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Novel Synthesis of Methylenecyclobutanols and 4-Methylenetetrahydrofurans from γ-Oxide Ylides

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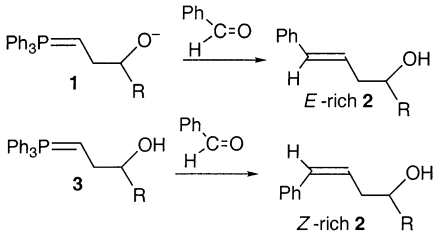
The reaction of δ-halo-γ-oxide ylide, prepared from methylenetriphenylphosphorane and epichlorohydrin, with aldehydes afforded alkylidenecyclobutanols in moderate yields. The reaction initially proceeded through internal nucleophilic attack on δ-carbon of this ylide. Another novel approach toward the synthesis of 4-methylenetetrahydrofurans was achieved by the reaction of γ-oxide ylides with paraformaldehyde.

Wittig reagents form an important class of compounds because of their versatile synthetic utility.[1] It is well-known that γ-oxide ylides (**1**) react with aldehydes to give *E*-rich homoallylic alcohols (**2**) in good yields, whereas γ-hydroxy ylides (**3**) react with aldehydes to afford *Z*-rich homoallylic alcohols, **2**.[2] Maryanoff and Reits reviewed the stereochemistry of Wittig reaction, in which they described many examples of the reaction of **1** and **3** with aldehydes.[3] We have also prepared optically active homoallylic alcohols from **1** (Scheme 1).[4]

Alkylidenecyclopropylcarbinols (**4**), one of homoallylic alcohols, have been previously prepared by the reaction of methylenetriphenylphosphorane with epichlorohydrin followed by the addition of aldehydes.[5] Alkylidenecyclobutanes and substituted cyclobutanols are an important class of compounds from their synthetic and structural point of view.[6] Previously, we have communicated the direct synthesis of 3-alkylidenecyclobutanols (**5**) from methylenetriphenylphosphorane via γ-oxide ylides, **1**.[7] We have also reported that the reaction of 2,2,2-triphenyl-2,1λ^5-oxaphospholanes (**6**), which equilibrate to the corresponding γ-hydroxyalkyl ylides **3** at elevated

SCHEME 1



temperature, with paraformaldehyde gave 1,3-dioxepanes in moderate yields.[8] In this case, 3 equiv of formaldehyde reacted with **1**. These results prompted us to investigate the precise reaction mechanism of **1** and **3** with aldehydes. We report herein the reaction mechanisms and synthesis of 3-alkylidenecyclobutanols **5** and tetrahydrofurans from **1**.

Results and Discussion

Synthesis of 3-Alkylidenecyclobutanols 5. Treatment of methylenetriphenylphophorane derived from methyltriphenylphosphonium iodide and butyllithium with epichlorohydrin followed by the addition of butyllithium and benzaldehyde at −40 °C resulted in the formation of the corresponding 3-phenylmethylene-1-cyclobutanol (**5a**) in 62% yield (Scheme 2). Other reactions are shown in Table 1.

Generally, good yields were obtained by the use of aromatic aldehydes as starting aldehydes (entries 1 and 3). When THF was used as a solvent, 2-phenylmethylenecyclopropylmethanol (**4**) was obtained in 13% yield (entry 2). Other solvents such as ether, benzene, or dioxane gave **5** in poor yields (0−3%). When aldehydes were used as substrates, the yields were better than that of cyclo-

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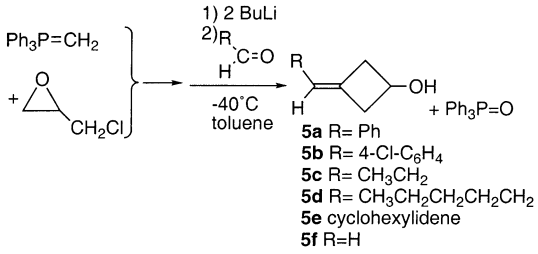
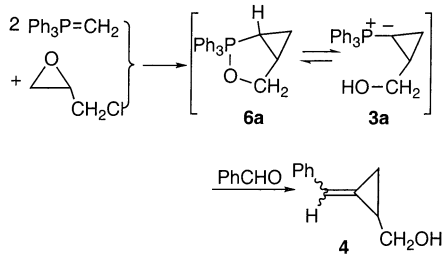
TABLE 1. Reaction of 1a with Epichlorohydrin and Carbonyl Compounds

entry	carbonyl compounds	base	temp (°C)	solvent	time (h)	product	yield (%)
1	benzaldehyde	BuLi	−40	toluene	1	**5a**	62
2	benzaldehyde	BuLi	−40	THF	1	**5a**	0
						4	13
3	4-chlorobenzaldehyde	BuLi	−40	toluene	1	**5b**	60
4	propionaldehyde	BuLi	−40	toluene	1	**5c**	56
5	hexanal	BuLi	−40	toluene	1	**5d**	35
6	cyclohexanone	BuLi	−40	toluene	4	**5e**	19
7	paraformaldehyde	BuLi	−40	toluene	4	**5f**	0

SCHEME 2



SCHEME 3



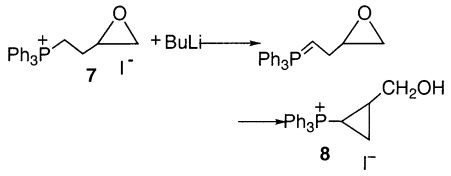
hexanone (entry 6). When paraformaldehyde was used, the corresponding cyclobutanol (**5f**) was not obtained under these conditions.

Previously, Turchant and Le Corre reported that the reaction of epichlorohydrin with 2 equiv of salt-free methylenetriphenylphosphorane afforded bicyclic 2,2,2-triphenyl-2,1λ^5-oxaphospholane (**6a**), which further reacted with benzaldehyde to give **4** (Scheme 3).[5,9]

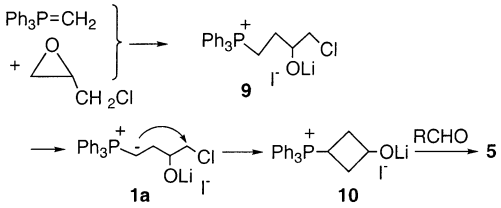
Their results were quite different from ours. To clarify the role of base used in this reaction, we have carried out the above reaction by using NaH as a base. Treatment of methyltriphenylphosphonium iodide and NaH followed by the addition of epichlorohydrin and benzaldehyde resulted in the formation of a cis and trans mixture of **4** in 45% yield. Thus, butyllithium plays an important role in the present reaction. We initially thought that the reaction might proceed through 3,4-epoxybutylphosphonium iodide (**7**). However, the reaction of **7** with butyllithium only afforded 2-hydroxymethylcyclopropyltriphenylphosphonium iodide (**8**) in 76% yield, suggesting that the real intermediate in the present reaction would not be **7** (Scheme 4).

Thus, the reaction might proceed as follows: Initial attack of ylide to epichlorohydrin results in the formation of betaine **9**, which changes into δ-chloro-γ-oxide ylide (**1a**) by α-proton abstraction of **9**. Since the lithium ion is tightly combined with the oxy anion of **1a** in a nonpolar solvent such as toluene, intramolecular nucleophilic substitution on the δ-carbon of **1a** affords the corresponding cyclobutylidenephosphorane (**10**), which finally reacts with aldehyde to afford **5** (Scheme 5).

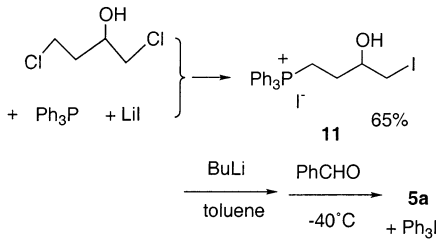
SCHEME 4



SCHEME 5



SCHEME 6



To confirm this possibility, 3-hydroxy-4-iodobutyltriphenylphosphonium iodide (**11**), which would be the precursor of γ-oxide ylide **1a**, was synthesized independently and reacted with butyllithium followed by the addition of benzaldehyde to afford the corresponding four-membered cyclic alcohol, **5a**, in 48% yield (Scheme 6). Thus, the reaction appears to proceed through γ-oxide ylide **1a**.

When the reaction was carried out in THF, the relatively nucleophilic oxy anion of **1a** further attacked the δ-carbon to afford via an intramolecular manner 3,4-epoxybutylphosphonium salts **7**, which further reacted with butyllithium followed by the addition of benzaldehyde to afford final product **4**.

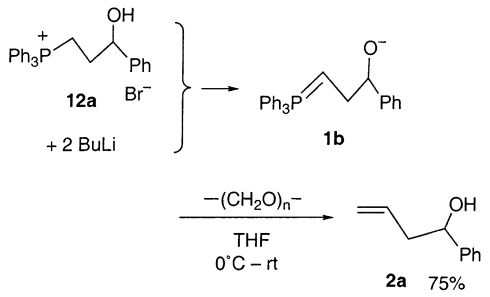
1-Propylidenecyclobutan-2-ol was previously prepared by the solvolysis of 1-iodo-1-cyclopropylpropene. However, many side products were obtained.[10] The present method provides a new convenient synthesis of alkylidenecyclobutanols **5**.

Synthesis of 4-Methylenetetrahydrofurans 13. We have also reported the synthesis of 1,3-dioxepanes from

(9) Turchant, A.; Le Corre, M. L. *Tetrahedron Lett.* **1977**, 787.

(10) Kelsey, D. R.; Bergman, R. G. *J. Am. Chem. Soc.* **1970**, *92*, 229.

SCHEME 7



SCHEME 8

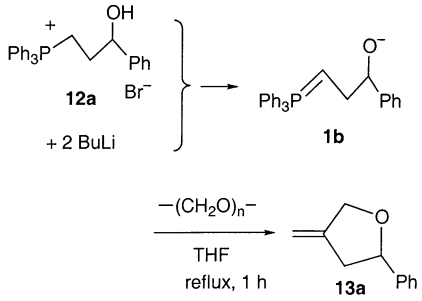


TABLE 2. Reaction of 12 with BuLi Followed by the Addition of Paraformaldehyde

	oxide ylide			temp		time		yield
12	R	R′	base	(°C)	solvent	(h)	product	(%)
12a	Ph	H	BuLi	reflux	THF	1	**13a**	62
12a	Ph	H	BuLi	65	toluene	6	**13a**	25
12b	4-Tol	H	BuLi	reflux	THF	1	**13b**	52
12c	4-ClC_6H_4	H	BuLi	reflux	THF	1	**13c**	54
12d	4-$MeOC_6H_4$	H	BuLi	reflux	THF	1	**13d**	45
12e	3,4-$MeO_2C_6H_3$	H	BuLi	reflux	THF	1	**13e**	42
12f	Ph	Ph	BuLi	reflux	THF	1	**13f**	0
							2b	85

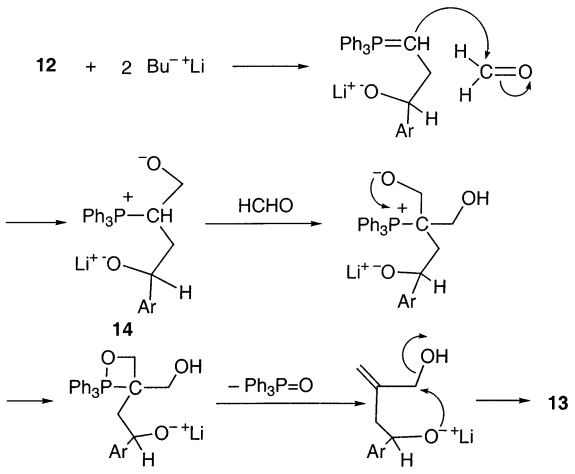
γ-hydroxy ylide **3** and paraformaldehyde.[8] We have been interested in the difference in the reactivity between **1** and **3**. Starting γ-hydroxyalkylphosphonium salts (**12**) were synthesized by the reaction of methylenetriphenylphosphorane with epoxides.[3] Treatment of phosphonium bromide (**12a**) with butyllithium resulted in the formation of γ-oxide ylide (**1b**), which when allowed to further react with paraformaldehyde at 0 °C to room temperature afforded only 1-phenyl-3-buten-1-ol (**2a**) in 75% yield (Scheme 7).

When the present reaction was carried out in refluxing THF, 2-phenyl-4-methylenetetrahydrofuran (**13a**) was obtained in 62% yield along with a small amount of **2a** (Scheme 8). When the reaction was carried out in toluene, the yield of **13a** was only 25%. Thus, the reaction proceeds best when carried out in refluxing THF as a solvent. Further examples are collected in Table 2.

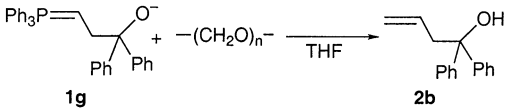
The reaction may proceed as follows. γ-Oxide ylide **1** reacts with paraformaldehyde to give the corresponding betaine intermediate (**14**), which further reacts with another equivalent of formaldehyde to give another betaine (**15**). The betaine **15** extrudes triphenylphosphine oxide and finally dehydrates to afford **13** (Scheme 9).

The reaction of a disubstituted oxide ylide such as 3,3-diphenyl-γ-oxide ylide (**1g**) with paraformaldehyde did not afford the corresponding **13f** but gave the normal Wittig reaction product (**2b**) in 85% yield (Scheme 10).

SCHEME 9



SCHEME 10



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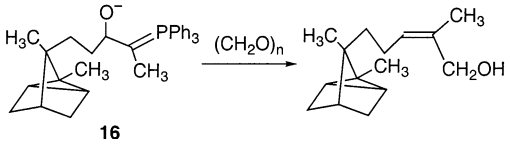
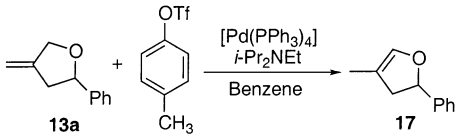


SCHEME 12



The present result is quit different from that of β-oxide ylide (**16**). Corey et al. reported the stereocontrolled synthesis of santalol and Cecropia juvenile hormone by the use of β-oxide ylides with paraformaldehyde (Scheme 11).[11] However, they did not mention the formation of two molar formaldehyde addition products.

Since tetrahydrofurans **13** were easily obtained, the reactivity of **13** was also of interest. Loiseleur et al. have reported the palladium-catalyzed arylation of dihydrofurans.[12] The reaction of **13a** with *p*-tolyl triflate in the presence of palladium catalyst was carried out. However, the obtained product was 4-methyl-2-phenyl-2,3-dihydrofurans (**17**) (Scheme 12). Actually, without *p*-tolyl triflate and diisopropylethylamine, the corresponding rearranged product **17** was obtained. Generally, arylation takes place with unsubstituted dihydrofuran, whereas arylated dihydrofuran does not afford the diarylated dihydrofurans.[12,13]

In summary, two new types of the reactions of γ-oxide ylides have been described. The reaction of methylenetriphenylphosphorane with epichlorohydrin followed by

(11) Corey, E. J.; Yamamoto, H. *J. Am. Chem. Soc.* **1970**, *92*, 226. Corey E. J.; Yamamoto, H. *J. Am. Chem. Soc.* **1970**, *92*, 6636.
(12) Loiseleur, O.; Hayashi, M.; Schmees, N.; Pfaltz, A. *Synthesis* **1977**, 1338.
(13) Jeffery, T.; David, M. *Tetrahedron Lett.* **1998**, *39*, 5751.

the addition of butyllithium gave the corresponding δ-chloro-γ-oxide ylide **1**, which reacted with aldehydes to give alkylidenecyclobutanols **5**. This is the first example of the one-pot synthesis of **5** from methylenetriphenylphosphorane. The reaction of γ-aryl-γ-oxide ylides **1** with paraformaldehyde afforded a novel class of compounds, methylenetetrahydrofurans **13**, in moderate yields.

Experimental Section

All reactions were carried out in nitrogen atmosphere. NMR spectra were measured at 400 MHz for ^{1}H and 100 MHz for ^{13}C. Melting points are uncorrected.

3-Hydroxyalkylphosphonium salts were prepared by the reaction of methylenetriphenylphosphorane with epoxides according to the literature.[3,14]

One-Pot Reaction of Methylenetriphenylphosphorane with Epichlorohydrin Followed by the Addition of Benzaldehyde. To a solution of methyltriphenylphosphonium iodide (2.02 g, 5.0 mmol) in dry toluene (40 mL) was added a solution of butyllithium (1.6 M in hexane, 3.13 mL, 5.0 mmol) via syringe at 0 °C. The clear yellow solution of the ylide was stirred for 30 min at this temperature. Epichlorohydrin (0.46 g, 5.0 mmol) was added to this solution via syringe. After 30 min of stirring, butyllithium (1.6 M in hexane, 6.25 mL, 10.0 mmol) was added to this solution via syringe. After being stirred for 30 min, the reaction mixture was cooled to −40 °C. After 30 min of stirring, benzaldehyde (0.80 g, 7.5 mmol) in toluene (3 mL) was added to this solution. After being stirred for 1 h, the solution was warmed to room temperature, which was quenched by saturated sodium chloride, washed with water, and extracted from dichloromethane (10 mL × 3). The combined extract was dried over magnesium sulfate and evaporated to afford a brown oil. The residue was chromatographed over silica gel by elution with hexane−dichloromethane to afford 3-phenylmethylene-cyclobutanol, **5a** (0.50 g, 3.1 mmol, 62%). 3-Phenylmethylene-cyclobutanol (**5a**): colorless crystals; mp 52−54 °C. ^{1}H NMR ($CDCl_3$) δ 2.85 (m, 1H, C*H*H), 2.97 (m, 1H, CH*H*), 3.13 (m, 1H, C*H*H), 3.28 (m, 1H, CH*H*) 6.23 (s, 1H, C*H*OH), 7.15−7.35 (m, 5H, phenyl). ^{13}C NMR ($CDCl_3$) δ 43.31 (CH_2), 43.84 (CH_2), 64.50 (CH), 122.59 (=CH), 126.14, 127.43, 128.59, 134.33 (Ph), 137.66 (=C). Found: C, 82.25; H, 7.70. Calcd for $C_{11}H_{12}O$: C, 82.46; H, 7.55. HRMS calcd for $C_{11}H_{12}O$: M^+ 160.0888. Found: M^+ 160.0887.

Other reactions were carried out in a similar manner.

3-[(4-Chlorophenyl)methylene]-cyclobutanol (**5b**, 0.22 g, 1.2 mmol, 60%): pale yellow crystals; mp 111.5−113.0 °C. ^{1}H NMR ($CDCl_3$) δ 2.90 (m, 2H, CH_2), 3.20 (m, 2H, CH_2), 4.51 (quintet, 1H, J = 6 Hz, CH), 6.18 (br s, 1H, =CH), 7.11 (d, 2H, J = 8 Hz, Ar), 7.26 (d, 2H, J = 8 Hz, Ar). ^{13}C NMR ($CDCl_3$) δ 43.22 (CH_2), 43.88 (CH_2), 64.49 (CH), 121.58 (=CH), 128.26, 128.49, 131.64, 135.21 (Ar), 136.12 (=C). Found: C, 68.01; H, 5.80. Calcd for $C_{11}H_{11}ClO$: C, 67.87; H, 5.70.

3-(Ethylmethyene)-cyclobutanol (**5c**, 0.24 g, 2.24 mmol, 56%): colorless oil. ^{1}H NMR ($CDCl_3$) δ 0.92 (t, 3H, J = 7 Hz), 1.86 (q, 2H, J = 7 Hz), 2.45 (m, 2H, CH_2), 2.95 (m, 2H, CH), 4.36 (m, 1H, CHOH), 5.19 (m, 1H, =CH). HRMS calcd for $C_7H_{12}O$: M^+ 112.0888. Found: M^+ 112.0877.

3-(Pentylmethylene)-cyclobutanol (**5d**): colorless oil. ^{1}H NMR ($CDCl_3$) δ 0.88 (t, 3H, J = 7 Hz, CH_3), 1.23−1.33 (m, 6H, CH_2 × 3), 1.87 (m, 2H, CH_2), 2.55 (m, 2H, CH*H*), 2.98 (m, 2H, CH*H*), 4.35 (m, 1H, C*H*OH), 5.20 (m, 1H, =CH). ^{13}C NMR ($CDCl_3$) δ 14.13 (CH_3), 22.59 (CH_2), 28.74 (CH_2), 29.34 (CH_2), 31.46 (CH_2), 40.35 (cyclobutyl CH_2), 42.22 (cyclobutyl CH_2), 63.98 (CHOH), 122.83 (*C*H=C), 129.63 (CH=*C*). HRMS calcd for $C_{10}H_{18}O$: M^+ 154.1358. Found: M^+ 154.1357.

3-Cyclohexylidenecyclobutanol (**5e**, 19%): colorless oil. ^{1}H NMR ($CDCl_3$) δ =1.57 (br, 6H, cyclohexyl), 1.95 (br, 4H, cyclohexyl), 2.52 (m, 2H, CH_2), 2.95 (m, 2H, CH_2), 4.35 (quintet, 1H, J = 6 Hz, CH). HRMS calcd for $C_{10}H_{16}O$: M^+ 224.1201. Found: M^+ 224.1212.

Reaction of Methylenetriphenylphosphorane with Epichlorohydrin Followed by the Addition of NaH and Benzaldehyde. To a suspension of NaH (0.24 g, 60% mineral oil dispersion, 6.0 mmol) in THF (45 mL) was added methyltriphenylphosphonium iodide (2.02 g, 5.0 mmol) in on**e** portion at room temperature. After being refluxed for 2 h, the orange suspension was cooled to 0 °C. Epichlorohydrin (0.46 g 5.0 mmol) was added to this solution via syringe. After being stirred for 2 h, the reaction mixture was warmed to room temperature. After 2h of stirring, a suspension of NaH (0.48 g, 60% mineral oil dispersion, 12.0 mmol, washed with hexane) in THF (15 mL) was added to this solution portionwise. After being refluxed for 1 h, the solution was cooled to room temperature. Benzaldehyde (0.70 g, 6.6 mmol) in toluene (3 mL) was added to this solution. After being stirred for 3 h, the reaction mixture was quenched by saturated ammonium chloride, washed with water, dried over magnesium sulfate, and finally evaporated to afford a brown oil. The residue was chromatographed over silica gel by elution with hexanes−ethyl acetate to afford a cis and trans mixture of 2-phenylmethylene-cyclopropylmethanol (**4**, 0.36 g, 2.25 mmol, 45%): colorless oil. ^{1}H NMR ($CDCl_3$) δ 1.32 (m, 1H, C*H*H), 1.68 (m, 1H, CH*H*), 1.90 (m, 1H, CH), 3.59 (dd, 1H, C*H*HOH), 3.68 (dd, 1H, CH*H*OH), 6.83 (d, 1H, =CH), 7.12−7.37 (m, 5H, phenyl). HRMS calcd for $C_{11}H_{12}O$: M^+ 160.0888. Found: M^+ 160.0891.

Preparation of 3,4-Epoxybutyltriphenylphosphonium Iodide (7). To a suspension of methyltriphenylphosphonium iodide (8.08 g, 20.0 mmol) in dry THF (20 mL) was added a solution of butyllithium (1.6 M in hexane, 14.0 mL, 22.4 mmol) via syringe at 0 °C. The clear light orange solution of the ylide was stirred for 30 min and the solution was cooled to −78 °C. Epichlorohydrin (2.00 g, 21.6 mmol) in dry THF (3 mL) was added via syringe to this solution. After being stirred for 5 h, the reaction mixture was warmed to −35 °C. After being stirred for 12 h, the solution was finally warmed to room temperature. When the reaction mixture was quenched by saturated ammonium chloride, colorless crystals were precipitated. The crystals were washed with water and recrystallized from methanol−ether to give pure 3,4-epoxybutyltriphenylphosphonium iodide (**7**, 7.0 g, 15.2 mmol, 76%): mp 192−193 °C. ^{1}H NMR ($CDCl_3$) δ 1.71−1.82 (m, 1H, C*H*H), 2.13−2.24 (m, 1H, CH*H*), 2.69−2.71 (m, 1H, OC*H*H), 2.76−2.78 (m, 1H, OCH*H*), 3.41−3.45 (m, 1H, CH), 3.67−3.78 (m, 1H, PC*H*H), 3.93−4.05 (m, 1H, PCH*H*), 7.70−7.86 (m, 15H, Ar). ^{13}C NMR ($CDCl_3$) δ 19.48 (d, J = 51 Hz, PCH_2), 25.37 (CH_2), 47.43 (CH_2), 50.90 (d, J = 18 Hz, CH), 117.03, 117.89, 130.38, 130.51, 133.44, 133.55, 135.08 (Ar). Found: C, 57.60; H, 4.83. Calcd for $C_{22}H_{22}IOP$: C, 57.41; H, 4.82.

Reaction of 7 with Butyllithium. To a suspension of **7** (1.85 g, 4 mmol) in THF (10 mL) was added a solution of butyllithium (1.6 M in hexane, 5.4 mL, 8.5 mmol) via syringe at −40 °C. After being stirred for 1 h, the reaction mixture was warmed to room temperature, and saturated ammonium chloride (20 mL) was added to the mixture. The resulting suspension was extracted three times with dichloromethane (10 mL). The combined extract was dried over magnesium sulfate, filtered, and evaporated to give pale brown crystals of crude 2-hydroxymethylcyclopropyltriphenylphosphonium iodide (**8**). Salt **8** was purified by recrystallization from methanol (1.72 g, 3.1 mmol, 77%): colorless crystals; mp 166−168 °C. ^{1}H NMR ($CDCl_3$) δ 0.77 (m, 1H, cyclopropyl C*H*H), 1.50 (m, 1H, cyclopropyl CH), 1.70 (m, 1H, cyclopropyl CH*H*), 1.82 (br, 1H, OH), 3.05 (m, 1H, P−CH), 3.70 (m, 1H, C*H*HOH), 4.15 (m, 1H, CH*H*OH) 7.65−7.95 (m, 15H, Ar). ^{13}C NMR ($CDCl_3$) δ 4.60 (d, P−CH), 9.21 (cyclopropyl CH_2), 21.53 (CH), 60.51 (CH2), 118.76 (d), 130.65, 130.72, 133.95, 135.47 (Ar). Elemental analysis was carried out by adding sodium tetra-

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phenylborate for conversion into its tetraphenylborate: colorless crystals; mp 188−189 °C. Found: C, 85.00; H, 6.51. Calcd for $C_{46}H_{42}BOP$: C, 84.67; H, 6.44.

Preparation of 3-Hydroxy-4-iodobutyltriphenylphosphonium Iodide (11). To a refluxing solution of 1,4-dichloro-2-butanol (1.55 g, 11 mmol) and lithium iodide (2.60 g, 20 mmol) in THF (10 mL) was added a solution of triphenylphosphine (2.89 g, 11 mmol) in benzene (20 mL). After 12 h of refluxing, colorless oily crystals were precipitated. The resulting suspension was evaporated to give pale yellow oily crystals, which was dissolved in dichloromethane and filtered. The filtrate was evaporated to give an orange oil, which was washed with ether (10 mL × 2). This oil was solidified upon standing. The resulting pale yellow crystals were recrystallized from methanol−ether to afford colorless crystals of **11** (3.34 g, 5.8 mmol, 53%). 3-Hydroxy-4-iodobutyltriphenylphosphonium iodide (**11**): mp 166−168 °C. ^{1}H NMR ($CDCl_3$) δ 1.88−1.95 (m, 1H, C*H*H), 2.03−2.16 (m, 1H, CH*H*), 3.28−3.39 (m, 2H, CH_2I), 3.65−3.92 (m, 2H, P−CH_2), 4.07−4.18 (m, 1H, C*H*OH), 4.52 (d, 2H, J = 7 Hz, CHO*H*), 7.60−7.90 (m, 15H, Ph). ^{13}C NMR ($CDCl_3$) δ 12.80 (CH_2I), 20.10 (d, P−CH_2), 29.09 (CH_2), 69.14 (CHOH), 117.48, 118.34, 130.64, 133.57, 135.58 (Ph). Found: C, 44.92; H, 3.94. Calcd for $C_{22}H_{23}I_2OP$: C, 44.86; H, 3.91.

Reaction of 11 with Butyllithium Followed by the Addition of Benzaldehyde. To a suspension of **11** (2.35 g, 4.0 mmol) in THF (35 mL) was added a solution of butyllithium (1.6 M in hexane, 5.5 mL, 8.8 mmol) in hexane at 0 °C via syringe. After 2 h of stirring, a solution of benzaldehyde (0.42 g, 4.0 mmol) was added to this solution at −40 °C. After being stirred for 3 h, the reaction mixture was warmed to room temperature. The resulting solution was washed with water, dried over magnesium sulfate, and evaporated to give a brown oil. The residue was chromatographed over silica gel by elution from hexanes−ethyl acetate to afford cyclobutanol, **5a**, in 48% yield (0.31 g, 1.92 mmol).

Reaction of 3-Hydroxyalkyltriphenylphosphonium Bromide with Butyllithium Followed by the Addition of Paraformaldehyde. To a suspension of 3-hydroxy-3-phenyltriphenyphosphonium bromide (**12a**, 0.955 g, 2 mmol) in THF (30 mL) was added butyllithium THF solution (1.6 M, 2.8 mL, 4.4 mmol) at −20 °C, and the mixture was stirred for 30 min. The resulting red solution was warmed to room temperature, and paraformaldehyde (0.30 g, 10 mmol) was added in one portion. After being stirred for 5 h, the reaction mixture was washed with water, dried over magnesium sulfate, and finally evaporated to afford a colorless oil. This oil was extracted with hexane to separate triphenylphosphine oxide. The hexane extract was evaporated and chromatographed over silica gel by hexan−-dichloromethane to give **2a** (0.22 g, 1.5 mmol).[15] ^{1}H NMR ($CDCl_3$) δ 2.51 (m, 2H, CH_2), 4.72 (m, 1H, CH), 5.17 (m, 2H, =CH_2), 5.80 (m, 1H, =CH), 7.24−7.38 (m, 5H, Ph).

In Refluxing THF. To a suspension of 3-hydroxy-3-phenyltriphenyphosphonium bromide (**12a**, 0.955 g, 2 mmol) in THF (30 mL) was added butyllithium THF solution (1.6 M, 2.8 mL, 4.4 mmol) at −20 °C, and the mixture was stirred for 30 min. The resulting red solution was warmed to 40 °C, and paraformaldehyde (0.30 g, 10 mmol) was added in one portion. After refluxing for 1 h, the reaction mixture was washed with water, dried over magnesium sulfate, and finally evaporated to afford a colorless oil. This oil was extracted with hexane to separate triphenylphosphine oxide. The hexane extract was evaporated and chromatographed over silica gel by hexane−dichloromethane to give 2-phenyl-4-methylenetetrahydrofuran (**13a**, 0.21 g, 62%) and homoallylic alcohol, **2a** (0.020 g, 7%). 2-phenyl-4-methylenetetrahydrofuran **13a**: colorless oil; bp 120−125 °C/10 mmHg. ^{1}H NMR ($CDCl_3$) δ 2.57 (m, 1H, C*H*H), 2.95 (m, 1H, C*H*H), 4.41 (br d, 1H, J = 13 Hz, OCH*H*), 4.58 (d, 1H, C*H*H), 4.95 (m, 1H, PhC*H*), 4.96 (m, 1H, =CH), 5.03 (m, 1H, =CH), 7.27−7.38 (m, 5H, Ph). ^{13}C NMR ($CDCl_3$) δ 41.11 (CH_2), 71.31 (OCH_2), 81.07 (PhCH), 104.33 (=CH_2), 125.85, 127.53, 128.35, 141.76 (Ph), 147.88 (=C). HRMS calcd for $C_{11}H_{12}O$: M^+ 160.0888. Found: M^+ 160.0878.

Other reactions were carried out in a similar manner.

2-(4-Tolyl)-4-methylenetetrahydrofuran (**13b**): colorless oil; bp 120−125 °C/8 mmHg. ^{1}H NMR ($CDCl_3$) δ 2.33 (T*o*l-Me), 2.56 (m, 1H, C*H*H), 2.92 (m, 1H, C*H*H), 4.39 (br d, 1H, J = 13 Hz, OCHH), 4.56 (br d, 1H, J = 13 Hz, OCHH), 4.92 (m, 1H, PhCH), 4.95 (m, 1H, =CH), 5.02 (m, 1H, =CH), 7.15 (d, 2H, J = 8 Hz, p-Tol), 7.25 (d, 2H, J = 8 Hz, p-Tol). ^{13}C NMR ($CDCl_3$) δ 21.24 (Me), 41.21 (CH_2), 71.28 (OCH_2), 81.01 (ArCH), 104.14 (=C), 125.73, 128.88, 137.03, 138.57, 147.89 (=CH_2). Found: C, 82.51; H, 7.93. Calcd for $C_{12}H_{14}O$: C, 82.72; H, 8.10.

2-(4-Methoxyphenyl)-4-methylenetetrahydrofuran(**13c**): colorless oil; bp 130−135 °C/8 mmHg. ^{1}H NMR ($CDCl_3$) δ 2.57 (m, 1H, C*H*H), 2.90 (m, 1H, C*H*H), 3.79 (s, 3H, OMe), 4.37 (br d, 1H, J = 13 Hz, OCHH), 4.55 (br d, 1H, J = 13 Hz, OCHH), 4.90 (dd, 1H, J = 6 and 8 Hz, ArCH), 4.95 (m, 1H, =CH), 5.02 (m, 1H, =CH), 6.87 (m, 2H, Ar), 7.28 (m, 2H, Ar). ^{13}C NMR ($CDCl_3$) δ 41.12 (CH_2), 55.33 (OMe), 71.21 (OCH_2), 80.85 (ArCH), 113.62, 127.12, 133.56, 147.94 (=CH_2), 158.89 (Ar). Found: C, 75.97; H, 7.78. Calcd for $C_{12}H_{14}O_2$: C, 75.76; H, 7.42.

2-(4-Chlorophenyl)-4-methylenetetrahydrofuran (**13d**): colorless oil; bp 120−125 °C/8 mmHg. ^{1}H NMR ($CDCl_3$) δ 2.51 (m, 1H, C*H*H), 2.93 (m, 1H, C*H*H), 4.40 (br d, 1H, J = 13 Hz, OCHH), 4.56 (br d, 1H, J = 13 Hz, OCHH), 4.93 (dd, 1H, J = 6 and 8 Hz, ArCH), 4.96 (m, 1H, =CH), 5.03 (m, 1H, =CH), 7.26−7.33 (m, 4H, Ar). ^{13}C NMR ($CDCl_3$) δ 41.26 (CH2), 71.36 (OCH_2), 80.36 (PhCH), 104.61 (=CH_2), 127.09, 128.36, 133.04, 140.16 (Ar), 147.20 (=C). Found: C, 67.54; H, 5.71. Calcd for $C_{11}H_{11}ClO$: C, 67.87; H, 5.70.

2-(3,4-Dimethoxylphenyl)-4-methylenetetrahydrofuran (**13e**): colorless oil (bp 130−140 °C/6 mmHg): ^{1}H NMR ($CDCl_3$) δ 2.57 (m, 1H, C*H*H), 2.93 (m, 1H, C*H*H), 3.87 (s, 3H, MeO), 3.89 (s, 3H, MeO), 4.38 (br d, 1H, J = 13 Hz, OCHH), 4.57 (br d, 1H, J = 13 Hz, OCHH), 4.90 (dd, 1H, J = 6 and 8 Hz, PhCH), 4.95 (m, 1H, =CH), 5.03 (m, 1H, =CH), 6.83 (d, 1H, J = 8 Hz, meta-H), 6.89 (br d, 1H, J = 8 Hz, ortho-H), 6.93 (br s, 1H, ortho-H). ^{13}C NMR ($CDCl_3$) δ 55.84 (OMe), 55.94 (OMe), 71.28 (OCH_2), 81.03 (ArCH), 104.23 (=CH_2), 109.05, 110.83, 118.20, 134.05, 147.82 (=CH_2), 148.33, 148.84. Found: C, 70.46; H, 7.20. Calcd for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. When the present reaction was carried out in refluxing benzene, 2-phenyl-4-methylenetetrahydrofuran (**13a**) was obtained in 25% yield.

Reaction of 3,3-Diphenyl-3-hydroxypropyltriphenylphosphonium Bromide (12f) with Butyllithium Followed by the Addition of Paraformaldehyde. To a suspension of **12f** (1.11 g, 2 mmol) in THF was added butyllithium THF solution (1.6 M, 2.8 mL, 4.4 mmol) at −20 °C, and the mixture was stirred for 30 min. The resulting red solution was warmed to 40 °C, and paraformaldehyde (0.30 g, 10 mmol) was added in one portion. After refluxing for 1 h, the reaction mixture was washed with water, dried over magnesium sulfate, and finally evaporated to afford a colorless oil. This oil was extracted with hexane to separate triphenylphosphine oxide. The hexane extract was evaporated and chromatographed over silica gel by hexane−dichloromethane to give 1,1-diphenyl-3-buten-1-ol (**2b**, 0.38 g, 85%): colorless oil. ^{1}H NMR ($CDCl_3$) δ 3.07 (d, 2H, J = 7 Hz, CH_2), 5.16 (d, 1H, J = 10 Hz, cis =CH), 5.22 (d, 1H, J = 17 Hz, trans =CH), 5.67 (m, 1H, =CH), 7.20 (m, 2H, para-H), 7.30 (m, 4H, meta-H), 7.44 (m, 4H, ortho-H). HRMS calcd for $C_{16}H_{16}O$: M^+ 160.0888. Found: M^+ 160.0891.

Reaction of 13a with Phenyl Triflate in the Presence of Tetrakis(triphenylphosphine) Palladium. To a solution of **13a** (0.16 g, 1 mmol) and diisopropylethylamine (0.26 g, 2 mmol) in benzene (15 mL) was added tetrakis(triphenylphosphine) palladium (0.037 g, 0.03 mmol) in one portion. After

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30 min of stirring, *p*-tolyl triflate (0.24 g, 1 mmol) was added via syringe to this solution. After being stirred for 50 h at 60 °C, the reaction mixture was washed with water, dried over magnesium sulfate, and evaporated to give colorless oil. The reaction mixture was chromatographed over silica gel by elution with hexane to give dihydrofuran (**17**, 0.115 g, 0.72 mmol, 72%). Starting **13a** was recovered in 15% yield (0.024 g, 0.15 mmol). 2-Phenyl-4-methyl-2,3-dihydrofuran **17**: colorless oil. ^{1}H NMR ($CDCl_3$) δ 1.67 (s, 3H, Me), 2.53 (dd, 1H, J = 15 and 8 Hz, CHH), 2.98 (dd, 1H, J = 15 and 10 Hz, CHH), 5.51 (dd, 1H, J = 8 and 10 Hz, PhCH), 6.17 (s, 1H, =CH), 7.23−7.38 (m, 5H, Ph). ^{13}C NMR ($CDCl_3$) δ 11.92 (Me), 42.85 (CH_2), 82.40 (CH), 108.94 (=C), 125.38, 127.34, 128.31, 139.27 (=CH), 143.25. HRMS calcd for $C_{11}H_{12}O$: M^+ 160.0888. Found: M^+ 160.0892

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