Nickel(0)-Catalyzed Synthesis of Silyl Bicyclic α-Pyrones (Eq 1 and 2)[a]

diyne	ligand (L)	temp, °C	bicyclic α-pyrone,[b] %	
2a	$P(n\text{-}C_8H_{17})_3$	80	**3a**, 0	**4a**, 34
		100	0	59
		120	0	25
	dppb	100	39	9
	1	60	44	4
		60	52[f] [46][c,f]	5
		80	53	28
		100	32	20
2b	$P(n\text{-}C_8H_{17})_3$	100	**3b**, trace[e]	**4b**, 0
	$P(n\text{-}Bu)_3$–pyridine (1:1)	100	trace[e]	0
	dppb	100	14	0
		100	23[g]	0
	1	120	22[d]	0
		100	33[e]	0
		100	52 [43][c]	0
		120	45	0
5	PCy_3	120	**6**, trace	
	$P(n\text{-}C_8H_{17})_3$	120	33	
	dppb	120	38	
	1	100	74	
		120	80 [57][c]	

[a] Diyne, 0.25 mmol; $Ni(cod)_2$/diyne = 0.10; L/$Ni(cod)_2$ = 2; CO_2 (initial pressure at room temperature), 50 kg/cm²; solvent, THF (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. [d] $Ni(cod)_2$/diyne = 0.05. [e] Solvent, THF (10 mL). [f] Time, 40 h. [g] L/$Ni(cod)_2$ = 1.

The results of Tables I and II indicate that the functionalized phosphine ligand **1** was effective for the reactions of all five silyl-substituted diynes examined in the present study. Coupled with our previous work on the synthesis of unsubstituted and monoalkyl-substituted bicyclic α-pyrones,[6] it may be concluded that **1** is an excellent ligand that permits a variety of diynes to be used in the Ni(0)-catalyzed synthesis of bicyclic α-pyrones from diynes and CO_2.[9]

Elucidation of the reaction mechanism, the function of the ligand **1**, and the regiocontrol by the phosphine ligand are interesting subjects of a further study. In the formation of the bicyclic α-pyrones **3b** and **6** with a fused cyclohexane ring where steric factors are less important, it may be suggested that the carbon–carbon triple bond deactivated by the trimethylsilyl group permits the unsubstituted or ethyl-substituted carbon–carbon triple bond to react first with the Ni(0) catalyst and CO_2,[5] which leads to the re-

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(7) Tsuda, T.; Kunisada, K.; Nagahama, N.; Morikawa, S.; Saegusa, T. *Synth. Commun.* **1990**, *20*, 313.
(8) Recently the cycloaddition of bis(trimethylsilyl)-substituted diynes with isocyanide in the presence of a stoichiometric amount of $Ni(cod)_2$ has been reported: Tamao, K.; Kobayashi, K.; Ito, Y. *J. Org. Chem.* **1989**, *54*, 3517.
(9) The ligand **1** has been found to be also effective for the Ni(0)-catalyzed cycloaddition of terminally dialkyl-substituted diynes with CO_2. See ref 10.

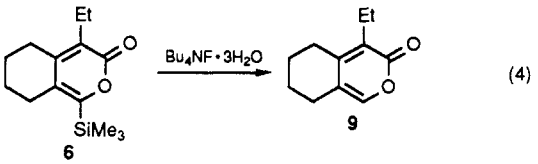
Table II. Nickel(0)-Catalyzed Synthesis of Silyl Bicyclic α-Pyrones (Eq 3)[a]

diyne (mmol)	$Ni(cod)_2$/diyne	ligand (L)	THF (mL)	temp (°C)	diyne conversion (%)[b]	bicyclic α-pyrone (%)[c]
7a, 0.10	0.50	$P(n\text{-}C_8H_{17})_3$	10	100	100	**8a**, 9
0.25	0.10	dppb	20	100	13	0
0.25	0.10	1	20	120	74	25
0.125	0.30		10	100	100	43
0.10	0.50		10	100	100	31
7b, 0.25	0.10	$P(n\text{-}C_8H_{17})_3$	10	100	5	**8b**, trace
0.10	0.50		10	100	100	75
0.25	0.10	dppb	10	100	12	0
0.25	0.10	1	10	100	18	14
0.125	0.30		10	100	77	38
0.10	0.50		10	100	100	71 [61][d]

[a] $L/Ni(cod)_2 = 2$; CO_2 (initial pressure at room temperature), 50 kg/cm²; time, 20 h. [b] Determined by GC. [c] Yield was determined by GC using an internal standard. [d] The value in brackets is the isolated yield (percent) by PLC.

giospecific formation of **3b** and **6**. It is known that bicyclic α-pyrones are formed in competition with diyne oligomerization in the Ni(0)-catalyzed reaction of diynes and CO_2.[5] The diyne oligomerization may be an important side reaction, therefore, in the reactions of **2b**, **7a**, and **7b** where silyl bicyclic α-pyrones were less efficiently formed.

The transformation reaction of the silyl bicyclic α-pyrones obtained was briefly examined. Protodesilylation of **6** with $Bu_4NF{\cdot}3H_2O$ gave 3-ethyl-substituted bicyclic α-pyrone **9** quantitatively (eq 4). This finding is important



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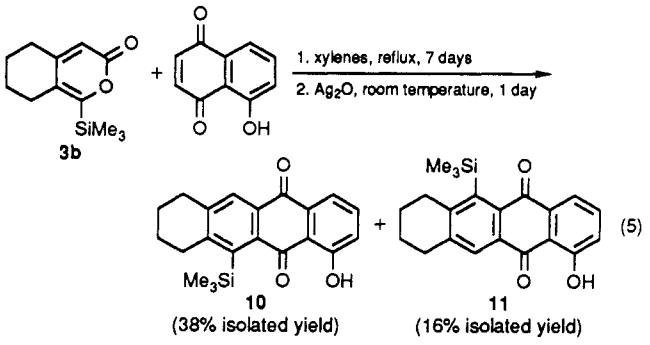
because **9** has not been obtained in a high yield by the Ni(0)-catalyzed cycloaddition of 1,7-decadiyne with CO_2.[10] Diels–Alder reaction of α-pyrones is known to be a useful synthetic reaction.[1] Cycloaddition of the silyl bicyclic α-pyrone **3b** with 5-hydroxy-1,4-naphthoquinone gave two regioisomeric cycloadducts, **10** and **11** (**10**/**11** = 70/30), after decarboxylation and oxidation (eq 5). The assign-



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ment of structures for **10** and **11** was impossible by simple spectroscopic means. The structure of **10** was determined by single-crystal X-ray analysis, which revealed two structural features of **10** (Figure 1). A phenolic proton forms a hydrogen bond with the adjacent carbonyl oxygen atom. Another interesting feature is a remarkable deviation of the trimethylsilyl group from the plane consisting of the anthraquinone moiety; the silicone atom is located ca. 0.5 Å away from a mean plane of the benzene ring bearing the trimethylsilyl group. This deviation of the trimethylsilyl group may be ascribed to its steric bulkiness. Thus it is noteworthy that the bicyclic α-pyrone **3b** bearing the trimethylsilyl group at C-6 underwent the facile Diels–Alder reaction. To our knowledge, this is the first example of the Diels–Alder reaction of silyl α-pyrones.

(10) Tsuda, T.; Morikawa, S.; Saegusa, T. Unpublished results.

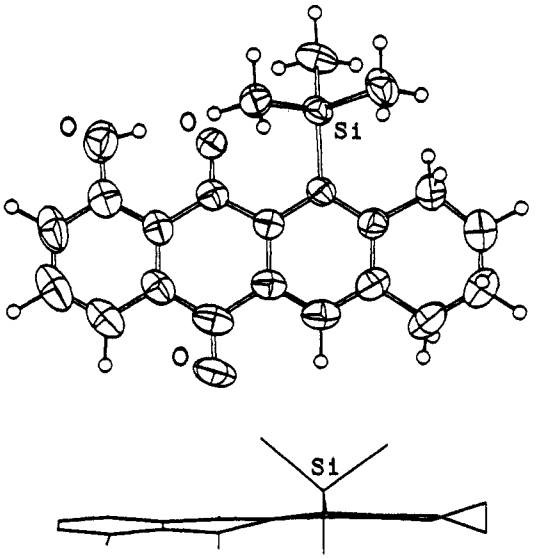

Figure 1. Orthogonal molecular views of **10**.

Experimental Section

IR spectra were determined on a Hitachi 260-50 grating spectrophotometer. ^1H NMR (200 MHz) spectra were taken in $CDCl_3$ on a Varian GEMINI-200 instrument. All chemical shifts are reported in δ determined by internal $CHCl_3$. 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. Preparative medium-pressure liquid chromatography (MPLC) was carried out by using a prepacked silica gel column (CPS-223L-1) supplied by Kusano Kagaku Co. Melting points were determined on a Yanaco MP melting point apparatus and are uncorrected.

Tetrahydrofuran (THF) was distilled from $LiAlH_4$ under nitrogen. Silyl diynes **2a**, **2b**, **5**, **7a**, and **7b** were prepared by silylation of the corresponding unsubstituted diynes according to the published methods.[11,12] 5-Hydroxy-1,4-naphthoquinone was a commercial reagent and was used without further purification. Bis(1,5-cyclooctadiene)nickel(0) ($Ni(cod)_2$) was purchased from Kanto Kagaku, Inc. Phosphorus ligands except 1-(2′-pyridyl)-2-(di-*n*-butylphosphino)ethane (**1**)[6] were commercial reagents and were used without further purification. Carbon dioxide was a commercial reagent (assay: minimum 99.99 vol %) supplied by Seitetsu Kagaku, Inc., and was used without further purification. Tetrabutylammonium fluoride trihydrate was obtained from Aldrich Chemical Co.

(11) Birkofer, L.; Hansel, E.; Steigel, A. *Chem. Ber.* **1982**, *115*, 2574.
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Nickel(0)-Catalyzed Cycloaddition of 1-(Trimethylsilyl)-1,7-decadiyne (5) with Carbon Dioxide to the Bicyclic α-Pyrone 6. The reaction was carried out under nitrogen. In a 50-mL stainless steel autoclave were placed a THF solution (1.05 mL) of $Ni(cod)_2$ (0.025 mmol), the ligand **1** (0.013 mL, 0.050 mmol), and THF (19.0 mL). After the mixture was stirred for several minutes, **5** (0.068 mL, 0.250 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 120 °C. The remaining CO_2 gas was purged off and the reaction mixture was transferred to a flask using ether (20 mL). Addition of *n*-docosane (0.0388 g, 0.125 mmol) as a GC internal standard and subsequent GC analysis (a silicone DC 550 column) showed formation of **6** in 80% yield. The solution was concentrated to give a residue that was purified by PLC (hexane/ether = 2:1 (v/v)) to give **6** (0.0358 g, 57%): IR (neat, cm^{-1}) 1690, 1595, 1550; ^{1}H NMR 0.32 (s, 9 H), 1.08 (t, J = 7.5, 3 H), 1.59–1.83 (m, 4 H), 2.41–2.57 (m, 4 H), 2.62 (t, J = 6.4, 2 H); MS *m/e* (relative intensity) 250 (M$^+$, 97), 235 (52), 222 (100), 207 (81), 73 (58); HRMS (*m/e*) 250.1398, calcd for $C_{14}H_{22}O_2Si$ 250.1389. The purity of the product **6** was judged to be ≥95% by ^{1}H NMR spectral determination.

The reactions of **2a**, **2b**, **7a**, and **7b** were carried out as described above and the corresponding bicyclic α-pyrones were identified as follows. The product purity was judged to be ≥95% for the products **3a** and **8a** by ^{1}H NMR spectral determinations. **3a** (PLC, hexane/ether = 1:1 (v/v)): IR (neat, cm^{-1}) 1680, 1630, 1560; ^{1}H NMR 0.27 (s, 9 H), 1.97 (quint, J = 7.4, 2 H), 2.65 (t, J = 7.4, 4 H), 6.09 (s, 1 H); MS, *m/e* (relative intensity) 208 (M$^+$, 60), 193 (100), 165 (14), 135 (17), 73 (88); HRMS (*m/e*) 208.0928, calcd for $C_{11}H_{16}O_2Si$ 208.0919. **4a** (PLC, hexane/ether = 1:1 (v/v)): IR (neat, cm^{-1}) 1665, 1630, 1540; ^{1}H NMR 0.27 (s, 9 H), 1.96 (quint, J = 7.4, 2 H), 2.56 (t, J = 7.3, 2 H), 2.75 (t, J = 7.4, 2 H), 7.30 (s, 1 H); MS, *m/e* (relative intensity) 208 (M$^+$, 24), 193 (100), 165 (48), 73 (11), 57 (11); HRMS (*m/e*) 208.0913, calcd for $C_{11}H_{16}O_2Si$ 208.0919. Anal. Calcd for $C_{11}H_{16}O_2Si$: C, 63.42; H, 7.74. Found: C, 63.34; H, 7.89. **3b** (PLC, hexane/ether = 1:1 (v/v)): IR (neat, cm^{-1}) 1710, 1605, 1535; ^{1}H NMR 0.31 (s, 9 H), 1.60–1.71 (m, 4 H), 2.50 (t, J = 6.3, 2 H), 2.58 (t, J = 6.1, 2 H), 6.00 (s, 1 H); MS, *m/e* (relative intensity) 222 (M$^+$, 45), 207 (36), 179 (65), 73 (100); HRMS (*m/e*) 222.1086, calcd for $C_{12}H_{18}O_2Si$ 222.1076. Anal. Calcd for $C_{12}H_{18}O_2Si$: C, 64.83; H, 8.16. Found: C, 64.63; H, 8.25. **8a** (PLC, hexane/ether = 3:1 (v/v), a white solid): mp 87.2–89.3 °C; IR (Nujol paste, cm^{-1}) 1670, 1605, 1540; ^{1}H NMR 0.29 (s, 18 H), 1.95 (quint, J = 7.4, 2 H), 2.61 (t, J = 7.4, 2 H), 2.72 (t, J = 7.5, 2 H); MS, *m/e* (relative intensity) 280 (M$^+$, 46), 265 (42), 147 (30), 133 (37), 73 (100); HRMS (*m/e*) 280.1295, calcd for $C_{14}H_{24}O_2Si_2$ 280.1314. **8b** (PLC, hexane/ether = 2:1 (v/v)): IR (neat, cm^{-1}) 1680, 1575, 1520; ^{1}H NMR 0.29 (s, 18 H), 1.60–1.70 (m, 4 H), 2.45 (t, J = 6.6, 2 H), 2.64 (t, J = 6.6, 2 H); MS, *m/e* (relative intensity) 294 (M$^+$, 6), 279 (55), 266 (91), 133 (26), 73 (100); HRMS (*m/e*) 294.1456, calcd for $C_{15}H_{26}O_2Si_2$ 294.1471. Anal. Calcd for $C_{15}H_{26}O_2Si_2$: C, 61.17; H, 8.90. Found: C, 61.07; H, 8.88.

Protodesilylation of the Silyl Bicyclic α-Pyrone 6 to the Bicyclic α-Pyrone 9. A THF solution (1.2 mL) of tetrabutylammonium fluoride trihydrate (0.38 g, 1.2 mmol) was added to a magnetically stirred THF solution (5.0 mL) of **6** (0.146 g, 0.583 mmol) at 0 °C under nitrogen. The mixture was stirred for 15 min, treated with water (30 mL), and extracted with ether (30 mL). The ether solution was dried over anhydrous magnesium sulfate, filtered, and concentrated. A residue was purified by PLC (hexane/ether = 1:1 (v/v)) to give **9** (0.101 g, 97%): IR (neat, cm^{-1}) 1705, 1630, 1535; ^{1}H NMR 1.02 (t, J = 7.5, 3 H), 1.49–1.80 (m, 4 H), 2.32–2.52 (m, 4 H), 2.57 (t, J = 6.4, 2 H), 7.08 (s, 1 H); MS, *m/e* (relative intensity) 178 (M$^+$, 100), 150 (38), 135 (75); HRMS (*m/e*) 178.1006, calcd for $C_{11}H_{14}O_2$ 178.0994. The purity of the product **9** was judged to be ≥95% by ^{1}H NMR spectral determination.

Diels–Alder Reaction of the Silyl Bicyclic α-Pyrone 3b with 5-Hydroxy-1,4-naphthoquinone. The reaction was carried out under nitrogen. In a 50-mL stainless steel autoclave were placed **3b** (0.0422 g, 0.190 mmol), 5-hydroxy-1,4-naphthoquinone (0.0693 g, 0.398 mmol), and xylenes (5.0 mL). The reaction mixture was magnetically stirred for 7 days at 130 °C. Then Ag_2O (0.20 g, 0.86 mmol) and $MgSO_4$ (0.20 g, 1.7 mmol) were added. The reaction mixture was magnetically stirred for 1 day at room temperature. The reaction mixture was filtrated. The filtrate was concentrated to give a residue, which was purified by PLC (hexane/ethyl acetate = 5:1 (v/v)) to give the mixture of regioisomeric Diels–Alder cycloadducts **10** and **11**. Regioisomers **10** (0.025 g, 38%) and **11** (0.010 g, 16%) were separated by MPLC (hexane/ethyl acetate = 10:1 (v/v)) and were crystallized in hexane at 0 °C as yellow prisms. The structure of **10** was determined by X-ray crystallography. **10** (mp 138.5–141.2 °C): IR (KBr, cm^{-1}) 3433, 1668, 1633, 1570; ^{1}H NMR 0.38 (s, 9 H), 1.65–1.90 (m, 4 H), 2.92 (t, J = 6.4, 2 H), 2.95 (t, J = 6.2, 2 H), 7.25 (dd, J = 7.5, 1.6, 1 H), 7.60 (t, J = 7.8, 1 H), 7.74 (dd, J = 7.3, 1.5, 1 H), 7.95 (s, 1 H), 12.28 (s, 1 H); MS, *m/e* (relative intensity) 350 (M$^+$, 3.6), 335 (100), 319 (4.3), 149 (4.6); HRMS (*m/e*) 350.1309, calcd for $C_{21}H_{22}O_3Si$ 350.1332. **11** (mp 180.7–183.0 °C): IR (KBr, cm^{-1}) 3444, 1662, 1633, 1566; ^{1}H NMR 0.37 (s, 9 H), 1.70–1.90 (m, 4 H), 2.92 (t, J = 6.6, 2 H), 2.95 (t, J = 6.2, 2 H), 7.23, (dd, J = 7.3, 2.2, 1 H), 7.55–7.65 (m, 2 H), 7.96 (s, 1 H), 12.49 (s, 1 H); MS, *m/e* (relative intensity) 350 (M$^+$, 1.8), 355 (100), 307 (8.9); HRMS (*m/e*) 350.1309, calcd for $C_{21}H_{22}O_3Si$ 350.1332. The purity of the products **10** and **11** was judged to be ≥95% by ^{1}H NMR determinations.

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Supplementary Material Available: Crystal structure data of compound **10** and ^{1}H NMR spectra showing the purity of the products **3a**, **6**, **8a**, **9**, **10**, and **11** (18 pages). Ordering information is given on any current masthead page.

A New Method for Coupling Aromatic Aldehydes and Ketones To Produce α-Glycols Using Zn–$ZnCl_2$ in Aqueous Solution and in the Solid State

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The coupling of aromatic aldehydes and ketones to afford α-glycols has been carried out by heating with Zn–AcOH,[1] Mg–MgX_2,[2] or Al(Hg).[3] These methods were improved by using more active metals such as Al,[4] $TiCl_4$,[5] or $TiCl_4$–Zn.[6] However, these reactions should be carried out at low temperature and in the presence of an inert gas, since the active reagents are sensitive to oxygen and the reaction with the reagents at high temperature gives an olefin.

Previously, we have reported that Zn–$ZnCl_2$ is an effective reagent for the reduction of activated olefins[7] and ketones.[8] Recently, we found further that the reagent is effective for the coupling of aromatic aldehydes and ketones to produce α-glycols, both in solution and in the solid state. Since the Zn–$ZnCl_2$ reagent is effective at room temperature and not sensitive to oxygen, its handling is easy.

For example, when a solution of benzaldehyde (**1a**), commercially available Zn powder, and $ZnCl_2$ in 50%

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