the Harvard University MRL. The rotating-anode facility is part of the MRL. The synchrotron measurements were carried out at the National Synchrotron Light Source (NSLS) at Brookhaven National Laboratory. Research at the NSLS is supported by the Office of Basic Energy Sciences, U.S. Department of Energy, under contract DE-AC02-76CH00016. Ian Tidswell was the recipient of a NATO studentship. We are grateful to Dr. David Osterman and Dr. Thomas Rabedeau for assistance in these experiments, to Dr. Abraham Ulman of Eastman Kodak for providing preprints of articles, and to Dr. Ralph Nuzzo of AT&T Bell Laboratories for helpful discussions.

Registry No. HTS, 120905-09-1; Si, 7440-21-3; $Cl_3Si(CH_2)_{14}CH_3$, 60592-74-7; $Cl_3Si(CH_2)_9CH_3$, 13829-21-5; $Cl_3Si(CH_2)_{11}CH_3$, 4484-72-4; $Cl_3Si(CH_2)_{13}CH_3$, 18402-22-7; $Cl_3Si(CH_2)_{15}CH_3$, 5894-60-0; $Cl_3Si(CH_2)_{17}CH_3$, 112-04-9; $Cl_3Si(CH_2)_2(CF_2)_7CF_3$, 78560-44-8.

Supplementary Material Available: An appendix outlining the intensity of reflected X-rays for certain electron-density profiles (4 pages). Ordering information is given on any current masthead page.

Kinetic (Not Equilibrium) Factors Are Dominant in Wittig Reactions of Conjugated Ylides

Edwin Vedejs* and Thomas J. Fleck

Contribution from the S. M. McElvain Laboratory of Organic Chemistry, Chemistry Department, University of Wisconsin, Madison, Wisconsin 53706. *Received November 9, 1988*

Abstract: The Wittig reaction of ester-, vinyl-, or benzyl-stabilized ylides is examined in detail. Extensive control experiments have been performed to probe the oxaphosphetane intermediates, and reversal in these systems is ruled out as a significant (>5%) process. Betaine reversal, on the other hand, can be detected in the control experiments, depending on the conditions. Maximum betaine reversal is associated with formation of the anti betaine rotamers, while syn betaines can be generated in ethanol or THF without significant reversal in several cases. It is emphasized that betaines are obligatory intermediates in the control experiments, but they are neither obligatory nor likely intermediates in Wittig reactions, especially the *E*-selective examples conducted in aprotic solvents. Only the oxaphosphetanes are required to describe the overall Wittig process from ylide to alkene. Other intermediates are not necessary, including zwitterions, specific conformers, pseudorotamers, etc. The traditional control experiments are more complex and are shown to involve anti betaines as well as syn betaines (**2**, **24**, **25**), and in certain cases, hydroxy ylides (**28**) derived from the betaines. The *E*-selective reactions of ester-stabilized ylides are described as asynchronous cycloadditions with a relatively advanced, oxaphosphetane-like transition state. Exceptionally *E*-selective olefination is achieved using the allylic dibenzophosphole ylide **11a**. The intermediate oxaphosphetanes **14a**, **15a**, and **15b** are observed for the first time in a conjugated-ylide reaction.

The stereochemistry of the Wittig reaction is influenced by the presence of π-acceptor groups at the α-carbon.[1,2] Ylides $Ph_3P{=}CHX$ or $Ph_2RP{=}CHX$ (X = ester, acyl, vinyl, aryl, etc.) generally react with high (*E*)-olefin selectivity compared to the "nonstabilized" ylides $Ph_3P{=}CHCH_3$ or $Ph_2RP{=}CHCH_3$. House et al. reported increased (*Z*)-olefin formation from $Ph_3P{=}CHCO_2Me$ in methanol vs aprotic solvents and considered possible explanations based on the interconversion of betaine diastereomers **2a** and **3a** (eq 1).[2b] Although House did not choose among the mechanistic alternatives due to insufficient kinetic data, the connection between betaine interconversion and *E* selectivity became widely accepted in the review literature.[1] Some years later, extensive studies of solvent effects were interpreted to favor a cycloaddition mechanism for carbonyl-stabilized ylides.[3] Shortly thereafter, it was shown that oxaphosphetanes, not betaines, are observed in Wittig reactions where an intermediate can be detected.[4a] Subsequent proposals for interconversion of diastereomeric intermediates have discussed pathways that do not depend on betaines.[5] However, there is limited experimental evidence regarding the extent of equilibration by any means in conjugated ylide reactions.

Two important studies have appeared that support the idea that *betaines* can equilibrate. Speziale and Bissing found that treatment of ethyl *trans*-phenylglycidate with triphenylphosphine (refluxing ethanol) in the presence of *m*-ClC_6H_4CHO affords crossover products corresponding to the reversal of an intermediate betaine **2a** (eq 2).[6] Analogous results were obtained with stilbene oxide and other epoxides under more drastic conditions.[6,7] Trippett and Jones demonstrated that a betaine, **2b**, generated by deprotonation of the β-hydroxy phosphonium salt **6b** with NaOEt/EtOH, also affords extensive crossover products with ClC_6H_4CHO (Scheme I).[8] All of the essential features of these studies have been confirmed in our laboratory. However, when the betaine **2b** is formed by the quaternization of a phosphine alkoxide, **7b**, with methyl iodide in THF, (*Z*)-stilbene is obtained with 98% retention.[9] Furthermore, when **2c** is generated by the deprotonation method from **6c** in methanol, (*Z*)-cinnamate is formed in high yield.[10] These observations imply that equilibration of

(1) (a) Trippett, S. *Q. Rev. Chem. Soc.* **1963**, *17*, 406. (b) Schlosser, M. *Top Stereochem.* **1970**, *5*, 1. (c) Gosney, I.; Rowley, A. G. *Organophosphorus Reagents in Organic Synthesis*; Cadogan, J. I. G., Ed.; Academic Press: New York, 1979. (d) Maryanoff, B. E.; Reitz, A. B. *Chem. Rev.* In press. We thank the authors for a copy of this review prior to publication.

(2) (a) House, H. O.; Rasmusson, G. H. *J. Org. Chem.* **1961**, *26*, 4278. (b) House, H. O.; Jones, V. K.; Fank, G. A. *J. Org. Chem.* **1964**, *29*, 3327.

(3) (a) Froyen, P. *Acta Chem. Scand.* **1972**, *26*, 2163. (b) Aksnes, G.; Khalil, F. Y. *Phosphorus* **1972**, *2*, 105. Aksnes, G.; Khalil, F. Y. *Ibid.* **1973**, *3*, 37, 79, 109. (c) Recent studies have included the evaluation of empirical solvent polarity parameters in stabilized-ylide reactions: Maccarone, E.; Perrini, G. *Gazz. Chim. Ital.* **1982**, *112*, 447.

(4) (a) Vedejs, E.; Snoble, K. A. J. *J. Am. Chem. Soc.* **1973**, *95*, 5778. (b) Vedejs, E.; Meier, G. P.; Snoble, K. A. J. *J. Am. Chem. Soc.* **1981**, *103*, 2823. (c) Vedejs, E.; Marth, C. F. *J. Am. Chem. Soc.* **1988**, *110*, 3948. (d) Vedejs, E.; Marth, C. F. *J. Am. Chem. Soc.* **1989**, *111*, 1519.

(5) (a) Bestmann, H. J. *Pure Appl. Chem.* **1979**, *51*, 515 and references therein. Bestmann, H. J. *Pure Appl. Chem.* **1980**, *52*, 771. Bestmann, H. J.; Vostrowsky, O. *Top. Curr. Chem.* **1983**, *109*, 85. (b) Schlosser, M.; Schaub, B. *J. Am. Chem. Soc.* **1982**, *104*, 5821. Piskala, A.; Rehan, A. H.; Schlosser, M. *Collect. Czech. Chem. Commum.* **1983**, *48*, 3539. (c) Maryanoff, B. E.; Reitz, A. B.; Mutter, M. S.; Inners, R. R.; Almond, H. R., Jr.; Whittle, R. R.; Olofson, R. A. *J. Am. Chem. Soc.* **1986**, *108*, 7664.

(6) Bissing, D. E.; Speziale, A. J. *J. Am. Chem. Soc.* **1965**, *87*, 2683.

(7) Wittig, G. Haag, W. *Chem. Ber.* **1955**, *88*, 1654. Boskin, M. J.; Denney, D. B. *Chem. Ind. (London)* **1959**, 330.

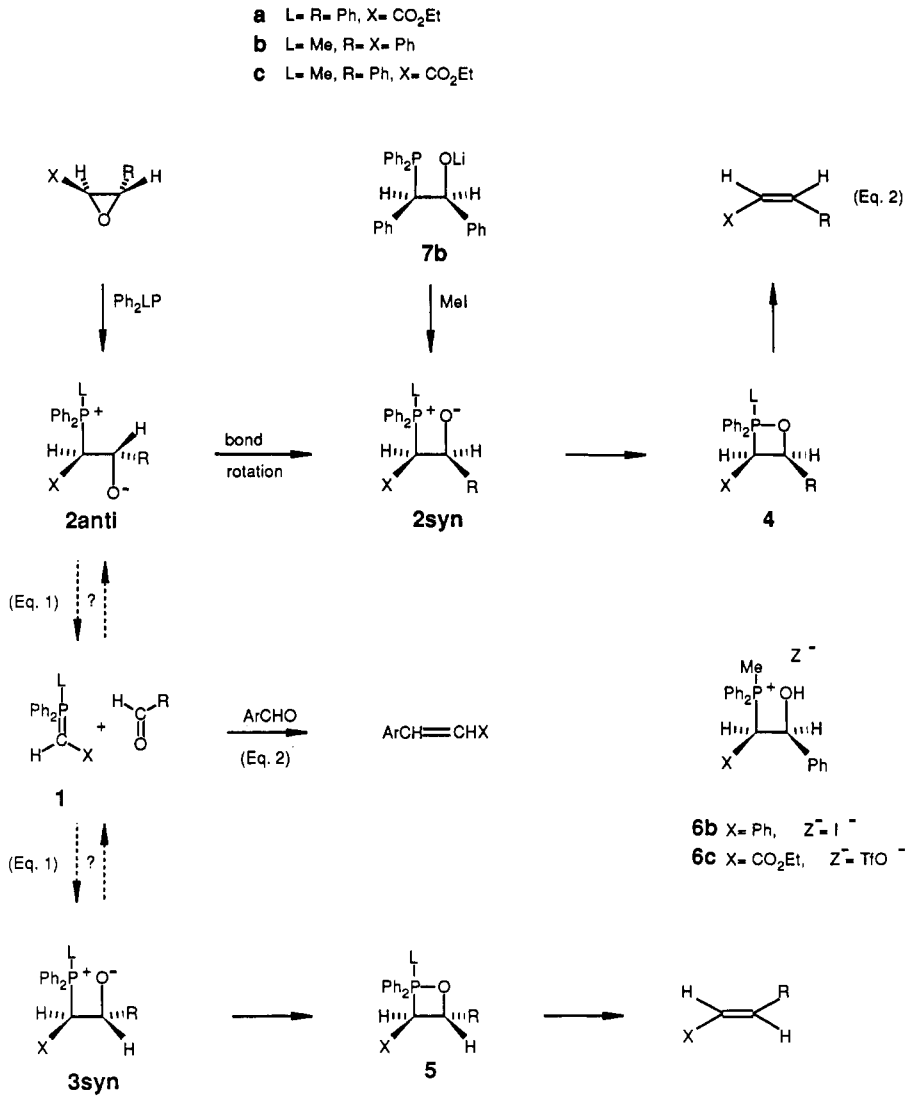
(8) Jones, M. E.; Trippett, S. *J. Chem. Soc. C* **1966**, 1090.

(9) (a) Vedejs, E.; Snoble, K. A. J.; Fuchs, P. L. *J. Org. Chem.* **1973**, *38*, 1178. (b) Vedejs, E.; Fuchs, P. L. *J. Am. Chem. Soc.* **1973**, *95*, 822.

(10) Vedejs, E.; Fleck, T.; Hara, S. *J. Org. Chem.* **1987**, *52*, 4637.

0002-7863/89/1511-5861$01.50/0

Scheme I



intermediates in reactions of **1a** and **1b** may not be important, but the issue depends on the mechanistic details of betaine generation as well as of the Wittig reaction as will be shown.

So far, no experimental test has been devised to prove whether or not betaines are intermediates in the conjugated ylide/aldehyde system. If they are, then equilibration of stereochemistry must be evaluated for betaines and also for oxaphosphetanes. If the mechanism involves asynchronous cycloaddition and betaines are not intermediates,[3,4,11c,12] then it is sufficient to know whether diastereomeric oxaphosphetanes **4** and **5** can interconvert.[4c,5c] Attempts to resolve this question by observing representative **4** and **5** by NMR methods have failed because oxaphosphetanes corresponding to conjugated ylides (X = acyl, vinyl, aryl, etc) decompose too rapidly.[13,5c] The alternative is to use methods for independent betaine generation or to study modified ylides where the intermediates are more stable.

Results

"Moderated" Ylides. Oxaphosphetanes **8** prepared from a nonstabilized dibenzophosphole (DBP) ylide decompose at temperatures ca. 80–100 °C higher than do analogues such as **9**.[14] This dramatic increase in oxaphosphetane stability is related to destabilization of tetrahedral vs trigonal-bipyramidal phosphorus by the ca. 94° C–P–C bond angle of the strained 5-membered ring and suggests that conjugated DBP ylides **10** or **11** might afford observable Wittig intermediates **12–15** (eq. 3).

Wittig reaction of the highly air-sensitive **10** with cyclohexanecarboxaldehyde occurred at −78 °C, and pentavalent phosphorus species were detected with some difficulty. An oxaphosphetane structure **12** is consistent with the transient ^{31}P absorption (δ-72 ppm, decomposition at −50 °C, half-life ca. 10 min) and formation of 1-cyclohexyl-1,3-butadiene, >95% *E* by NMR analysis. A firm assignment could not be made due to marginal stability of both the ylide and the oxaphosphetane and because **13** was not available for comparison. However, both

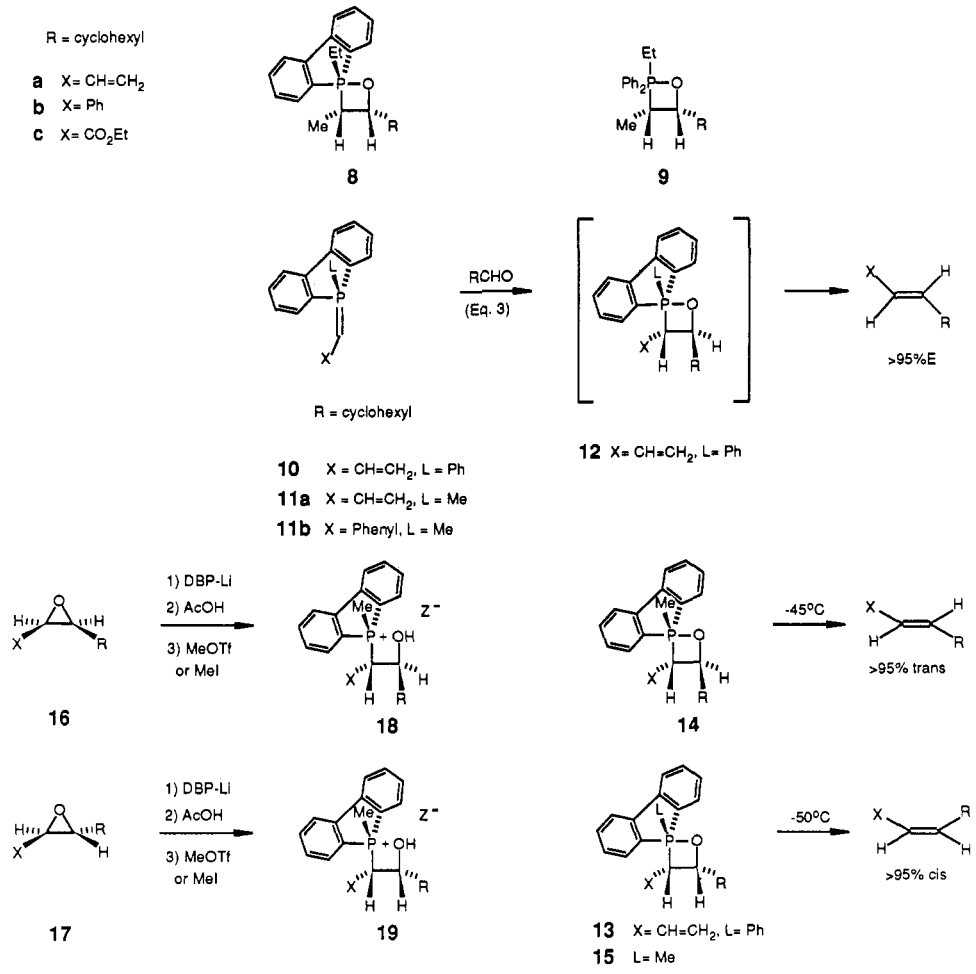
(11) (a) Speziale, A. J.; Bissing, D. E. *J. Am. Chem. Soc.* **1963**, *85*, 3878. (b) Ruchardt, C.; Panse, P.; Eichler, S. *Chem. Ber.* **1967**, *100*, 1144. (c) Nesmeyanov, N. A.; Vishtok, E. V.; Reutov, O. A. *Dokl. Akad. Nauk SSSR* **1973**, *210*, 1102. Giese, B.; Schoch, J.; Ruchardt, C. *Chem. Ber.* **1978**, *111*, 1395. (d) Kuchar, M.; Kakac, B.; Nemecek, O.; Kraus, E.; Holubek, J. *Collect. Czech. Chem. Commun.* **1973**, *38*, 447. (e) Isaacs, N. S.; Abed, O. H. *Tetrahedron Lett.* **1986**, *27*, 995; these authors also report activation volumes that are consistent with a cycloaddition process although this option was not considered. (f) Donxia, L.; Dexian, W.; Yaozhong, L.; Huaming, Z. *Tetrahedron* **1986**, *42*, 4161; the titrimetric determination of rates for benzylidene ylides in methanol did not take into account incomplete ylide formation under protic conditions. The reported rates include an unknown component corresponding to the equilibrium constant between phosphonium salt + alkoxide vs ylide + methanol.

(12) (a) Trindle, C.; Hwang, J.-T.; Carey, F. A. *J. Org. Chem.* **1973**, *38*, 2664. (b) Höller, R.; Lischka, H. *J. Am. Chem. Soc.* **1980**, *102*, 4632. (c) Volatron, F.; Eisenstein, O. *J. Am. Chem. Soc.* **1987**, *109*, 1. (d) Bestmann, H. J.; Chandrasekhar, J.; Downey, W. G.; Schleyer, P. von R. *J. Chem. Soc., Chem. Commun.* **1980**, 978.

(13) (a) Vedejs, E.; Huang, W.-F. *J. Org. Chem.* **1984**, *49*, 210. (b) Tamura, R.; Saegusa, K.; Kakihana, M.; Oda, D. *J. Org. Chem.* **1988**, *53*, 2723. (c) For early examples of phosphorus ligand effects causing enhanced *E* selectivity, see: Bladé-Font, A.; VanderWerf, C. A.; McEwen, W. E. *J. Am. Chem. Soc.* **1960**, *82*, 2396. Bestmann, H.-J.; Kratzer, O. *Chem. Ber.* **1962**, *95*, 1894.

(14) Vedejs, E.; Marth, C. F. *Tetrahedron Lett.* **1987**, *28*, 3445.

Scheme II



oxaphosphetane diastereomers **14a** and **15a** could be prepared via stereospecific opening of epoxide **16a** or **17a** with DBPLi[4c,8,9] and eventual betaine generation as shown in Scheme II. Deprotonation of the β-hydroxy phosphonium salts **18a** or **19a** (Z = trifluoromethanesulfonate) respectively afforded a unique oxaphosphetane **14a** or **15a** in each case at −78 °C (^{31}P NMR: **14a**, δ -74.3 ppm; **15a**, δ -75.6 ppm). There was no observable interconversion of diastereomers up to the temperature for decomposition (half-lives: 70 min for **15a** at −50 °C; 60 min for **14a** at −45 °C) and each diastereomer decomposed to the corresponding (*E*)- or (*Z*)-1-cyclohexyl-1,3-butadiene with >95% selectivity. Analogous experiments starting from epoxide **17b** resulted in the formation and detection of oxaphosphetane **15b** (δ -76.0 ppm), corresponding to the benzylic ylide **11b** (decomposition within 10 min at ca. −20 °C to 99% (*Z*)-2-cyclohexylstyrene).

The Wittig reaction of ylide **11a** with cyclohexanecarboxaldehyde was highly selective for the (*E*)-alkene (99:1 *E*:*Z*, GLPC analysis). A somewhat lower but still excellent *E*:*Z* ratio of 32:1 was obtained with benzylide **11b**. Oxaphosphetane formation in both cases was essentially complete within seconds at −78 °C, and the terms "moderated" or "semistabilized" certainly do not reflect the reactivity of these conjugated ylides. Both **11a** and **11b** resemble analogous "nonstabilized" ylides in qualitative reaction rates, but they display a higher preference for (*E*)-alkene formation. By comparison, $Ph_2MeP{=}CHX$ reacts with a useful but lower preference for (*E*)-alkenes while ylides $Ph_3P{=}CHX$ (X = vinyl or phenyl) are marginally selective.[13] Since the diastereomeric oxaphosphetanes **14** and **15** decompose without substantial interconversion, it follows that the exceptional (*E*)-olefin selectivity of **11a** and **11b** is due to dominant kinetic control. We conclude that the trend for increased (*E*)-olefin formation from conjugated ylides (R)DBP=CHX, $RPh_2P{=}CHX$, or $Ph_3P{=}CHX$ (X = vinyl, aryl) compared to that for analogues with X = alkyl is related to the decreased steric demands of the sp^2-hybridized substituent X in the highly congested Wittig transition state as recently proposed.[4c]

Ester-Stabilized Ylides. To date, no ester-substituted oxaphosphetane has proved sufficiently stable for direct observation. Even the DBP derivative **15c** generated by the deprotonation of precursor **19c** at −95 °C with KHMDS/THF decomposed too rapidly to be detected (probe temperature <−80 °C). Further studies therefore focused on the generation of transient intermediates corresponding to the ester-stabilized ylides **1** by deprotonation of β-hydroxy phosphonium salts or by epoxide deoxygenation. The only method to provide indirect access to both diastereomeric oxaphosphetanes or betaines proved to be a modified Speziale–Bissing experiment[6] involving the reaction of Ph_3P or Ph_2PMe with ethyl phenylglycidate (eq 2). In a search for conditions where betaine decomposition might be highly stereospecific, we examined the above experiments at the temperature threshold for olefin formation (Table I). The reaction of ethyl *trans*-phenylglycidate + Ph_3P + ClC_6H_4CHO at 20 °C in ethanol was slow, but sufficient product was formed for analysis at 2-day intervals. A constant 4:1 ratio of ethyl cinnamate:ethyl chlorocinnamate was present throughout the period monitored (9 days, 12% conversion). The crossover product $ClC_6H_4CH{=}CHCO_2Et$ was formed as a mixture of isomers (15:85 *Z*:E), but the ethyl cinnamate was >98% *Z*. Thus, a maximum of 20% of the betaine **2a** was subject to reversal at 20 °C and 80% was converted into the oxaphosphetane **4a** and ethyl (*Z*)-cinnamate without stereochemical equilibration by other mechanisms. As also noted by Speziale and Bissing, crossover increased at higher temperatures and product isomerization catalyzed by triphenylphosphine became significant (Table I, entries 4, 5).

A second series of deoxygenations was examined with methyldiphenylphosphine in place of triphenylphosphine. This re-

Table I. Enoate Formation from α,β-Epoxy Esters + Phosphines in Ethanol or THF (Entries 9, 11) Solution

entry	starting mtls	conditions	RCH=CHCO$_2$Et Z	RCH=CHCO$_2$Et E	ArCH=CHCO$_2$Et Z	ArCH=CHCO$_2$Et E	% conversion
1	*trans*-2-phenylglycidate, ArCHO/Ph_3P[b]	216 h/20 °C	80	–	–	20	12
2	ethyl (*Z*)-cinnamate, Ph_3P	120 h/20 °C	98	2			
3	*trans*-2-phenylglycidate, Ph_3P[b]	120 h/65 °C	69	31[c]			72
4	*trans*-2-phenylglycidate, ArCHO/Ph_3P[b]	120 h/65 °C	61	7[d]	5	27	70
5	ethyl (*Z*)-cinnamate, Ph_3P	36 h/65 °C	82	18			
6	*trans*-2-phenylglycidate, ArCHO/Ph_2MeP[b]	96 h/20 °C	71	23[d]	1	5	31
7	ethyl (*Z*)-cinnamate, Ph_2MeP	72 h/20 °C	50	50			
8	*cis*-2-phenylglycidate, ArCHO/Ph_2MeP[e]	960 h/20 °C	<2	97	–	3[e]	60
9	*cis*-2-phenylglycidate, ArCHO/Ph_3P[e,f]	960 h/20 °C	14	83	–	3[e]	3
10	*trans*-2-cyclohexylglycidate, ArCHO/Ph_2PMe[g]	1080 h/20 °C	6	77	1	16	50[h]
11	*trans*-2-cyclohexylglycidate, ArCHO/Ph_2PMe[f,g]	1080 h/20 °C	<2	79	–	21	1[h]

[a] Relative yields based on NMR integration unless otherwise noted. [b] Starting epoxide was contaminated by 3% of the less-reactive cis isomer (GLPC analysis). [c] *E* isomer due to reversal + isomerization of *Z* isomer. [d] *E* isomer due to product equilibration only (reversal ylide is scavenged by ArCHO); see next entry for control experiment. [e] Starting epoxide was contaminated by 5% of the more reactive trans epoxide; cis/trans isomerization of the cis epoxide was not monitored and is not ruled out. [f] THF conditions. [g] Starting epoxide 99.3% trans by GLPC analysis. [h] Yield by GLPC analysis vs internal standard.

Table II. Crossover Studies: Betaine Generation from β-Hydroxy Phosphonium Salts **22** + DBU

entry	salt + ArCHO	conditions[a]	R′CH=CHCO$_2$Et	%Z:%E[b]	% ArCH=CHCO$_2$Et	% yield
1	**22a** + ClC_6H_4CHO	DBU/THF	R′ = Ph	87:8	(5)	95
2	**22a** + ClC_6H_4CHO	DBU/EtOH	R′ = Ph	91:1	(5)	98
3	**22b** + ClC_6H_4CHO	DBU/THF	R′ = $PhCH_2CH_2$	>98:2		50
4	**22b** + ClC_6H_4CHO	DBU/EtOH	R′ = $PhCH_2CH_2$	>98:2		59
5	**22c** + ClC_6H_4CHO	DBU/THF	R′ = C_6H_{11}	99:1		96
6	**22c** + ClC_6H_4CHO	DBU/EtOH	R′ = C_6H_{11}	>98:2		96
7	**22d** + ClC_6H_4CHO	DBU/THF	R′ = $PhCH_2CMe_2$	96:3	(1)	99
8	**22d** + ClC_6H_4CHO	DBU/EtOH	R′ = $PhCH_2CMe_2$	96:2	(2)	99

[a] Reaction at 20 °C unless otherwise noted. [b] Relative yield by NMR integration.

Table III. Betaine Generation from β-Hydroxy Phosphonium Salts **22** + Strong Base

entry	salt	conditions[a]	% R′CH=CHCO$_2$Et[b] Z	% R′CH=CHCO$_2$Et[b] E	% R′CH=CDCO$_2$Et Z	% R′CH=CDCO$_2$Et E	% ArCH=CHCO$_2$Et	% yield
1	D_1-**22a**	KHMDS/THF/20 °C[c]	6	17	32	<2	43	97
2	**22a**	NaOEt/EtOH/20 °C	95	5			–	96
3	**22a**	NaOEt/EtOH/20 °C[c]	95				5	96
4	**22b**	KHMDS/THF/20 °C	37	55			8	90
5	D_1-**22b**	MstlLi/THF/20 °C	8	39	53	<2	–	53
6	D_1-**22b**	KHMDS/THF/20 °C	15	39	46	<2	–	99
7	**22c**	KHMDS/THF/20 °C[c]	63	29			5	97
8	**22c**	NaOEt/EtOH/20 °C[d]	98	<2			<2	91
9	D_1-**22c**	MstlLi/THF/20 °C	22	27	51	<2	–	87
10	D_1-**22c**	KHMDS/THF/20 °C	13	50	37	<2	–	94
11	D_1-**22c**	KHMDS/THF/−78 °C	6	3	91	<2	–	99
12	D_1-**22d**	NaOEt/EtOH/20 °C[c]	2	2	94	<2	2	95
13	D_1-**22d**	MstlLi/THF/20 °C	21	38	41	<2	–	83
14	D_1-**22d**	KHMDS/THF/20 °C[c]	8	48	44	<2	23	99
15	D_1-**22d**	KHMDS/THF/20 °C[e]	10	62	28	<2	–	83

[a] Reaction time 15 min unless otherwise stated; Mstl = mesityl; HMDS = hexamethyldisilazide. [b] Relative yields determined by NMR integration. [c] Excess ClC_6H_4CHO added immediately after base; reaction quenched after 9 h. [d] Excess ClC_6H_4CHO added after base; reaction quenched after 15 min. [e] Reaction quenched with trifluoromethanesulfonic acid 10 s after addition of base.

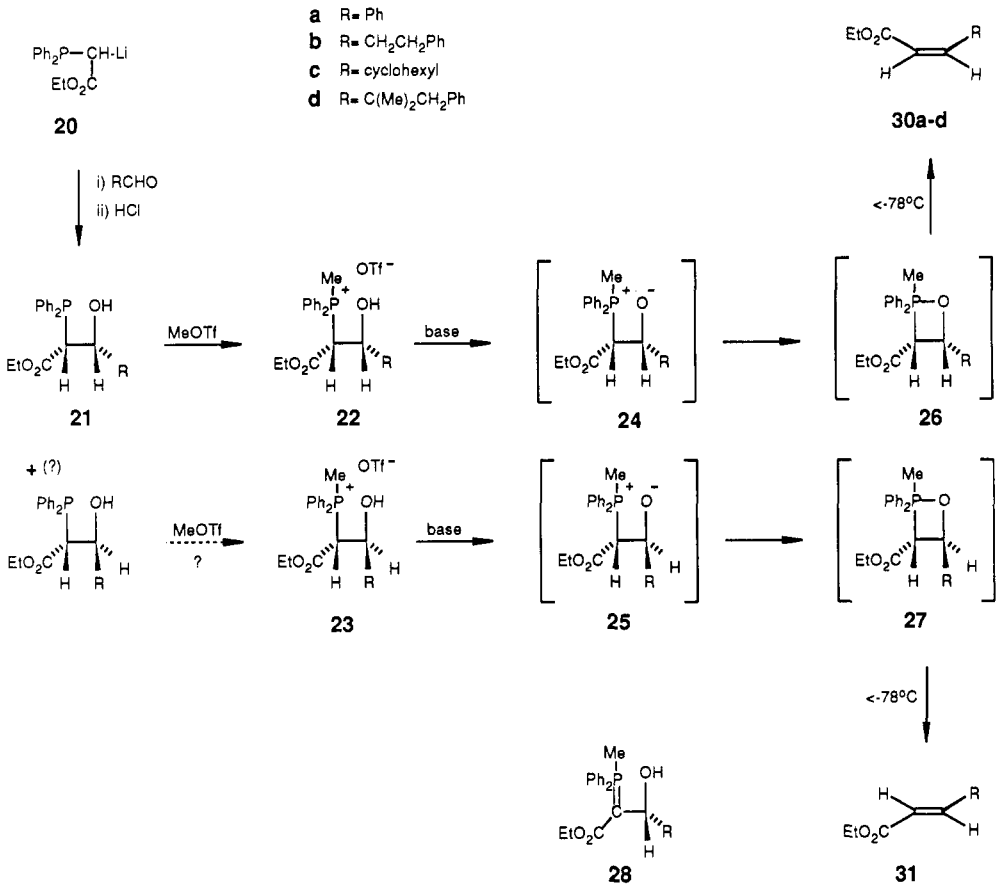
action occurred at a somewhat increased rate due to improved phosphine nucleophilicity and gave a constant 94:6 ratio of cinnamate:chlorocinnamate over a 4-day period (31% conversion in ethanol, 20 °C). The more reactive phosphine caused increased *Z* to *E* isomerization of the product alkenes, a result that was confirmed by control experiments. Therefore, product *E*/*Z* geometry does not provide useful information. However, the level of crossover (6%) proves that 94% of **2c** proceeds to alkenes (ethanol solvent) without reversal to the starting ylide. The isomeric *cis*-phenylglycidate ester (entry 8) was considerably less reactive, and the results were harder to quantify because traces of the *trans*-phenylglycidate isomer were present in the starting epoxide. After correcting for the crossover due to the *trans*-phenylglycidate contaminant, it was shown that conversion of ethyl *cis*-phenylglycidate into ethyl (*E*)-cinnamate occurred without measurable (<2%) crossover.

A detailed evaluation of intermediates is possible in this series because betaine **2c** can be generated by a second, unrelated technique as reported in a preliminary communication.[10] Addition of the enolate **20**[15] to benzaldehyde gave a mixture of products (Scheme III). The initially formed (hydroxyalkyl)phosphines proved surprisingly unstable and all attempts at isolation resulted in decomposition. However, the products did survive in solution and it was possible to obtain fractions enriched in one isomer, **21a**, by chromatography. Solvent removal lead to decomposition, but addition of methyl triflate directly to the eluant resulted in the precipitation of a phosphonium salt which proved to be the isomer **22a**. The same qualitative behavior was noted with several other aldehydes, and precipitated salts **22b–d** (and the DBP derivative **19c** mentioned earlier, starting from DBP-Li) were obtained in low yield. Diastereomeric salts **23** were not isolated in any of the examples studied. In the cyclohexanecarboxaldehyde experiments, P-methylation of a less polar chromatography fraction did produce a small amount of >98% *E* enoate. This result suggests the intermediacy of **23c** and is consistent with stereospecific decomposition of betaine **25c** to the (*E*)-cinnamate. However, we cannot comment further on **25c** because the precursor **23c** could not be isolated.

Treatment of the salts **22** with a variety of bases at room temperature resulted in decomposition to give enoates (Tables II and III). High yields were the rule except in the case of **22b**, which was the only salt that could not be crystallized. Base-in-

(15) Reetz, M. T.; Eibach, F. *Liebigs Ann. Chem.* **1977**, 242.

Scheme III



duced decomposition of **22** was essentially instantaneous in all cases, but the recombination of any $Ph_2MeP{=}CHCO_2Et$ with R′CHO that might be formed by betaine reversal was slow. This is due to the modest reactivity of the stabilized ylide and also to the second-order kinetics under dilute conditions for the Wittig recombination step. It was therefore possible to assay reversal by adding at least 2 equiv of ClC_6H_4CHO 30 s after the addition of base. In this way, any perturbation of the betaine decomposition step by the chlorobenzaldehyde should be avoided. Control experiments proved that the trapping of $Ph_2MeP{=}CHCO_2Et$ by ClC_6H_4CHO under the conditions used for reversal assay (9 h, 20 °C) was complete (75% yield of $ClC_6H_4CH{=}CHCO_2Et$ isolated).

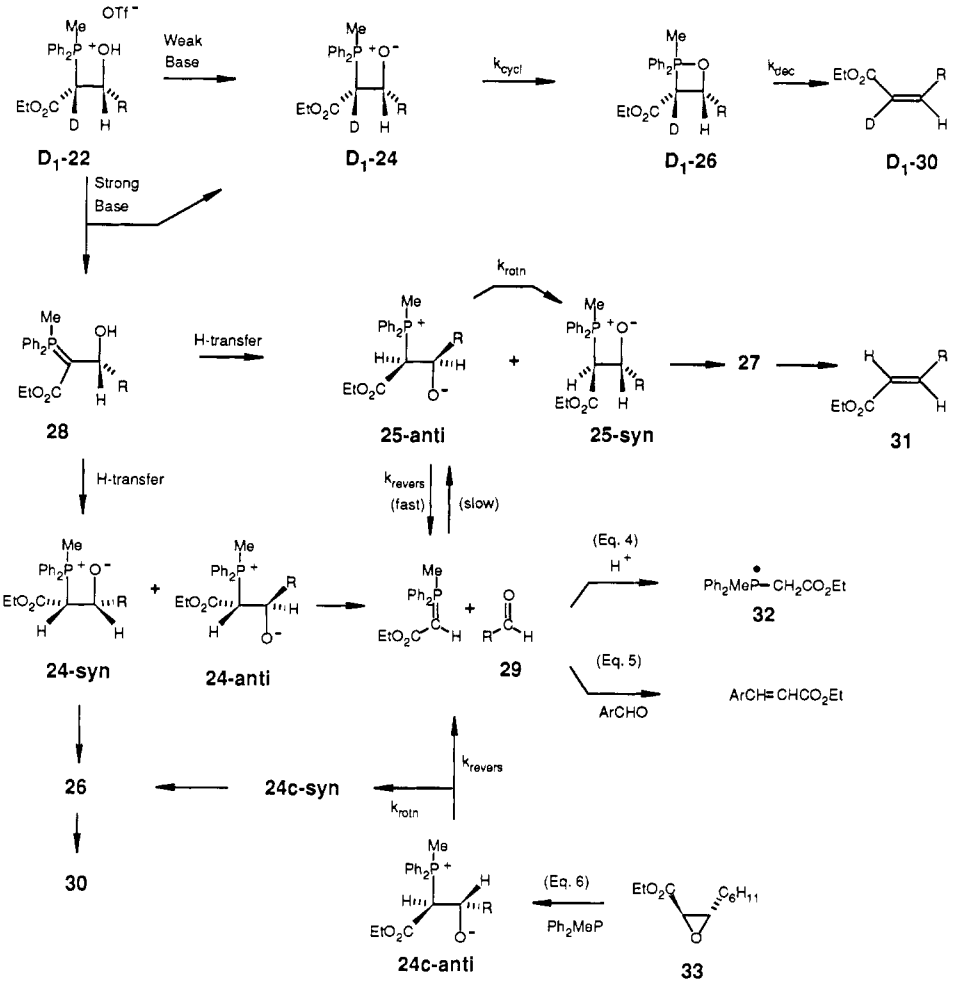
Relatively simple results were obtained with diazabicycloundecene (DBU) in THF or DBU/ethanol to generate the betaines (Table II). No crossover products could be detected starting from the primary or secondary alkyl examples **22b** or **22c** and the (*Z*)-enoates were obtained with no more than traces of the *E* isomer (>98:2 *Z*:*E*). Marginal crossover was observed in the tertiary aldehyde derived **22d** (2% maximum) in both ethanol or THF, but the enoate was formed in excellent (>90%) yield, and the *Z*:*E* ratio was again ≥98:2.

The benzaldehyde-derived **22a** proved more complex. Somewhat increased crossover was detected (5%) with DBU/ethanol, consistent with the result from epoxide deoxygenation described earlier. However, under the DBU/THF conditions, **22a** produced substantial amounts of the (*E*)-cinnamate (8%) even though excess ClC_6H_4CHO should have completely suppressed any recombination of PhCHO + $Ph_2MeP{=}CHCO_2Et$. The (*Z*)-cinnamate was shown to be stable under the reaction conditions. Therefore, equilibration of betaine **24a** or oxaphosphetane **26** geometry by means other than the betaine-reversal process must have been involved. Eventually, it was found that betaine equilibration occurs via the hydroxy ylide **28** and that this process can be observed in all four substrates **22** if strongly basic conditions are used for deprotonation at room temperature. An investigation of this phenomenon has also established that the betaine-reversal process can be influenced by the choice of base as shown in the next section. However, we have found no evidence to indicate that **28** intervenes in the Wittig reactions of $Ph_2MeP{=}CHCO_2Et$.

The hydroxy ylide pathway[1a,9a] for loss of stereochemistry without betaine reversal was established by studying analogues of **22** deuterated α to phosphorus (Scheme IV). Some of the most informative results were obtained starting with D_1-**22d**. First, several experiments were performed on a short time scale (15 min total), conditions that prevent any significant contribution from the recombination step of $Ph_2MeP{=}CHCO_2Et$ + aldehyde **29d** in those examples where some betaine reversal might have occurred. As expected, the DBU/THF conditions produced the (*Z*)-enoate with deuterium at the α-carbon (>98% *Z*, >98% D_1, 99% yield estimated by NMR vs internal standard). In contrast, the use of the strong bases potassium hexamethyldisilazide (K^+HMDS^-) or mesityllithium (MstlLi) in THF at 20 °C afforded enoate products in lower yield and with much lower deuterium content (Table III, entries 13, 14). Especially striking were the results of an experiment where KHMDS was added to D_1-**22d** at room temperature, followed 10 s later by acid to quench the basic species (Table III, entry 15). This produced a 1.6:1 ratio of the (*E*)-enoate **31d** and the (*Z*)-enoate **30d**. The (*Z*)-enoate retained 0.74 α-D/molecule, but the (*E*)-enoate was deuterium-free! Furthermore, 16% of the phosphonium salt **32** was also present, presumably derived from the protonation of $Ph_2MeP{=}CHCO_2Et$ by the acid-quenching step (Scheme IV, eq 4). The most likely source of **32** and of the precursor ylide would have to be the betaine-reversal process, but the extent of reversal under the strong-base conditions is much greater than from the reaction of **22d** + DBU in the same solvent. This conclusion was confirmed by a crossover experiment (Scheme IV, eq 5) where ClC_6H_4CHO was added immediately after the KHMDS, resulting in 23% of $ClC_6H_4CH{=}CHCO_2Et$ after 9 h (Table III, entry 14). Some of the aldehyde **29d** was also detected, although in lower yield (15%).

In view of the apparent increase in crossover in the tertiary alkyl derived **22d** from the DBU/THF experiment (1%) to the

Scheme IV



KHMDS/THF experiment (23%), we reexamined **22a–c** under the strong-base conditions. Neither **22b** nor **22c** had given detectable crossover products from the DBU/THF conditions, but the KHMDS/THF procedure (specific conditions as described for **22d**) afforded 8% crossover product from **22b** and 5% from **22c**. Neither experiment produced a significant amount of the aldehydes **29b** or **29c** that should have been formed from simple betaine reversal. Nevertheless, the strong-base effect is consistent for all of the salts **22** and is especially dramatic for the benzaldehyde-derived **22a**. In this case, the KHMDS/THF procedure afforded 48% crossover products.

The issue of deuterium content in the product enoates was explored further using D_1-**22c** as the starting material. The reaction with KHMDS/THF proved to be strongly temperature dependent. Thus, at 20 °C a 1:1 ratio of *E*:*Z* enoates was observed while at −78 °C the *Z* isomer predominated by a ratio of 97:3. Deuterium label could not be detected in the (*E*)-enoate **31c** under any conditions. In the *Z* isomer **30c**, the deuterium content increased as the reaction temperature decreased, and at −78 °C, ca. 95% of the expected label was present at the (*Z*)-enoate α-carbon by NMR integration.

All of the evidence supports the involvement of the hydroxy ylide **28** in the strong-base experiments. In contrast to DBU, KHMDS (or mesityllithium) discriminates poorly between the OH proton and the acidic α-CD (or CH) next to positive phosphorus in **22**. Removal of the OH proton leads to betaine D_1-**24** and then to the oxaphosphetane D_1-**26** or, in some cases, to betaine-reversal products. However, competing formation of **28** via α-CD removal is substantial at room temperature. Proton transfer from oxygen to carbon in **28** then leads to a mixture of deuterium-free betaines **24** and **25**. At room temperature, **25** is strongly favored and substantial amounts of deuterium-free **31** are formed via the corresponding oxaphosphetane **27**. Some of the (*Z*)-enoate **30** is also derived from **28**, depending on the stereochemistry of the proton transfer from oxygen to carbon, and this process accounts for the relatively minor loss of deuterium label from **30**. The mechanistic details for the proton transfer remain unknown, but this ambiguity does not affect the interpretation of the results in the context of Wittig reactions because **28** plays at most a minor role in the absence of strong base.

The KHMDS experiments indicate that betaine reversal can be dependent on subtle experimental details. According to the crossover criterion, the extent of reversal is substantially increased in THF when KHMDS is used in place of DBU for the deprotonation step. One possible explanation is that the weaker base discriminates between "syn" and "anti" rotamers of **22** and produces only the betaine **24-*syn*** which closes rapidly (k_{cycl}) to the oxaphosphetane **26**. The strong bases probably deprotonate various rotamers of **22** randomly, and this lack of kinetic discrimination produces other betaine geometries. The betaine rotamer **24-*anti*** has additional opportunities for reversal if the latter process (k_{revs}) is fast enough to compete with bond rotation (k_{rotn}). A second possible rationale for the difference between strong bases vs DBU is that proton transfer from OH in **22** to the DBU creates the betaine **24** in a geometry where negative oxygen is in the proximity of the positively charged [DBU H]$^+$. This ion pairing might stabilize the betaine sufficiently to prevent reversal on the time scale for C–C bond rotation and conversion of anti into syn rotamers and, eventually, into the oxaphosphetane **26**.

Treatment of **22a** or **22b** with the stronger base NaOEt in ethanol (Table III) involves the same low levels of reversal as in the ethanol/DBU conditions. Although ethanolic ethoxide is considerably less basic than KHMDS/THF, at least some formation of anti betaines was expected. If this occurred, then improved solvation of the betaine alkoxide by the protic solvent might be responsible for decreased betaine reversal. A single

Table IV. Wittig Reactions of Ester-Stabilized Ylides **1a** and **1c**

entry	aldehyde	ylide	*Z*:*E* ratio (% conversion)[a] THF/KHMDS	THF/DBU	EtOH/DBU	EtOH/NaOEt
1	PhCHO	**1a**		7:93 (73)	20:80 (90)	15:85[b]
2	PhCHO	**1c**	23:77 (73)	17:83 (87)	37:63 (54)	23:77 (79)
3	$PhCH_2CH_2CHO$	**1a**		4:96 (70)	33:67 (93)	
4	$PhCH_2CH_2CHO$	**1c**	11:89 (85)	19:81 (87)	50:50 (71)	56:44 (73)
5	$C_6H_{11}CHO$	**1a**		3:97 (34)	13:87 (67)	
6	$C_6H_{11}CHO$	**1c**	4:96 (88)	15:85 (95)	35:65 (64)	37:63 (81)
7	$PhCH_2CMe_2CHO$	**1a**		5:95 (3)	35:65 (5)	
8	$PhCH_2CMe_2CHO$	**1c**	9:91 (26)	22:78 (7)	58:42 (10)	63:37 (15)

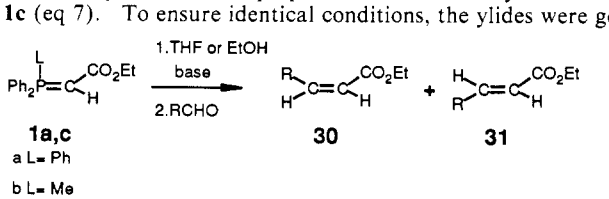
[a] All reactions at 20 °C unless otherwise noted, 4-h reaction time. [b] At 15 °C for 16 h; no yield reported (ref 17).

equivalent of a potential hydroxylic proton donor is not enough to stabilize the betaine, however, since KO-*t*-C_4H_9/THF had the same effect on **22a** as did KHMDS/THF (ca. 50% crossover).

To further probe the role of solvent and the importance of syn-anti-betaine geometry as a potentially decisive factor in the percent of betaine reversal, specific generation of **24c**-*anti* was studied. As discussed earlier, the reaction of an epoxide such as **33** with Ph_2MeP should initially produce only the betaine rotamer **24c**-*anti* (eq 6). The reaction proved exceedingly slow in THF at room temperature, the conditions used for the deprotonation experiments. Nevertheless, it was possible to detect conversion of **33** to **30c** + **31c** after 50 days. With 2 equiv of ClC_6H_4CHO present, the experiment produced a ratio of ca. 79:21 of the enoates [**30c** + **31c**]:crossover product $ClC_6H_4CH{=}CHCO_2Et$ in THF (Table I, entry 11). Somewhat decreased reversal was observed from a similar experiment in ethanol (83:17 [**30c** + **31c**]:crossover product). The loss of stereochemistry in **30c** has no significance because there is ample time for *E*/*Z* isomerization catalyzed by the Ph_2MeP. However, the extent of betaine reversal indicated by 16–21% crossover is clearly increased relative to that found in β-hydroxy phosphonium salt deprotonation experiments in the same solvent (KHMDS/THF + **22c**) or in ethanol. This difference indicates that the deprotonation experiments produce mostly **24c**-*syn*, and that any betaine **24c**-*anti* that may be generated undergoes reversal at a rate (k_{rev}) comparable to the rate of C–C bond rotation (k_{rotn}). Once formed, rotamer **24c**-*syn* closes rapidly to the oxaphosphetane **26c**, which proceeds to the (*Z*)-enoate **30c** without further reversal or equilibration by other means.

Experimental conditions are especially important in the extent of betaine reversal observed for **2b**.[8,9b,5c] The 98% stereospecificity for (*Z*)-stilbene formation obtained via the quaternization of alkoxide phosphine **7b** in tetrahydrofuran[9b] can be attributed to highly selective formation of the most stable betaine conformer **2b**-*syn*. A decrease in selectivity (94% (*Z*)-stilbene) is reported for the deprotonation of **6b** using LiHMDS in THF at 23 °C,[5c] a reasonable consequence of increased formation of **2b**-*anti* as in our strong-base experiments. When **2b** is generated from **6b** with sodium methoxide/methanol, a dramatic increase in betaine reversal is observed.[8] In support of the original interpretation,[8] we find that crystalline benzylmethyldiphenylphosphonium iodide is formed in 60% yield upon quenching the room-temperature reaction with acetic acid 5 min after the addition of sodium methoxide. If reversal of **2b** depends on the population of the anti betaine, then substrate-dependent solvation effects are implicated by the methanol result.

Wittig Reactions. A series of standardized Wittig experiments were performed to allow direct comparison between the above control experiments and preparative reactions of ylides **1a** and **1c** (eq 7). To ensure identical conditions, the ylides were generated in situ using the same bases employed for β-hydroxy phosphonium salt decomposition, and the aldehyde was added shortly thereafter (20 °C). In general, the results (Table IV) reflect increased (*Z*)-enoate formation in alcoholic vs ether solvents although the differences are not large. The marginally reactive aldehyde **29** consistently gave a higher proportion of (*Z*)-enoate, but again the effect is modest and becomes significant only under protic conditions. Of the two ylides **1a** and **1c**, **1a** is consistently more selective for the (*E*)-enoate products.

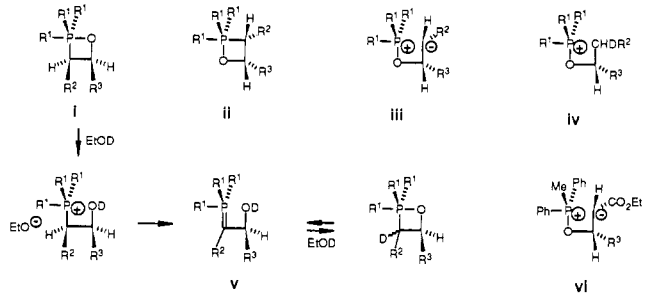


(Eq. 7)

Conclusions

The fact that highly stereospecific conversion of **22** to (*Z*)-enoates **30** can occur proves that olefin formation is fast compared to reversal of the obligatory oxaphosphetane intermediates **26** or **27**. The increased (*E*)-olefin selectivity of ester-stabilized ylides is therefore not related to a kinetic advantage for decomposition of the trans- vs the cis- disubstituted oxaphosphetanes. Under conditions where some loss of stereochemistry in the control experiments starting from **22** (independent betaine generation) does take place, the deuterium labeling studies are consistent with betaine reversal. Deuterium exchange at the carbon α to phosphorus can occur via the hydroxy ylide **28**. However, our results rule out oxaphosphetane equilibration or deuterium exchange by reversible C–P bond cleavage.[5a,16] This would require the formation of (*E*)-enoates containing α-deuterium from α-deuterated **22**, a result that was never observed under the relevant conditions (Tables II, III). Betaine reversal in the β-hydroxy phosphonium deprotonation control experiments is attributed to the generation of the anti rotamers and is most pronounced with **24a** and **24d**. The epoxide deoxygenation results define the upper limits of

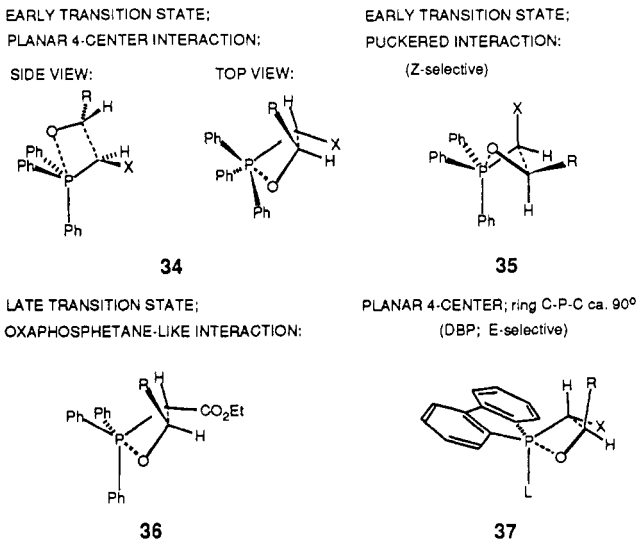
(16) An earlier report of labeling results mentions the incorporation of deuterium into the eventual alkene product when i is allowed to decompose



in C_2H_5OD.[5a] This result was attributed to oxaphosphetane pseudorotation to ii, heterolysis of an apical C–P bond to give iii, conversion to iv by deuterated ethanol, and base-induced elimination of iv to the deuterated alkene.[5a] The only specific case mentioned involves the preparation of D-labeled β-carotene (R^1 = phenyl; $R^2 = R^3$ = sp² carbon in a polyene chain).[5a] Deuterium incorporation via the hydroxy ylide v is a possibility under these conditions, but this alternative was not discussed.[5a] We have ruled out equilibration via intermediates such as iii in the closely related **4b**, **12–15**, or in simple alkyl-substituted analogues.[9,4c] Since vi is ruled out by the labeling studies of Tables I–III, we conclude that iii is not formed from oxaphosphetanes with R^2 = ester, phenyl, alkenyl, or alkyl in the examples studied so far. Significant C–P heterolysis does not take place in the above examples, and no evidence remains to support the suggested connection with pseudorotation or the Westheimer rules for apical departure.[5a] We have recently shown that pseudorotation of oxaphosphetanes related to **4** or **12–15** is fast at 0 °C and does not affect Wittig decomposition rates.[4d]

(17) (a) Tronchet, J. M. J.; Gentile, B. *Helv. Chim. Acta* **1979**, *62*, 2091. (b) Valverde, S.; Martin-Lomas, M.; Herradon, B.; Garcia-Ochoa, S. *Tetrahedron* **1987**, *43*, 1895.

Scheme V



conceivable reversal since these reactions produce the most reversal-prone anti betaines. However, the Wittig reactions are not obliged to form either the syn or the anti betaines by any of the available evidence.

The *E*-selective reactions of ester-stabilized ylides (solvents such as benzene, THF, DMF) have been described as asynchronous cycloadditions.[3b,c,4c,11c] A related cycloaddition process has been proposed to account for nonstabilized-ylide reactions.[4c] Although several variables are responsible for transition-state geometry, the following points are most important. Briefly stated, parallel approach of ylide and carbonyl π-systems is difficult in an early transition state because the ylide phosphorus is sp^3 hybridized and at least one phosphorus ligand must project toward the approaching aldehyde as in trans-selective **34** (Scheme V). Any distortion that lowers phenyl–oxygen interactions in this geometry results in increased 1,2- or 1,3-interactions. A better compromise of 1,2- and 1,3-interactions can be achieved in the puckered geometry **35** (cis selective, early transition state). For stabilized ylides, a later transition state is likely, and the advantages of puckering will be smaller as phosphorus geometry approaches trigonal bipyramidal. The preference for (*E*)-enoate formation in aprotic solvents is consistent with a late four-center transition state **36** that resembles the oxaphosphetane.[4c] There is no need to invoke equilibration of stereochemistry to explain *E* selectivity because related trans-disubstituted oxaphosphetanes are more stable than the cis isomers[4c,5c] and a late transition state will feel similar nonbonded interactions.[4c] In qualitative support of this argument, increased bulk in the phosphorus ligands of $R_3P{=}CHCO_2Et$[18] or in **1a** relative to **1c** is associated with somewhat enhanced (*E*)-enoate formation. The opposite trend was noted for phosphorus ligands in analogous nonstabilized ylides where the transition state is early, although there are other important factors as well.[4c]

The situation is different in alcohol solvents. Wittig reactions of $Ph_3P{=}CHCO_2Et$ with certain α,β-dialkoxy aldehydes are reported to occur with an astonishing degree of *Z* selectivity as high as 100:1 in methanol, and a related example is known where selectivity can be inverted from 80–86% *E* in aprotic solvents (benzene or DMF) to 92% *Z* in methanol.[17] The influence of solvent on the reactions of $Ph_2RP{=}CHCO_2Et$ with simple aldehydes (Table IV) is less pronounced, but it is significant by comparison to analogous nonstabilized ylide reactions.[1,4] Ylides such as $Ph_3P{=}CHCH_3$ (lithium-free) are > 90% *Z* selective in hexane, toluene, ethers, alcohols, DMSO, and so on under conditions of kinetic control.[1]

Logic suggests that origins of *Z* selectivity in stabilized and nonstabilized ylides are related. For example, the rate-accelerating effect of methanol[3,11a,b] may result in an earlier cycloaddition transition state that resembles the puckered, four-center geometry proposed for nonstabilized ylides.[4c] *However, contrasting P-ligand effects and the striking substrate dependence of Z selectivity in stabilized ylides caution against a simple analogy.* Intermediates corresponding to the α,β-dialkoxy aldehydes have not been studied to date, and we can make no choice among mechanistic possibilities for this class of *Z*-selective ester stabilized ylide reactions. As usual, two-step (ionic) mechanisms are difficult to reconcile with the relationship between activation parameters and solvent properties in related reactions,[3b,11b,c] but two *Z*-selective variations cannot be ruled out. The first is a solvated syn betaine that resembles the *Z*-selective asynchronous cycloaddition transition state[4c] with respect to bond angles. The second is the solvated anti betaine proposal of House et al.,[2] modified in accordance with our control experiments that indicate minor betaine reversal in alcohol solvents. Either of these transition state structures might be more stable in the orientation leading to cis disubstituted oxaphosphetanes and could become competitive for some of the alkoxy aldehydes.[17] Further discussion must await proof that betaines are (or are not) intermediates in the methanol or ethanol Wittig experiments. However, the *E*-selective reaction of carbonyl-stabilized ylides fits the pattern expected for the late transition state cycloaddition process.

Direct observation of decomposition rates for oxaphosphetanes corresponding to conjugated ylides is described for the first time. A qualitative comparison of **14** or **15** vs analogous DBP oxaphosphetanes **8** with R′ = saturated alkyl indicates that the unsaturated substituent in **14** or **15** lowers the activation barrier for olefin formation by ca. 8–10 kcal/mol! The C–P bond must be considerably stretched in the transition state leading to conjugated alkenes, a conclusion that has also been reached by computational methods.[12] Decomposition of the ester-substituted oxaphosphetanes is even more facile, and so far, no example has been found where this process can be retarded sufficiently to allow detection of intermediates derived from carbonyl-stabilized ylides, even in the case of the DBP adduct derived **15c** generated by the deprotonation method from **19c**. Failure to detect **15c** cannot be considered conclusive in view of the technical difficulty of the low-temperature experiment, but the barrier for decomposition appears to be significantly smaller than the pseudorotational barrier measured for related, DBP-derived oxaphosphetanes.[4d] This observation supports our previous conclusion that pseudorotation phenomena are coincidental to the mechanism of the Wittig decomposition step.[4d] Essentially instantaneous olefin formation from several of the above oxaphosphetanes at −78 °C offers interesting possibilities for the synthesis of sensitive carbon–carbon double bonds. Further studies on this topic are under way.

Stereochemical trends in the reactions of allylic or benzylic ylides have been discussed previously.[4c] The only additional feature encountered in the present study is the exceptional *E* selectivity that results from the combination of the DBP phosphorus environment, a compact *P*-methyl substituent, and a planar sp^2 carbon substituent placed at the ylide α-carbon. The DBP ring system facilitates parallel approach of C=P and C=O, even in an early transition state such as **37**, by compressing the critical C–P–C ring bond angle. A nearly planar four-center transition state prefers the trans arrangement of substituents, and the result is the observed kinetic preference for (*E*)-alkene formation.

Experimental Section

Epoxidations. *cis*- and *trans*-1-Cyclohexyl-2-vinyloxirane (16a and 17a). A mixture (ca. 2:1 trans:cis) of 1-cyclohexyl-1,3-butadiene[19] (14.3 mmol) was dissolved in CH_2Cl_2 (60 mL) and cooled to 0 °C, and MCPBA (Aldrich, 14.3 mol) in CH_2Cl_2 (20 mL) was added dropwise via a cannula. The solution was stirred for 2 h, and the resulting cloudy mixture was washed with 10% $NaHCO_3$ (2 × 30 mL) and dried ($MgSO_4$), and the solvent was removed in vacuo. HPLC purification (sem-

(18) Bissing, D. E. *J. Org. Chem.* **1965**, *30*, 1297.

(19) (a) Ukai, J.; Ikeda, Y.; Ikeda, N.; Yamamoto, H. *Tetrahedron Lett.* **1983**, *24*, 4029. (b) Ikeda, Y.; Yamamoto, H. *Bull Chem. Soc. Jpn.* **1986**, *59*, 657.

ipreparative μ-Porisil, 50 cm × 25 mm i.d.) provided, in order of elution, 0.50 g (21%) of *cis*-1-cyclohexyl-2-vinyloxirane (**16a**), 0.45 g (23%), of *trans*-1-cyclohexyl-2-vinyloxirane (**17a**), and 0.28 g (13%) of terminal epoxides (not characterized).

16a: oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.44; MS base peak : 83.9510; exact mass calcd for $C_{10}H_{16}O$ 152.1201, found 152.1183, error = 11.8 ppm; IR (neat, cm^{-1}) C–O, 1180; 270-MHz NMR ($CDCl_3$) δ 5.71 (1 H, ddd, J = 7.3, 10.2, 17.2 Hz), 5.45 (1 H, dd, J = 1.8 17.2 Hz), 5.32 (1) H, dd, J = 1.8, 10.2 Hz), 3.37 (1 H, dd, J = 4.4, 7.3 Hz), 2.75 (1 H, dd, J = 4.3, 8.3 Hz), 2.02–1.87 (1 H, m), 1.82–1.42 (4 H, m), 1.30–0.95 (6 H, m).

17a: oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1 R_f = 0.40; MS base peak = 81.0699; exact mass calcd for $C_{10}H_{16}O$ = 152.1201, found 152.1190, error = 7.2 ppm; IR (neat, cm^{-1}) C–O, 1255; 270-MHz ($CDCl_3$) δ 6.58 (1 H, ddd, J = 7.8, 11.0, 18.1 Hz), 6.41 (1 H, dd, J = 1.3, 18.1 Hz), 6.22 (1 H, dd, J = 1.3, 11.0 Hz), 3.14 (1 H, dd, J = 3.2, 7.8 Hz), 2.92–2.80 (1 H, m), 2.80–2.60 (4 H, m), 2.62 (1 H, dd, J = 3.2, 7.1 Hz), 1.34–1.03 (6 H, m).

***trans*-1-Cyclohexyl-2-phenyloxirane (17b).** (*E*)-2-Cyclohexylstyrene (4.9 mmol) was dissolved in CH_2Cl_2 (15 mL). MCPBA (Aldrich, 0.94 mmol) in CH_2Cl_2 (5 mL) was added dropwise via a cannula. The solution was stirred for 20 h, and the resulting cloudy solution was washed with 10% NaOH (1 × 50 mL) and dried ($MgSO_4$), and solvent was removed in vacuo. Flash chromatography (Kieselgel 60) provided **17b**: 0.92 g (92%): oil, analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.75; MS base peak = 107.0522; exact mass calcd for $C_{14}H_{18}O_1$ 202.1358, found 202.1358, error = 0.2 ppm; IR (neat, cm^{-1}) C–O, 1270; 270-MHz NMR ($CDCl_3$) δ 7.39–7.21 (5 H, m), 3.67 (1 H, d, J = 2.1 Hz), 2.76 (1 H, dd, J = 2.2, 6.8 Hz), 2.00–1.90 (1 H, m), 1.83–1.62 (4 H, m), 1.42–1.10 (6 H, m).

General Procedure for the Preparation of β-Hydroxy-*P*-methyldibenzophospholium Salts. 5*H*-Dibenzophosphole[20] (0.35 M in THF, 0.43 mmol) was measured into a dry round-bottom flask (N_2 atmosphere throughout) containing THF (3 mL) and cooled to −78 °C. *n*-BuLi (0.43 mmol) was added by syringe, and the resulting orange solution was warmed to room temperature. The epoxide **16** or **17** (0.43 mmol) in THF (0.5 mL) was added via a syringe resulting in a fading of the red color upon complete addition of the epoxide. The resulting light green solution was quenched with AcOH (0.43 mmol) to give the intermediate phosphine. This phosphine was not isolated but was directly alkylated in the same pot with MeOTf (0.64 mmol, 1.5 equiv) or MeI (2.16 mmol, 3 equiv). The solution was stirred for 4 h. Solvent removal resulted in an amorphous solid which was crystallized in two of the three cases to provide pure phosphonium salt.

***P*-[*threo*-(4-Cyclohexyl-4-hydroxybut-1-en-3-yl)]-*P*-methyldibenzophospholium trifluoromethanesulfonate (18a)**: 30%; solid; mp 181–182 °C (crystallized from hexane/EtOAc/CH_3CN); 500-MHz NMR (C_2D_6CO) δ 8.80 (1 H, t, J = 8.5 Hz), 8.62–8.52 (3 H, m), 8.22 (1 H, t, J = 7.3 Hz), 8.16 (1 H, t, J = 7.3 Hz), 8.03–7.94 (2 H, m), 6.56 (1 H, d, J = 5.4 Hz), 5.91 (1 H, ddd, J = 10.1, 16.3, 20.7 Hz), 5.64 (1 H, dd, J = 5.8, 16.9 Hz), 5.50 (1 H, dd, J = 4.5, 10.2 Hz), 4.73 (1 H, td, J = 10.2, 24.4 Hz), 4.36 (1 H, br d, J = 6.5 Hz), 2.94 (3 H, d, J = 15.4 Hz), 2.20–2.00 (1 H, m), 1.80–1.55 (4 H, m), 1.55–1.30 (6 H, m); ^{31}P NMR (C_2D_6CO) δ 35.9 ppm. Anal. Calcd for $C_{24}H_{28}O_4F_3PS$: C, 57.58; H, 5.65. Found: C, 57.54; H, 5.77.

***P*-[*erythro*-(4-Cyclohexyl-4-hydroxybut-1-en-3-yl)]-*P*-methyldibenzophospholium trifluoromethanesulfonate (19a)**: 56%; solid; mp 148–150 °C (crystallized from EtOAc/CH_3CN); 270-MHz NMR ($CDCl_3$) δ 8.42 (1 H, t, J = 9.0 Hz), 8.28 (1 H, t, J = 9.3 Hz), 7.91–7.83 (2 H, m), 7.79–7.71 (2 H, m), 7.67–7.51 (2 H, m), 5.55 (1 H, dddd, J = 5.1, 10.1, 15.5, 16.9 Hz), 5.02 (1 H, dd, J = 6.2, 10.1 Hz), 4.80 (1 H, dd, J = 6.5, 17.1 Hz), 4.08 (1 H, td, J = 4.0, 9.3 Hz), 3.94 (1 H, ddd, J = 3.3, 10.1, 13.3 Hz), 2.53 (3 H, d, J = 16.1 Hz), 2.12 (1 H, br d, J = 10.3 Hz), 1.80–0.90 (11 H, m); ^{31}P NMR ($CDCl_3$) δ 36.7 ppm. Anal. Calcd for $C_{24}H_{28}O_4F_3PS$: C, 57.58; H, 5.65. Found: C, 57.62; H, 5.66.

***P*-[*erythro*-(2-Cyclohexyl-2-hydroxy-1-phenylethyl)]-*P*-methyldibenzophospholium trifluoromethanesulfonate (19b)**: 21%; the precipitated solid could not be crystallized but was sufficiently pure for deprotonation experiments; 270-MHz NMR (C_2D_6CO) δ 8.79 (1 H, t, J = 8.4 Hz), 8.49 (1 H, t, J = 8.8 Hz), 7.97–7.91 (2 H, m), 7.81–7.73 (2 H, m), 7.69–7.64 (2 H, m), 7.10–6.92 (5 H, m), 6.31 (1H, d, J = 5.6 Hz), 5.31 (1 H, dd, J = 2.9, 16.6 Hz), 4.49 (1 H, dtd, J = 2.9, 5.6, 13.6 Hz), 0.95 (3 H, d, J = 12.9 Hz), 2.20–2.10 (1 H, m), 1.70–0.70 (10 H, m); ^{31}P NMR (C_2D_6CO) δ 39.2 ppm.

Low-Temperature Observation of Oxaphosphetanes by Deprotonation of β-Hydroxy Phosphonium Salts. General Procedure. The β-hydroxy phosphonium salt (0.038 mmol) was dissolved in THF-d_8 in a 5-mm NMR tube (some warming was required). The tube was flushed with N_2 and cooled to −78 °C, and NaHMDS (0.78M in toluene-d_8, 0.038 mmol) was added dropwise while shaking the tube in the cooling bath, 30-s total addition time. The tube was quickly seated in a precooled Bruker 500-MHz NMR spectrometer. Observation of the ^{31}P region initially showed >85% oxaphosphetane for both allylic salts **18a** and **19a**, together with the phosphine oxide (δ 40.0 ppm). Approximately 50% oxaphosphetane was observed for the erythro benzylic salt **19b**. Careful monitoring of the ^{31}P region upon gradual warming of the NMR probe allowed for determination of half-lives. Decomposition of oxaphosphetane **14a** was detected at −45 °C, $t(1/2)$ = 70 min. Decomposition of oxaphosphetane **15a** was detected at −50 °C, $t(1/2)$ = 60 min. Decomposition of oxaphosphetane **15b** was detected at −20 °C. Flash chromatography (Kieselgel 60, plug) provided the olefins. Salt **18a** yielded 0.0040 g (80%) of 1-cyclohexyl-1,3-butadiene (some product was lost during solvent removal). GLPC analysis (Becker 409) showed a *Z*:*E* ratio of 2:98. Salt **19a** yielded 0.0038 g (76%) of 1-cyclohexyl-1,3-butadiene (some product was lost during solvent removal). GLPC analysis showed a *Z*:*E* ratio of 96:4. Salt **19b** yielded 0.0059 g (85%) of 2-cyclohexylstyrene. GLPC analysis showed a *Z*:*E* ratio of 99:1.

Low-Temperature Observation of Oxaphosphetanes by Wittig Condensation. The dry dibenzophospholium salt (0.34 mmol), prepared[13a] from 5*H*-dibenzophosphole[20] was dissolved in THF-d_8 (0.9mL), N_2 atmosphere throughout. The base (0.34 mmol) was added via a syringe, and the mixture was stirred for 10 min. The deep purple solution was added via a cannula into a dry, N_2-flushed NMR tube and frozen at −196 °C. Cyclohexanecarboxaldehyde (0.34 mmol) in THF-d_8 (0.1 mL) was added via a syringe to the frozen ylide layer. The solution was warmed to −78 °C, and the layers were mixed. The sample was quickly seated into a precooled Bruker 500-MHz spectrometer. Observation of the ^{31}P region for ylide **10** showed ca. 75% oxaphosphetane **12** (δ -71.0 ppm), 10% ylide **10** (δ -12.5 ppm), and 15% phosphine oxide (δ 28.5 ppm). Decomposition of oxaphosphetane **12** was detected at −50 °C. Flash chromatography (Kieselgel 60, plug) provided 0.028 g (58%) of 1-cyclohexyl-1,3-butadiene (some product was lost during solvent removal). NMR analysis showed a *Z*:*E* ratio of 5:95.

Condensation of ylide **11a** with cyclohexanecarboxaldehyde provided 0.038 g (82%) of 1-cyclohexyl-1,3-butadiene (some product was lost during solvent removal). GLPC analysis showed a *Z*:*E* ratio of 1:99. Condensation of ylide **11b** with cyclohexanecarboxaldehyde provided 0.054 g (85%) of 2-cyclohexylstyrene. GLPC analysis showed a *Z*:*E* ratio of 3:97.

Epoxide Opening by Phosphines. General Procedure. (1) Ethyl *trans*-Phenylglycidate + Ph_3P, Table I. Ethyl *trans*-phenylglycidate (0.29 mmol), triphenylphosphine (0.29 mmol), and *p*-chlorobenzaldehyde (Aldrich, 0.87 mmol) were dissolved in EtOH (3 mL). The solution was stirred at room temperature under N_2. Aliquots were taken at intervals, the solvent was removed in vacuo, and olefin ratios were determined from integration of the vinyl region on a Bruker 270-MHz NMR spectrometer ($CDCl_3$ as reference solvent). Peaks used to determine ratios are as follows: ethyl(*E*)-*p*-chlorocinnamate δ 6.37 (1 H, d, J = 16.5 Hz); ethyl (*Z*)-*p*-chlorocinnamate δ 6.85 (1 H, d, J = 13.0 Hz), 5.94 (1 H, d, J = 13.0 Hz); ethyl (*E*)-cinnamate δ 6.41 (1 H, d, J = 16.6 Hz); ethyl (*Z*)-cinnamate δ 6.93 (1 H, d, J = 13.0 Hz), 5.92 (1 H, d, J = 13.0 Hz).

(2) Ethyl *trans*-Phenylglycidate + $MePh_2P$, Table I. Ethyl *trans*-phenylglycidate (0.34 mmol), methyldiphenylphosphine (0.34 mmol), and *p*-chlorobenzaldehyde (Aldrich, 1.02 mmol) were dissolved in EtOH (10 mL) in a N_2 atmosphere. The solution was stirred at room temperature. Aliquots were taken at intervals, the solvent was removed in vacuo, and olefin ratios were determined as above.

(3) Ethyl *cis*-Phenylglycidate + Ph_3P. Ethyl *cis*-phenylglycidate (0.36 mmol), triphenylphosphine (0.36 mmol), and *p*-chlorobenzaldehyde (Aldrich, 1.09 mmol) were dissolved in EtOH (4 mL). The solution was stirred at room temperature under N_2. Aliquots were taken at intervals, the solvent was removed in vacuo, and olefin ratios were determined as above.

(4) Ethyl *trans*-3-Cyclohexyloxirane-2-carboxylate. Ethyl *trans*-3-cyclohexyloxirane-2-carboxylate (0.026 mmol), methyldiphenylphosphine (0.026 mmol), and *p*-chlorobenzaldehyde (Aldrich, 0.052 mmol) were dissolved in THF (1.3 mmol) in a 10-mm tube. The tube was degassed over three freeze–thaw cycles and sealed. After 40 days the tube was opened, and solvent was removed in vacuo. No olefin was seen by NMR, but olefin ratios were obtained by GLPC vs authentic samples. Retention times (Becker 409 GLPC, 150 °C): ethyl (*Z*)-2-cyclohexylacrylate, 1.77 min; ethyl (*E*)-2-cyclohexylacrylate, 2.34 min; ethyl (*Z*)-*p*-(chloroethyl)cinnamate, 4.34 min; ethyl (*E*)-*p*-(chloroethyl)cinnamate, 6.71 min.

Isomerization Control Experiments. (1) Ethyl (*Z*)-Cinnamate. A 5-mm NMR tube was charged with ethyl (*Z*)-cinnamate (0.067 mmol), triphenylphosphine (0.067 mmol), and EtOH-d_6 (0.35 mL). The tube was sealed under N_2 and *Z*:*E* olefin ratios were determined periodically as described for the epoxide openings. No olefin isomerization was

(20) Braye, E. H. *Tetrahedron* **1971**, *27*, 5523.

detected at 25 °C, but significant isomerization occurred at 65 °C (Table I, entries 3 and 5).

Ethyl (*Z*)-cinnamate (0.20 mmol) and methyldiphenylphosphine (0.20 mmol) were dissolved in EtOH (6 mL). The solution was stirred under N_2 at room temperature. Aliquots were taken periodically, the solvent was removed in vacuo, and olefin ratios were determined as previously described for the epoxide openings. Significant isomerization occurred. (Table I, entry 7).

(2) Ethyl (*Z*)-2-Cyclohexylacrylate. A 5-mm NMR tube was charged with ethyl (*Z*)-2-cyclohexylacrylate (0.087 mmol), methyldiphenylphosphine (0.087), and EtOH-d_6 (0.5 mL). The tube was sealed under N_2 and olefin ratios were determined periodically from integration of the vinyl region on a Bruker 270-MHz spectrometer ($CDCl_3$ as reference solvent). Peaks used to determine ratios are as follows: ethyl (*E*)-2-cyclohexylacrylate δ 6.88 (1 H, dd, J = 6.86, 15.8 Hz), 5.72 (1 H, dd, J = 1.5, 15.8 Hz); ethyl (*Z*)-2-cyclohexylacrylate δ 6.00 (1 H, dd, J = 10.1, 11.4 Hz), 5.62 (1 H, d, J = 11.4 Hz). After 168 h, integration showed a *Z*:*E* ratio of 7:93.

Preparation of Ethyl (Diphenylphosphino)acetate-d_2. Ethyl (diphenylphosphino)acetate[15] (15.4 mmol) was dissolved in dry THF (100 mL). D_2O (1.37 mol, degassed through four freeze–thaw cycles) was added via a cannula followed by syringe addition of DBU (3.3 mmol). The solution was stirred at room temperature for 9 h. Ether (50 mL) and hexane (50 mL) were added. The organic layer was separated and dried ($MgSO_4$), and the solvent was removed in vacuo. Purification via flash chromatography (Kieselgel 60) provided ethyl (diphenylphosphino)acetate-d_2: oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.68; MS base peak = 201.0566; exact mass calcd for $C_{16}H_{15}O_2D_2P$ 274.1088, found 274.1080, error = 2.9 ppm; IR (neat, cm^{-1}) C=O, 1735; 270-MHz NMR ($CDCl_3$) δ 7.55–7.24 (10 H, m); 4.02 (2 H, q, J = 7.1 Hz), 1.08 (3 H, t, J = 7.1 Hz).

Preparation of *P*-(Carbethoxymethyl)dibenzophosphole. Na_2CO_3 (4.0 mmol) and ethyl bromoacetate (4.0mmol) were added to a 0.4 M solution of 5*H*-dibenzophosphole[20] (4.0 mmol), nitrogen atmosphere throughout. The solution was stirred for 24 h, and the solvent was removed in vacuo. Flash chromatography of the crude mixture (Kieselgel 60, hexane/ether/CH_2Cl_2 10:1:1) provided 0.16 g (14%) of *P*-(carbethoxymethyl)dibenzophosphole: oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.67; MS base peak = 183.0343; exact mass calcd for $C_{16}H_{15}O_2P$ 270.0806, found 270.0801, error = 1.9 ppm; IR (neat, cm^{-1}) C=O, 1735; 270-MHz NMR ($CDCl_3$) δ 7.88 (2 H, d, J = 7.7 Hz), 7.76 (2 H, dd, J = 5.5, 6.9 Hz), 7.45 (2 H, t, J = 7.4 Hz), 7.34 (2 H, dt, J = 2.8, 7.4 Hz), 3.82 (2 H, q, J = 7.1 Hz), 2.80 (2 H, d, J = 2.6 Hz), 0.98 (3 H, t, J = 7.1 Hz).

General Procedure for the Preparation of Ester-Substituted β-Hydroxy Phosphonium Salts. Diisopropylamine (3.67 mmol) was measured into a dry round-bottom flask (N_2 atmosphere throughout *all* operations) containing THF (25 mL). *n*-BuLi (3.81 mmol) was added by syringe at 0 °C, and the solution was stirred for 15 min. After cooling of the solution to −78 °C, ethyl (diphenylphosphino)acetate[15] (3.67 mmol) in THF (5 mL) was added dropwise via a cannula. The resulting lemon-yellow solution of anion **20** was stirred 15 min after which the aldehyde (3.89 mmol) was added dropwise via a syringe. After 15 min, the solution was quenched with 10% HCl (10 mL) and diluted with ether (25 mL). The organic layer was removed via a syringe and dried ($MgSO_4$), and the solvent was removed at low pressure. The intermediate phosphines were purified by flash chromatography (20 g Kieselgel 60, hexane/ether/CH_2Cl_2 8:1:1, R_f = 0.10–0.30, 40-mL fractions) and a total of three fractions were collected. Chromatography fractions 6–8 were combined and methylated with a 5–10-fold excess of MeOTf. A white, crystalline solid precipitated in all cases except from $PhCH_2CH_2CHO$. Crystallization yielded the pure phosphonium salt **22** (Tables II and III). The same procedure starting from $Ph_2PCD_2CO_2C_2H_5$ gave the deuterated analogues D_1-**22**, >98% D_1 by NMR analysis.

***P*-[*erythro*-(Carbethoxy-1-deuterio-2-hydroxy-2-phenylethyl)]-*P*,*P*-diphenyl-*P*-methylphosphonium trifluoromethanesulfonate (D_1-22a)**: 0.18 g; 8%, solid; mp 153–154 °C (crystallized from EtOAc/CH_3CN); 270-MHz NMR (C_2D_6CO) δ 8.20–8.05 (4 H, m), 7.93–7.83 (2 H, m), 7.82–7.71 (4 H, m), 7.40–7.26 (5 H, m), 5.75 (1 H, br s), 5.33 (1 H, d, J = 5.1 Hz), 3.90 (2 H, q, J = 7.1 Hz), 3.00 (3 H, d, J = 14.4 Hz), 0.87 (3 H, t, J = 7.1 Hz); ^{31}P NMR (C_2D_6CO) δ 23.1 ppm. Anal. Calcd for $C_{25}H_{25}O_6DF_3PS$: C, 55.24; H, 4.65; found: C, 55.35; H, 4.90.

***P*-[*erythro*-(1-Carbethoxy-2-hydroxy-2-phenylethyl)]-*P*,*P*-diphenyl-*P*-methylphosphonium trifluoromethanesulfonate (22a)**: 0.15 g; 6%; solid; mp 153–154 °C (crystallized from EtOAc/CH_3CN); 270-MHz NMR (C_2D_6CO) δ 8.19–8.05 (4 H, m), 7.92–7.83 (2 H, m), 7.81–7.70 (4 H, m), 7.38–7.27 (5 H, m), 5.68 (1 H, br s), 5.33 (1 H, t, J = 5.0 Hz), 5.10 (1 H, dd, J = 5.0, 13.4 Hz), 3.89 (2 H, q, J = 7.1 Hz), 2.99 (3 H, d, J = 14.4 Hz), 0.86 (3 H, t, J = 7.1 Hz); ^{31}P NMR (C_2D_6CO) δ 23.1 ppm.

***P*-[*erythro*-(Carbethoxy-1-deuterio-2-hydroxy-4-phenylbut-1-yl)]-*P*,*P*-diphenyl-*P*-methylphosphonium trifluoromethanesulfonate (D_1-22b)**: 0.25 g; 12%; oil; ca. 85% pure by NMR; formula = $C_{27}H_{29}O_6DF_3PS$; 270-MHz NMR ($CDCl_3$) δ 7.85–7.42 (10 H, m), 7.20–7.00 (5 H, m), 4.06 (2 H, q, J = 7.0 Hz), 3.89 (1 H, td, J = 7.7, 15.3 Hz), 2.80–2.50 (2 H, m), 2.77 (3 H, d, J = 14.1 Hz), 2.03–1.89 (2 H, m), 1.03 (3 H, t, J = 7.0 Hz); 1.00 (1 H, br s); ^{31}P NMR ($CDCl_3$) δ 25.2 ppm.

***P*-[*erythro*-(1-Carbethoxy-2-cyclohexyl-1-deuterio-2-hydroxyethyl)]-*P*,*P*-diphenyl-*P*-methylphosphonium trifluoromethanesulfonate (D_1-22c)**: 0.16 g; 8%, solid; mp 162–164 °C (crystallized from EtOAc/CH_3CN); 500-MHz NMR (C_2D_6CO) δ 8.16–8.09 (4 H, m), 7.92–7.84 (2 H, m), 7.77–7.71 (4 H, m), 5.00 (1 H, br s), 4.19 (1 H, qd, J = 7.1, 13.2 Hz), 4.15 (1 H, qd, J = 7.1, 13.2 Hz), 3.72 (1 H, dd, J = 8.8, 11.2 Hz), 3.08 (3 H, d, J = 14.1 Hz), 2.03–1.55 (5 H, m), 1.25–0.71 (6 H, m), 1.12 (3 H, t, J = 7.1 Hz); ^{31}P NMR (C_2D_6CO) δ 30.0.

***P*-[*erythro*-(1-Carbethoxy-2-cyclohexyl-2-hydroxyethyl)]-*P*,*P*-diphenyl-*P*-methylphosphonium trifluoromethanesulfonate (22c)**: 0.20 g; 10%; solid; mp 162–164 °C (crystallized from EtOAc/CH_3CN); 500-MHZ NMR (C_2D_6CO) δ 8.18–8.10 (4 H, m), 7.90–7.82 (2 H, m), 7.77–7.70 (4 H, m), 5.00 (1 H, br s), 4.32 (1 H, dd, J = 1.9, 13.2 Hz), 4.19 (1, H, qd, J = 7.1, 13.2 Hz), 4.15 (1 H, qd, J = 7.0, 13.2 Hz), 3.72 (1 H, ddd, J = 1.9, 8.8, 11.2 Hz), 3.07 (3 H, d, J = 14.1 Hz), 2.04–1.55 (4 H, m), 1.25–0.70 (6 H, m), 1.12 (3 H, t, J = 7.0 Hz); ^{31}P NMR (C_2D_6CO) δ 30.3 ppm. Anal. Calcd for $C_{25}H_{32}O_6F_3PS$: C, 54.73; H, 5.89. Found: C, 54.63; H, 5.94.

***P*-[*erythro*-(1-Carbethoxy-1-deuterio-3,3-dimethyl-2-hydroxy-4-phenylbut-1-yl)]-*P*,*P*-diphenyl-*P*-methylphosphonium trifluoromethanesulfonate (D_1-22d)**: 0.24 g; 12%, solid; mp 167–168 °C (crystallized from EtOAc/CH_3CN); 270-MHz NMR (C_2D_6CO) δ 8.20–7.92 (4 H, m), 7.88–7.60 (6 H, m), 7.22–7.15 (3 H, m), 7.09–7.02 (2 H, m), 5.15 (1 H, br s), 4.15 (2 H, q, J = 7.1 Hz), 3.94 (1 H, d, J = 16.6 Hz), 3.10 (3 H, d, J = 14.2 Hz), 2.77 (1 H, d, J = 12.9 Hz), 2.41 (1 H, d, J = 12.9 Hz), 1.09 (3 H, t, J = 7.1 Hz), 0.86 (3 H, s), 0.69 (3 H, s); ^{31}P NMR (C_2D_6CO) δ 31.9 ppm. Anal. Calcd for $C_{29}H_{33}O_6DF_3PS$: C, 58.08; H, 5.56. Found: C, 58.31; H, 5.60.

***P*-[*erythro*-(1-Carbethoxy-2-cyclohexyl-2-hydroxyethyl)]-*P*-methyldibenzophospholium trifluoromethanesulfonate (19c)** was prepared in low yield from *P*-(carbethoxymethyl)dibenzophosphole according to the general procedure: amorphous solid; 270-MHz NMR (C_2D_6CO) δ 8.50–8.20 (4 H, m), 7.94 (2 H, t, J = 10.1 Hz), 7.79–7.62 (2 H, m),4.86 (1 H, dd, J = 3.1, 14.7 Hz), 4.07 (2 H, q, J = 7.1 Hz), 3.92 (1 H, dt, J = 3.1, 9.3 Hz), 3.36 (1 H, br s), 2.69 (3 H, d, J = 15.2 Hz), 2.10–1.50 (5 H, m), 1.20–0.80 (6 H, m), 0.97 (3 H, t, J = 7.1 Hz); ^{31}P NMR (C_2D_6CO) δ 33.9 ppm.

Crossover Experiments with β-Hydroxy Phosphonium Salts 22. The salt (0.035 mmol) was suspended in THF (2 mL) or EtOH (2 mL) at room temperature under N_2. The base (0.033 mmol) was added via a syringe to the stirred mixture, and 30 s later, 2 equiv of crossover aldehyde (*p*-chlorobenzaldehyde) was added. The solution was stirred for 8 h and then quenched with AcOH (0.070 mmol). Solvent was removed in vacuo, and *p*-dinitrobenzene (Aldrich, 0.030–0.070 mmol) was added to the residue as an internal standard. Acetone-d_6 was added, and olefin ratios were determined by integration of the vinyl region peaks. Yields were determined by integral comparison of the standard and the product olefins (Tables II and III).

Ethyl (*Z*)-2-deuterio-5-phenyl-2-pentenoate (D_1-30a): oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2, 4:1:1, R_f = 0.74; MS base peak = 91.0522; exact mass calcd for $C_{16}H_{15}O_2D$ 205.1213, found 205.1214, error = 0.6 ppm; IR (near, cm^{-1}) C=O, 1715; 270-MHz NMR ($CDCl_3$) δ 7.31–7.12 (5 H, m), 6.21 (1 H, t, J = 7.3 Hz), 4.14 (2 H, q, J = 7.2 Hz), 2.97 (2 H, q, J = 7.5 Hz), 2.75 (2 H, t, J = 7.3 Hz), 1.26 (3 H, t, J = 7.1 Hz).

Ethyl (*Z*)-3-cyclohexyl-2-propenoate (30b): oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.60; MS base peak = 131.0498; exact mass calcd for $C_{11}H_{18}O_2$ 182.1306, found 182.1312, error = 3 ppm; IR (neat, cm^{-1}) C=O, 1705; 270-MHz NMR ($CDCl_3$) δ 6.00 (1 H, dd, J = 10.1, 11.4 Hz), 5.62 (1 H, d, J = 11.4 Hz), 4.13 (2 H, q, J = 7.1 Hz), 3.26 (1 H, br q, J = 10.7 Hz), 1.80–1.00 (10 H, m), 1.26 (3 H, t, J = 7.1 Hz).

Ethyl (*Z*)-4,4-dimethyl-5-phenyl-2-pentenoate (30c): oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.82; MS base peak = 91.0547; exact mass calcd for $C_{15}H_{20}O_2$ 232.1463, found 232.1468, error = 2.2 ppm; IR (neat, cm^{-1}) C=O, 1720; 270-MHz NMR ($CDCl_3$) δ 7.40–7.20 (5 H, m), 5.91 (1 H, d, J = 13.1 Hz), 5.71 (1 H, d, J = 13.1 Hz), 4.16 (2 H, q, J = 7.1 Hz), 2.86 (2 H, s), 1.29 (3 H, t, J = 7.1 Hz), 1.16 (6 H, s).

Ethyl (*Z*)-2-deuterio-4,4-dimethyl-5-phenyl-2-pentenoate (D_1-30c): oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.82; MS base peak = 91.0457; exact mass calcd for $C_{15}H_{19}O_2D$ 233.1526, found 233.1526, error = 0.1 ppm; IR (neat, cm^{-1}) C=O, 1720;

270-MHz NMR ($CDCl_3$) δ 7.40-7.20 (5 H, m), 5.91 (1 H, s), 4.16 (2 H, q, J = 7.1 Hz), 2.86 (2 H, s), 1.29 (3 H, t, J = 7.1 Hz), 1.16 (6 H, s).

Ethyl (*E*)-5-phenyl-2-pentenoate (31b): oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.69; MS base peak = 91.0525; exact mass calcd for $C_{13}H_{16}O_2$ 204.115, found 204.1142, error = 3.9 ppm; IR (neat, cm^{-1}) C=O, 1720; 270-MHz NMR ($CDCl_3$) δ 7.28-7.08 (5 H, m), 6.93 (1 H, td, J = 7.1, 14.1 Hz), 5.77 (1 H, td, J = 1.3, 14.1 Hz); 4.11 (2 H, q, J = 7.1 Hz); 2.70 (2 H, t, J = 9.0 Hz), 2.44 (2 H, q, J = 9.0 Hz), 1.21 (3 H, t, J = 7.1 Hz).

Ethyl (*E*)-4,4-dimethyl-5-phenyl-2-pentenoate (31d): oil; analytical TLC (silica gel F254), hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.78; MS base peak = 91.0538; exact mass calcd for $C_{15}H_{20}O_2$ 232.1463, found 232.146, error = 1.3 ppm; IR (neat, cm^{-1}) C=O, 1720; 270-MHz NMR ($CDCl_3$) δ 7.30-7.19 (3 H, m), 7.10-7.03 (2 H, m); 7.01 (1 H, d, J = 15.9 Hz), 5.61 (1 H, d, J = 12.9 Hz), 4.17 (2 H, q, J = 7.1 Hz), 2.63 (2 H, s), 1.27 (3 H, t, J = 7.1 Hz), 1.04 (6 H, s).

Wittig Reactions of Phosphoniumn Ylides 1a and 1c. Standard Conditions. The dry phosphonium salt (0.19 mmol) was dissolved in THF or EtOH (4 mL). The base (0.18 mmol) was added via a syringe, and the mixture was allowed to stir for 15 min. The aldehyde (0.18 mmol) was added neat and stirred for 4 h. Ether (20 mL) and 10% HCl (20 mL) were added, the organic layer was separated and dried ($MgSO_4$), and solvent was removed in vacuo. Purification via flash chromatography (Kieselgel 60) provided the olefins. Olefin product ratios were determined by integration of the vinyl region (enoates) or GLPC analysis (dienes or substituted styrenes) (Table IV).

(*E*)-1-Phenyl-2-cyclohexylethene: oil; analytical TLC (silica gel F254) hexane/ether/CH_2Cl_2 4:1:1, R_f = 0.81; MS base peak = 104.0613; exact mass calcd for $C_{14}H_{18}$ 186.1409, found 186.1413, error = 2.4 ppm; 270-MHz NMR ($CDCl_3$) δ 7.40-7.25 (4 H, m), 7.22-7.13 (1 H, m), 6.35 (1 H, d, J = 16.08 Hz), 6.18 (1 H, dd, J = 6.78, 15.98 Hz), 2.20-2.08 (1 H, m), 1.88-1.63 (4 H, m), 1.40-1.13 (6 H, m).

Acknowledgment. This work was supported by the National Science Foundation (Grant No. CHE-8603163).

Registry No. 1a, 1099-45-2; **1c**, 110223-71-7; **10**, 121192-38-9; **11a**, 121192-39-0; **11b**, 121192-40-3; **12**, 121192-37-8; **14a**, 121192-35-6; **15a**, 121250-46-2; **15b**, 121192-36-7; **16a**, 77131-98-7; **17a**, 83877-82-1; **17b**, 116544-25-3; **18a**, 121192-30-1; **19a**, 121192-32-3; **19b**, 121192-34-5; **19c**, 121192-54-9; **20** (anion), 72884-89-0; **22a**, 121192-47-0; D_1-**22a**, 121192-45-8; **22b**, 121192-56-1; D_1-**22b**, 121192-49-2; **22c**, 110223-70-6; D_1-**22c**, 121192-50-5; **22d**, 121192-58-3; D_1-**22d**, 121192-52-7; D_1-**30b**, 121192-59-4; **30c**, 18521-02-3; **30d**, 121192-60-7; D_1-**30d**, 121192-61-8; **31b**, 55282-95-6; **31d**, 121192-62-9; **33**, 121192-41-4; $C_6H_{11}CHO$, 2043-61-0; Ph_3P, 603-35-0; $MePh_2P$, 1486-28-8; PhCHO, 100-52-7; $PhCH_2CH_2CHO$, 104-53-0; $PhCH_2CMe_2CHO$, 1009-62-7; *trans*-1-cyclohexyl-1,3-butadiene, 25203-83-2; *cis*-1-cyclohexyl-1,3-butadiene, 25203-84-3; 5*H*-dibenzophosphole, 244-87-1; (*Z*)-2-cyclohexylstyrene, 40132-69-2; ethyl *trans*-phenylglycidate, 2272-55-1; ethyl (*Z*)-cinnamate, 4610-69-9; ethyl *cis*-phenylglycidate, 2272-49-3; *p*-chlorobenzaldehyde, 104-88-1; ethyl (*E*)-*p*-chlorocinnamate, 24393-52-0; ethyl (*Z*)-*p*-chlorocinnamate, 63757-30-2; ethyl (*E*)-cinnamate, 4192-77-2; ethyl (*E*)-2-cyclohexylacrylate, 17343-88-3; ethyl (*Z*)-2-cyclohexylacrylate, 18521-02-3; ethyl (diphenylphosphino)acetate-d_2, 121192-42-5; ethyl (diphenylphosphonium)acetate, 55552-24-4; *p*-(carbethoxymethyl)dibenzophosphole, 121192-43-6; ethyl bromoacetate, 105-36-2; (*E*)-2-cyclohexylstyrene, 18869-27-7.

Kinetic Facial Selectivity in Nucleophilic Displacements at Tetracoordinate Phosphorus: Kinetics and Stereochemistry in the Reaction of Sodium Ethoxide with *O,S*-Dimethyl Phenylphosphonothioate

Kenneth E. DeBruin,* Chen-lan W. Tang, David M. Johnson, and Ronnie L. Wilde

Contribution from the Department of Chemistry, Colorado State University, Fort Collins, Colorado 80523. *Received December 15, 1988*

Abstract: The reaction of ethoxide ion with *O,S*-dimethyl phenylphosphonothioate (**1a**) proceeds with competitive displacements of the methylthio and methoxy ligands. Each displacement occurs with complete inversion of configuration. The two products, ethyl methyl phenylphosphonate (**2ab**) and *O*-ethyl *S*-methyl phenylphosphonothioate (**1b**), respectively, react further with ethoxide ion to form diethyl phenylphosphonate (**2bb**). Displacement of the ethoxy ligand on **2ab** or **1b**, which leads to racemization, competes with formation of **2bb** in both of these reactions. The competitions favor displacement of methylthiolate over methoxide ion from **1a** (3/1), methoxide over ethoxide ion from **2ab** (6/1), and methylthiolate over ethoxide ion from **1b** (18/1). In addition, racemization of **1b** is 22 times faster than racemization of **2ab**, and displacement of methylthiolate ion from **1b** is 65 times faster than displacement of methoxide ion from **2ab**. The results rule out the possibility that methylthiolate ion is displaced in phosphonothioates with inversion stereochemistry simply because the retention pathway, seen in other related systems, is energetically blocked by the need for a high-energy isomerization process. The small preference for displacement of methylthiolate ion over methoxide ion from **1a** is identified to be the result of a methylthio ligand having a larger relative intrinsic kinetic affinity to occupy either an axial position or an equatorial position in a pentacoordinate intermediate or transition state, and these affinities partially cancel.

There has been and continues to be considerable interest in the mechanisms for nucleophilic displacement of a leaving group from phosphorus in tetracoordinate organophosphorus compounds. For associative processes with strong nucleophiles, it is generally assumed that the nucleophile approaches a trigonal face of the tetrahedral phosphorus center, forming a pentacoordinate intermediate (of idealized trigonal-bipyramidal geometry) with the nucleophile in an axial position (axial attack).[1] In systems with more than one potential leaving group, the particular face attacked (facial selectivity) would determine the positioning of the leaving groups in the resulting intermediate. If this intermediate then leads to a displacement, its structure may have an influence on determining which leaving group is displaced and will determine the resulting stereochemistry at phosphorus.[2] Therefore, we are

(1) Westheimer, F. *Acc. Chem. Res.* **1968**, *1*, 70.

(2) Mislow, K. *Acc. Chem. Res.* **1970**, *3*, 321.

(3) (a) De'ath, N. J.; Ellis, K.; Smith, D. J. H.; Trippett, S. *J. Chem. Soc., Chem. Commun.* **1971**, 714. (b) DeBruin, K. E.; Johnson, D. M. *J. Am. Chem. Soc.* **1973**, *95*, 4675.

0002-7863/89/1511-5871$01.50/0