a colorless, triclinic prismatic crystal, $C_{24}H_{24}Br_2$; space group $P\bar{1}$; a = 8.728 (2), b = 8.958 (2), and c = 7.155 (1) Å, α = 101.27 (2), β = 104.81 (1), and γ = 70.53 (1)°; Z = 1; M = 472.28; V = 506.2 (2) Å^3; ρ = 1.55 g cm^{-3}. Preliminary examination and intensity data were measured by using Mo Kα radiation (λ = 0.71073 Å) on a Nicolet P3F diffractometer ($2\theta_{max}$ = 55°), yielding 2346 unique reflections of which 1801 were used in the refinement. The structure was solved by direct methods (SHELXS-86). The final R value was 0.036.

Acknowledgment. We thank Dr. Donald R. Ward for the X-ray structure of 4 and the National Institutes of Health (GM-15997) and National Science Foundation (CHE 87-12118) for financial support.

Supplementary Material Available: Tables of atomic positional parameters, thermal parameters, bond lengths, and bond angles (7 pages). Ordering information is given on any current masthead page.

Stereoselective *E* and *Z* Olefin Formation by Wittig Olefination of Aldehydes with Allylic Phosphorus Ylides. Stereochemistry

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Sterically crowded allylic tributylphosphorus ylides such as β,γ-disubstituted allylic ylides react with various aldehydes to afford *E* olefins with high stereoselectivity (*E* > 92%). As the steric demand of the ylides was decreased, bulky aldehydes were required to achieve high *E* selectivity. On the other hand, predominant or exclusive formation of *Z* olefins was achieved by using allylic triphenylphosphorus ylides and tertiary aldehydes like pivaldehyde, while the combination of allylic triphenylphosphorus ylides and such large secondary aldehydes as cyclohexanecarboxaldehyde led to *E* olefin formation under the lithium salt free conditions. The distinct lithium salt effect was observed in the reaction effected with triphenylphosphorus ylides. The origin of the observed *E* or *Z* selectivity can be reasonably explained according to Vedejs' rationale on the Wittig reaction stereochemistry.

Introduction

The stereochemistry of the Wittig reaction for olefination of aldehydes with phosphorus ylides is strongly dependent on the type of ylide and exact reaction conditions.[1] Nonstabilized triphenylphosphorus ylides generally react with aldehydes to afford *Z* alkenes selectively while the corresponding trialkylphosphorus ylides give high *E* selectivity, especially under lithium salt free conditions. Stabilized ylides give predominantly *E* alkenes, regardless of the type of ligands on phosphorus. As to semistabilized ylides, marked stereoselectivity has not been observed except in two reported cases. The reaction of benzylic trialkylphosphorus ylides shows substantial *E* selectivity,[1a,2] as does the reaction of allylic diphenylalkylphosphorus ylides with bulky aldehydes.[3]

Recently, we reported that olefination of less bulky aldehydes with some allylic tributylphosphorus ylides results in high *E* stereoselectivity.[4] Thus, we began to study the scope and limitation of stereoselective *E* olefin synthesis with allylic tributylphosphorus ylides and compare such ylides with the corresponding triphenylphosphorus ylides. In these reactions, the steric effects of ylides and aldehydes turn out to have a crucial impact on the stereochemistry. In order to gain more insight into the stereochemistry, we have conducted a systematic study using structurally different allylic ylides and aldehydes. Our stereochemical results reveal a strong dependency of olefin stereoselectivity (both *E* and *Z*) on steric effects in both the allylic ylides and aldehydes as well as the selection of phosphorus ligands. Furthermore, the origin of the observed *E* or *Z* selectivity can be reasonably explained according to the Vedejs' rationale reported recently on the Wittig reaction stereochemistry.[5] Stereoselective olefination of aldehydes with allylic phosphorus ylides permits

Table I. Olefination of Aldehydes with β,γ-Substituted Allylic Phosphorus Ylide (eq 1)[a]

entry	phosphonium salt	aldehyde	product	isolated yield, %	*E*:*Z*[b]
1	**1a**	PhCHO	**2**	82 (41)[c]	*E* > 95 (*E* > 95)[c]
2	**1b**	PhCHO	**2**	63 (29)[c]	45:55 (47:53)[c]
3	**1a**	*n*-heptanal	**3**	84	92:8
4	**1b**	*n*-heptanal	**3**	60	58:42
5	**1a**	*i*-BuCHO	**4**	87	*E* > 95
6	**1b**	*i*-BuCHO	**4**	44	50:50
7	**1a**	*t*-BuCHO	**5**	67	*E* > 95
8	**1b**	*t*-BuCHO	**5**	44	15:85
9	**1a**	(*Z*)-MeCH=C(Ph)CHO	**6**	58	*E* > 95
10	**1b**	(*Z*)-MeCH=C(Ph)CHO	**6**	86	17:83
11	**1a**	c-C_6H_{11}CHO	**7**	80	*E* > 95
12	**1b**	c-C_6H_{11}CHO	**7**	45	73:27

[a] *n*-BuLi was used as base. See General Procedure in the Experimental Section. [b] Determined by GLC and ^{1}H NMR. [c] *t*-BuOK was used in place of *n*-BuLi.

(1) For reviews, see: (a) Gosney, I.; Rowley, A. G. In *Organophosphorus Reagents in Organic Synthesis*; Cadagan, J. I. G., Ed.; Academic: New York, 1979; pp 7–205. (b) Bestmann, H. J.; Vostrowsky, O. *Top. Curr. Chem.* **1983**, *109*, 85–163. (c) Pommer, H.; Thieme, P. C. *Ibid.* **1983**, *109*, 165–188. (d) Bestmann, H. J. *Pure. Appl. Chem.* **1980**, *52*, 771–788. (e) Pommer, H. *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 423–429. (f) House, H. O. *Modern Synthetic Reactions*, 2nd ed.; W. A. Benjamin, Inc.: Menlo Park, CA, 1972; pp 682–709. (g) Schlosser, M. *Top. Stereochem.* **1970**, *5*, 1–30. (h) Maercker, A. *Org. React. (N.Y.)* **1965**, *14*, 270–490. Also see ref 5 and 8.

(2) Bestmann, H. J.; Kratzer, O. *Chem. Ber.* **1962**, *95*, 1894–1901.

(3) Vedejs, E.; Fang, H. W. *J. Org. Chem.* **1984**, *49*, 210–212.

(4) Tamura, R.; Kato, M.; Saegusa, K.; Kakihana, M.; Oda, D. *J. Org. Chem.* **1987**, *52*, 4121–4124. In the present work, bis(dibenzylideneacetone)palladium(0) [Pd(dba)$_2$] was employed as catalyst (5 mol %) to prepare the allylic tributylphosphonium salts, which were purified by washing with ether or pentane to remove dba and unreacted PBu_3 and allylic substrate and used for further reactions.

(5) Vedejs, E.; Marth, C. F. *J. Am. Chem. Soc.* in press, and references cited therein. The authors thank Professor E. Vedejs for sending us the preprint.

0022-3263/88/1953-2723$01.50/0

Table II. Olefination of Aldehydes with Various Allylic Phosphorus Ylides (eq 2)[a]

entry	phosphonium salt	base	aldehyde	product	isolated yield, %	$E:Z$[b]
1	**8a**	*n*-BuLi	PhCHO	**12**	92	60:40
2	**8a**	*t*-BuOK	PhCHO	**12**	68	58:42
3	**8b**	*n*-BuLi	PhCHO	**12**	83	52:48
4	**8b**	*t*-BuOK	PhCHO	**12**	59	25:75
5	**8a**	*n*-BuLi	*t*-BuCHO	**13**	59	63:37
6	**8b**	*n*-BuLi	*t*-BuCHO	**13**	32	17:83
7	**8b**	*t*-BuOK	*t*-BuCHO	**13**	0	
8	**8a**	*n*-BuLi	c-C_6H_{11}CHO	**14**	71	82:18
9	**8a**	*t*-BuOK	c-C_6H_{11}CHO	**14**	57	95:5
10	**8b**	*n*-BuLi	c-C_6H_{11}CHO	**14**	71	46:54
11	**8b**	*t*-BuOK	c-C_6H_{11}CHO	**14**	65	70:30
12	**9a**	*n*-BuLi	PhCHO	**15**	82	71:29
13	**9a**	*t*-BuOK	PhCHO	**15**	63	78:22
14	**9b**	*n*-BuLi	PhCHO	**15**	82	40:60
15	**9b**	*t*-BuOK	PhCHO	**15**	57	22:78
16	**9a**	*n*-BuLi	*t*-BuCHO	**16**	61	77:23
17	**9b**	*n*-BuLi	*t*-BuCHO	**16**	47	95 < Z
18	**9a**	*n*-BuLi	c-C_6H_{11}CHO	**17**	72	85:15
19	**9a**	*t*-BuOK	c-C_6H_{11}CHO	**17**	61	95:5
20	**9b**	*n*-BuLi	c-C_6H_{11}CHO	**17**	67	56:44
21	**9b**	*t*-BuOK	c-C_6H_{11}CHO	**17**	60	80:20
22	**10a**	*n*-BuLi	PhCHO	**18**	98	85:15
23	**10b**	*n*-BuLi	PhCHO	**18**	85	30:70
24	**10a**	*n*-BuLi	*t*-BuCHO	**19**	49	85:15
25	**10b**	*n*-BuLi	*t*-BuCHO	**19**	30	22:78
26	**10a**	*n*-BuLi	c-C_6H_{11}CHO	**20**	52	88:12
27	**10b**	*n*-BuLi	c-C_6H_{11}CHO	**20**	33	66:34
28	**11a**	*n*-BuLi	PhCHO	**21**	75	84:16
29	**11a**	*t*-BuOK	PhCHO	**21**	35	84:16
30	**11b**	*n*-BuLi	PhCHO	**21**	60	69:31
31	**11b**	*t*-BuOK	PhCHO	**21**	21	45:55
32	**11a**	*n*-BuLi	$PhCH_2CH_2CHO$	**22**	63	92:8
33	**11a**	*t*-BuOK	$PhCH_2CH_2CHO$	**22**	41	92:8
34	**11b**	*n*-BuLi	$PhCH_2CH_2CHO$	**22**	45	71:29
35	**11b**	*t*-BuOK	$PhCH_2CH_2CHO$	**22**	23	61:39
36	**11a**	*n*-BuLi	c-C_6H_{11}CHO	**23**	54	E > 95
37	**11b**	*n*-BuLi	c-C_6H_{11}CHO	**23**	36	90:10

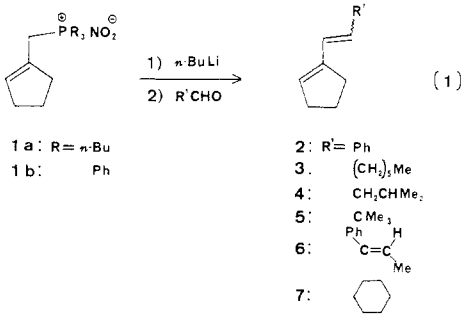
[a] See General Procedure in the Experimental Section. [b] Determined by GLC and ^{1}H NMR.

the stereoselective formation of various conjugated dienes.

Results

To observe the effect of substrate steric features on the stereochemistry of product olefins, we carried out the olefination of various aldehydes with allylic tributyl- and triphenylphosphorus ylides. The allylic phosphonium salt was treated with *n*-BuLi or *t*-BuOK in THF to generate the ylide, which was allowed to react with aldehydes at −78 °C and then warmed to room temperature. Results are summarized in Tables I and II.

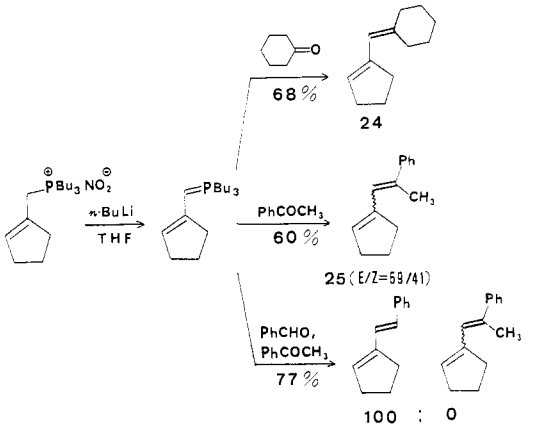
β,γ-Disubstituted Ylides. In general, the use of the tributylphosphorus ylide derived from **1a** with *n*-BuLi led to high *E* stereoselectivity irrespective of the type of aldehydes used, as seen in eq 1 and Table I. Even with



(1)

n-heptanal the ratio of *E* to *Z* for compound **3** was 92 to 8 (entry 3). With the use of sterically demanding aldehydes, *E* selectivity exceeded 95% (entries 5, 7, 9, and 11). The tributylphosphorus ylide also reacted with ketones

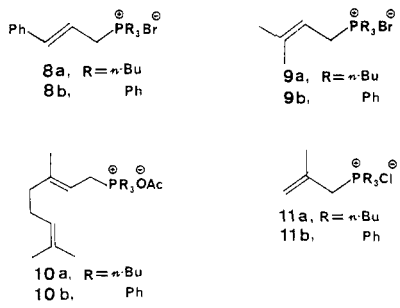
Scheme I



such as cyclohexanone and acetophenone (Scheme I). No stereoselectivity was observed in the olefination of acetophenone. In competition reactions with benzaldehyde and acetophenone, only benzaldehyde was consumed (Scheme I).

On the other hand, stereochemistry with the triphenylphosphorus ylide prepared from **1b** and *n*-BuLi was highly dependent on the structure of the aldehydes used. With *n*-heptanal, isovaleraldehyde, and benzaldehyde, no appreciable selectivity was observed (entries 2, 4, and 6). However, with sterically bulky aldehydes such as pivaldehyde and 2-phenyl-2-butenal, *Z* olefin was predominantly formed with about 85% selectivity (entries 8 and 10). Interestingly, the use of large secondary aldehydes such as cyclohexanecarboxaldehyde brought the selectivity

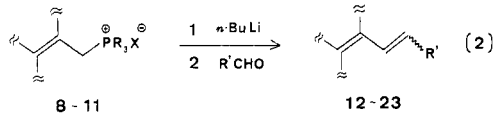
Chart I



to the predominant formation of *E* olefin (entry 12). These results imply that subtle changes in substrate steric features effect the stereochemistry of product olefins in the case of triphenylphosphorus ylides.

Almost no lithium salt effect was observed in the reaction of the ylides from **1a** and **1b** with benzaldehyde (see parentheses in entries 1 and 2).

γ-Monosubstituted and γ,γ-Disubstituted Ylides. Next we examined the reaction with less substituted or less sterically demanding ylides (eq 2 and Table II). The re-



(2)

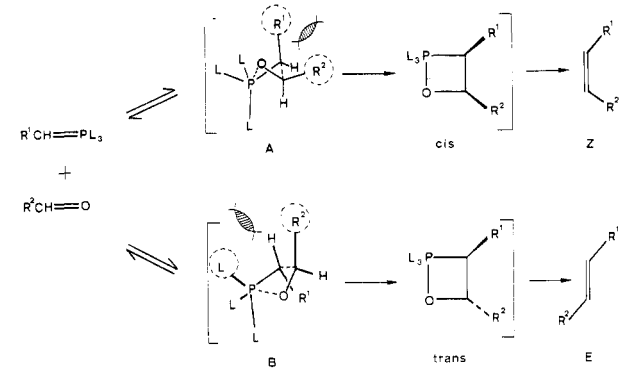
action with the tributylphosphorus ylide derived from cinnamylphosphonium bromide (**8a**) (Chart I) showed only moderate *E* selectivity (82%) even when cyclohexanecarboxaldehyde was employed (entries 1, 5, and 8). This may be attributed to the lack of sufficient steric hindrance in the ylide compared with that derived from **1a**. The use of the γ,γ-dimethylallylic tributylphosphorus ylide from **9a** and *n*-BuLi improved the *E* selectivity by 14% or less over that from **8a** (entries 1, 5, 8, 12, 16, and 18). Likewise, the reaction of geranyltributylphosphorus ylide from **10a** and *n*-BuLi with various aldehydes showed 85% to 88% *E* selectivity (entries 22, 24, and 26).

As to the corresponding triphenylphosphorus ylides prepared from **8b**, **9b**, and **10b** with *n*-BuLi, *Z* selectivity was observed in reaction with pivaldehyde (entries 6, 17, and 25). *Very high Z selectivity (Z > 95%) was realized in the lithium-containing reaction of the ylide from* **9b** *with pivaldehyde.* Cyclohexanecarboxaldehyde showed almost no selectivity or moderate *E* selectivity with the ylide from **10b** (entries 10, 20, and 27).

Noteworthy is the lithium salt effect on the stereochemistry of the reaction with these allylic phosphorus ylides, depending on the type of aldehydes and phosphorus ligands (triphenyl or tributyl). When *t*-BuOK was used in place of *n*-BuLi, considerable salt effect (respective 27% and 18% increase of *Z* selectivity) was observed in the reaction of triphenylphosphorus ylides from **8b** and **9b** with benzaldehyde (entries 3, 4 and 14, 15), while negligible and 7% increases of *E* selectivity were noted in the cases of the corresponding tributylphosphorus ylides, respectively (entries 1, 2 and 12, 13). Interestingly, cyclohexanecarboxaldehyde only showed an increase of *E* selectivity under the lithium salt free conditions irrespective of the type of phosphorus ligands: **8a** (13%), **8b** (24%), **9a** (10%), and **9b** (24%) (entries 8, 9, 10, 11, 18, 19 and 20, 21).

In order to probe the observed lithium salt effect, a preliminary crossover experiment was attemted. In the presence of LiBr, the triphenylphosphorus ylide derived from **9b** was allowed to react with benzaldehyde or cyclohexanecarboxaldehyde at −78 °C, immediately giving

Scheme II[a]



[a] Under salt-free conditions. Reference 5.

a precipitate (presumably the betaine–LiBr adduct) with the instantaneous disappearance of the red color of the ylide. Addition of 4-chlorobenzaldehyde to the precipitate at −78 °C followed by warming to room temperature resulted in the formation of extensive amounts of crossover product (ca. 50% crossover in both cases).[6] This positive crossover experiment suggests that the observed lithium salt effect may be ascribed to the reversible betaine–LiX adduct formation.

β-Monosubstituted Ylide. We examined the effect of β-substitution in allylic ylides. This substitution was quite effective for increasing *E* selectivity in the reaction with the tributylphosphorus ylide (eq 2 and Table II). In the olefination of β-phenylpropionaldehyde and cyclohexanecarboxaldehyde with the ylide from **11a** and *n*-BuLi, *E* selectivity reached 92% and more than 95%, respectively (entries 32 and 36). These results (the *E*:*Z* ratios) were rather similar to those with $Ph_2MeP{=}CHCMe{=}CH_2$.[3] The corresponding triphenylphosphorus ylide led to the predominant formation of the *E* isomer with all three aldehydes used (entries 30, 34, and 37). Again the lithium salt effect was observed in the reaction with the triphenylphosphorus ylide from **11b** (entries 30, 31 and 34, 35) but not with the corresponding tributylphosporus ylide (entries 28, 29 and 32, 33).

Discussion

Our stereochemical results with allylic ylides showed substantial similarity to those with nonstabilized ylides with respect to *E* and *Z* selectivity and the lithium salt effect. Recently Vedejs[7] and Maryanoff[8] conducted detailed studies of the Wittig intermediate (oxaphosphetanes)[9] using low-temperature ^{31}P NMR techniques and gave insight into the reaction mechanism of nonstabilized ylides. Detection of oxaphosphetanes implies that the rate-determining step of the reaction with nonstabilized ylides is the decomposition of such oxaphosphetane intermediates to the corresponding olefins and phosphine oxides. Their studies showed that formation of cis or trans oxaphosphetane is the decisive step of reaction stereo-

(6) This crossover experiment and conclusions are the same as those using allylic diphenylmethylphosphorus ylide by Vedejs, see ref 3. Also see ref 7.

(7) Vedejs, E.; Meier, G. P.; Snoble, K. A. J. *J. Am. Chem. Soc.* **1981**, *103*, 2823–2831, and references cited therein.

(8) 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*, 7664–7678.

(9) The structure of stable oxaphosphetane $PO_2(C_6H_5)_2(CF_3)_4C_4H_5$ has been established by X-ray analysis. The four-membered ring is slightly puckered and the dihedral angle is 11°, see: Ui-Hague, M.; Caughlan, C. N.; Ramirez, F.; Pilot, J. F.; Smith, C. P. *J. Am. Chem. Soc.* **1971**, *93*, 5229–5235.

chemistry and is affected by the presence of lithium salt in the system. Vedejs has recently proposed that formation of oxaphosphetane occurs by an asynchronous cycloaddition of ylides and aldehydes[7] and that the subtle interplay of 1,2-cis steric interaction between R^1 in ylides and R^2 in aldehydes and 1,3 interaction between R^2 and the nearest phosphorus ligand L in early four-center transition states (puckered geometry A or planar one B in Scheme II), where phosphorus is in a distorted square-pyramidal geometry, is responsible for kinetic cis or trans oxaphosphetane selectivity, respectively.[5]

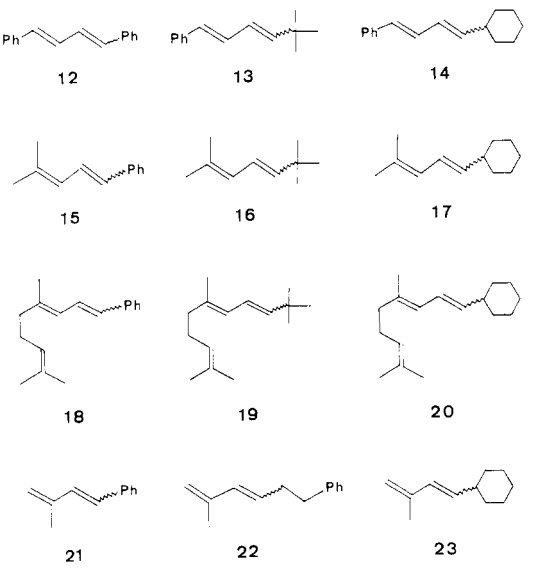
Much less is known about the reaction mechanism with semistabilized phosphorus ylides, because no direct evidence of the existence of oxaphosphetane intermediates from the simple ylides and aldehydes has been offered to date, despite considerable effort.[10] Nevertheless, the Vedejs' rationale (Scheme II)[5] helped us to understand our stereochemical results with semistabilized allylic ylides strongly resembling those with nonstabilized ylides.[11]

Under the lithium salt free conditions, the reaction of the triphenylphosphorus ylides from **8b** and **9b** with benzaldehyde showed considerable kinetic cis selectivity for oxaphosphetane formation mainly due to the steric reasons, leading to the predominant formation of *Z* olefins (entries 4 and 15 in Table II). A puckered four-center transition state (A) must dominate over a planar one (B) in an early transition state so as to avoid the 1,3 steric interaction between R^2 and L (Scheme II). The cis selectivity decreased in the lithium-containing reaction.[12] As shown in the crossover experiment, the reversible betaine–LiX adduct formation may affect the stereoselectivity. However, olefination of pivaldehyde with triphenylphosphorus ylides led to high *Z* selectivity despite the presence of dissolved lithium salt (entries 6, 17, and 25 in Table II). On the other hand, with cyclohexanecarboxaldehyde a 24% increase of trans selectivity was observed under the lithium salt free conditions (entries 10, 11, and 20, 21 in Table II).[13] This result indicates that a planar four-center transition state (B) is kinetically favored even for triphenylphosphorus ylides probably owing to the 1,2 steric interaction between R^1 and a large R^2 (cyclohexyl group) (Scheme II), together with the decreased 1,3 interaction between L (Ph) and the secondary alkyl group R^2.

With tributylphosphorus ylides, generally trans selectivity was observed in the lithium-containing reactions with tributylphosphorus ylides, giving *E* olefins predominantly. The lithium salt effect was noted in a few examples to the extent of less than a 13% increase of *E* selectivity (entries 8, 9, 12, 13, and 18, 19 in Table II).[13] These reactions should favor a more stable planar transition state (B) probably due to the great decrease of the 1,3 interaction between R^2 and a compact L (*n*-Bu).

Under the lithium salt free conditions, product yields decreased uniformaly in all cases as long as *t*-BuOK was used as base (Table I and II). This may be attributed to a side reaction (γ substitution) of allylic ylides, as inferred from the extreme decrease of the product yields in the reaction with the ylides from **11a** and **11b** bearing no substituent at the γ-position (entries 29, 31, 33, and 35 in Table II).[14]

Chart II

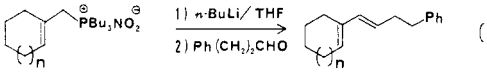


Thus, it is clear that the interplay of 1,2 (the planar B favored) and 1,3 (the puckered A favored) steric interaction in an early four-center transition state is responsible for trans or cis selectivity of oxaphosphetanes leading to *E* or *Z* olefins, respectively. Therefore, the steric profile of R^1 in the ylides and R^2 in the aldehydes as well as phosphorus ligand L must be taken into account to achieve the stereoselective formation of conjugated dienes. Generalizations from our stereochemical studies are described below.

With respect to *E* selectivity, as shown in Tables I and II, *the structure of the allylic group in the tributylphosphorus ylide most affects the stereochemistry.* The decreasing order of *E* selectivity with regard to the ylide is as follows:

$$R'CH{=}CRCH{=}PBu_3 > CH_2{=}CRCH{=}PBu_3 > RR'C{=}CHCH{=}PBu_3 > RCH{=}CHCH{=}PBu_3$$

As the steric demand of the ylide decreases, larger aldehydes are required to achieve high *E* selectivity. Thus, the degree of the 1,2 steric interaction between R^1 and R^2 in an early four-center transition state seems to induce the observed stereochemistry (Scheme II). In the case of tributylphosphorus ylides, the lithium salt effect was not so distinct as that with the corresponding triphenylphosphorus ylides. β,γ-Disubstituted ylides from **26** and **27** and *n*-BuLi react even with a primary aldehyde to achieve high *E* stereoselectivity (eq 3).



(3)

26, 27

28, n=1: 57%, E/Z=94/6
29, 2: 60%, E ≥ 95

In the case of triphenylphosphorus ylides, bulky R^2 groups such as the *tert*-butyl group favor the puckered transition state (A) due to the severe 1,3 steric interaction leading to the predominant or exclusive formation of *Z* olefins even under lithium salt present conditions, while

(10) We have recently learned in a private communication from Professor E. Vedejs that he has succeeded in detecting the oxaphosphetane from a certain allylic ylide and cyclohexanecarboxaldehyde and that he has proved the reaction of $MePh_2P{=}CHCH{=}CH_2$ with the same aldehyde to be under total kinetic control. See also ref 3 and 8.

(11) Although the Schlosser's "leeward approach" argument seemed reasonable, this rationale proved insufficient to explain all of the subtle steric effects observed in our stereochemical studies, see; Schlosser, M.; Schaub, B. *J. Am. Chem. Soc.* **1982**, *104*, 5821–5823. Some experimental results incompatible with this rationale have been reported in ref 5.

(12) In the lithium-containing Wittig reactions of nonstabilized triphenylphosphorus ylides, kinetic selectivity is known to be reduced; see ref 5, 7, and 8.

(13) The lithium salt effect is reported to significantly decrease the selectivity of certain allylic ylides which are inherently trans-selective; see ref 3.

(14) Vedejs, E.; Bershas, J. P.; Fuchs, P. L. *J. Org. Chem.* **1973**, *38*, 3625–3627.

the large secondary alkyl group R^2 such as the cyclohexyl group prefers the planar one (B) owing to the 1,2 steric interaction and the decreased 1,3 interaction to give *E* olefins predominantly under the salt-free conditions.[15] Thus, the decreasing order of *Z* selectivity with regard to the aldehyde is *t*-BuCHO > PhCHO > $Ph(CH_2)_2CHO$ > $C\text{-}C_6H_{11}CHO$. The lithium salt effect was obvious in most of these reactions.

Conclusion

The stereochemical results (*E* vs. *Z*) of the Wittig reaction of semistabilized allylic phosphorus ylides with aldehydes shows similarity to those with nonstabilized ylides and can be reasonably understood according to the Vedejs' rationale on the Wittig reaction stereochemistry.[5]

High *E* olefin selectivity was accomplished by using sterically crowded β,γ-disubstituted allylic tributylphosphorus ylides and various aldehydes. This selectivity stems from the 1,2 steric interaction between R^1 and R^2 in an early four-center transition state (the planar B favored in Scheme II). As the steric demand of the ylides decreases, larger aldehydes are required to achieve high *E* selectivity. On the other hand, the predominant or exclusive formation of *Z* olefins was achieved by using such bulky aldehydes as pivaldehyde and triphenylphosphorus ylides. In the case of triphenylposphorus ylides, one may consider the 1,3 steric interaction (the puckerd A favored; *Z* selective) between R^2 and the phosphorus ligands (Ph) in competition with the 1,2 interaction (the planar B favored; *E* selective) between R^1 and R^2 (Scheme II). Therefore, the combination of triphenylphosphorus ylides and large secondary aldehydes can lead to the predominant *E* olefin formation under the lithium salt free conditions. The distinct lithium salt effect was observed in most reactions effected with triphenylphosphorus ylides. These olefination methods afford various conjugated dienes stereoselectively.

Experimental Section

Spectral data were recorded on the following instruments: NMR, JEOL FX-90Q (90 MHz) or Varian XL-300 (300 MHz); IR, Shimadzu IR-27G or Bruker IFS113V. GLC analyses were performed on a Schimadzu GC-6AM chromatograph using a column packed with Silicon SE30 (3 mm × 2 m). Mass spectra were taken on a Hitachi M-80B mass spectrometer. Column chromatography was carried out with Merck silica gel 60 (less than 230 mesh) under moderate pressure (3 atm). Elemental analyses were performed by the Kyoto University Microanalytical Laboratories. All reactions were run under argon. THF was distilled from benzophenone ketyl. Allylic phosphonium salts were prepared from the corresponding allylic halides and allylic nitro compounds.[4] Commercial reagents were purified by distillation or recrystallization.

General Procedure for Olefination of Aldehyde with Allylic Phosphorus Ylide. To the allylic phosphonium salt (1.0 mmol) in THF (8 mL) was added *n*-BuLi (1.0 mmol, hexane solution) at −40 °C or *t*-BuOK (112 mg, 1.0 mmol) at 25 °C. The mixture was stirred at 25 °C for 2 h, and a solution of aldehyde (1.0 mmol) in THF (2 mL) was added at −78 °C. After being allowed to warm slowly to room temperature over 1 h and stirred at 25 °C for 24 h, the reaction mixture was diluted with ether (50 mL), washed with water (2 × 25 mL), dried over $MgSO_4$, and concentrated in vacuo. The crude product could be purified by column chromatography (hexanes). The isomer ratio was determined by GLC and ^1H NMR.

(*E*)-**2**: see ref 4.

(*Z*)-**2**: ^1H NMR (90 MHz, $CDCl_3$) δ 6.46 (d, *J* = 11.9 Hz, 1 H), 6.26 (d, *J* = 11.9 Hz, 1 H) for olefin protons in the styryl group.

(*E*)-**3**: see ref 4.

(*Z*)-**3**: ^1H NMR (90 MHz, $CDCl_3$) δ 6.00 (d, *J* = 11.4 Hz, 1 H), 5.56 (br s, 1 H), 5.32 (dt, *J* = 7.7, 11.4 Hz, 1 H), 2.71–2.17 (br m, 4 H), 2.17–1.66 (br m, 4 H), 1.57–1.11 (br, 8 H), 0.89 (t, *J* = 5.3 Hz, 3 H).

(*E*)-**4**: IR (neat) 963 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.24 (d, *J* = 15.4 Hz, 1 H), 5.59 (br, 1 H), 5.51 (dt, *J* = 15.4, 7.0 Hz, 1 H), 2.60–2.17 (br m, 4 H), 2.17–1.71 (br m, 4 H), 1.71–1.46 (m, 1 H), 0.885 (d, *J* = 6.6 Hz, 6 H); ^{13}C NMR (22.5 MHz) δ 142.7, 130.0, 128.1, 42.4, 32.7, 31.5, 28.7, 23.2, 22.4. Anal. ($C_{11}H_{18}$) C, H.

(*Z*)-**4**: IR (neat) 733 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.03 (d, *J* = 11.9 Hz, 1 H), 5.57 (br, 1 H), 5.31 (dt, *J* = 11.9, 7.7 Hz, 1 H), 2.69–2.19 (br m, 4 H), 2.19–1.83 (br m, 4 H), 1.83–1.37 (m, 1 H), 0.89 (d, *J* = 6.6 Hz, 6 H); mass spectrum, *m/e* 150.1 (P).

(*E*)-**5**: IR (neat) 970 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.23 (d, *J* = 15.8 Hz, 1H), 5.61 (br, 1H), 5.56 (d, *J* = 15.8 Hz, 1 H), 2.54–2.19 (br m, 4 H), 2.04–1.66 (br m, 2 H), 1.04 (s, 9 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 142.9, 142.0, 128.4, 121.9, 33.0, 32.8, 31.4, 29.8, 23.2. Anal. ($C_{11}H_{18}$) C, H.

(*Z*)-**5**: IR (neat) 735 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 5.62 (br, 1 H), 5.50 (d, *J* = 12.7 Hz, 1 H), 5.37 (d, 12.7 Hz, 1 H), 2.54–2.19 (br m, 4 H), 2.04–1.66 (br m, 2 H), 1.09 (s, 9 H); mass spectrum, *m/e* 150.1 (P).

(*E*)-**6**: IR (neat) 1600, 1495, 1450, 1075, 1028, 910 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.49–6.94 (m, 5 H), 6.31 (d, *J* = 15.4 Hz, 1 H), 5.86 (d, *J* = 15.4 Hz, 1 H), 5.80 (q, *J* = 7.2 Hz, 1 H), 5.14 (br, 1 H), 2.63–2.09 (br m, 4 H), 2.09–1.57 (br m, 2 H), 1.54 (d, *J* = 7.2 Hz, 3 H). Anal. ($C_{16}H_{18}$) C, H.

(*Z*)-**6**: ^1H NMR (90 MHz, $CDCl_3$) δ 7.54–7.00 (m, 5 H), 6.17 (d, *J* = 11.6 Hz, 1 H), 5.91 (d, *J* = 11.6 Hz, 1 H), 5.74 (q, *J* = 7.2 Hz, 1 H), 5.66 (br, 1 H), 2.63–2.06 (br m, 4 H), 2.06–1.63 (br m, 2 H), 1.74 (d, *J* = 7.2 Hz, 3 H). Anal. ($C_{16}H_{18}$) C, H for the mixture of (*E*)- and (*Z*)-**6**.

(*E*)-**7**: IR (neat) 960 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.24 (d, *J* = 15.8 Hz, 1 H), 5.57 (br, 1 H), 5.46 (dd, *J* = 15.8, 6.6 Hz, 1 H), 2.54–2.17 (br m, 4 H), 2.17–1.83 (br m, 3 H), 1.83–1.43 (br m, 4 H), 1.43–0.74 (br m, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 142.9, 137.0, 131.1, 128.3, 41.0, 33.2, 32.8, 31.5, 26.3, 26.2, 23.3. Anal. ($C_{13}H_{20}$) C, H.

(*Z*)-**7**: ^1H NMR (90 MHz, $CDCl_3$) δ 5.90 (d, *J* = 11.8 Hz, 1 H), 5.17 (dd, *J* = 11.8, 10.3 Hz, 1 H) for the olefin protons; mass spectrum, *m/e* 176.1 (P).

(*E*)-**12**: see ref 16.

(*Z*)-**12**: ^1H NMR (300 MHz, $CDCl_3$) δ 7.48–7.20 (m, 10 H), 6.71 (d, *J* = 15.4 Hz, 1 H), 6.52 (d, *J* = 11.3 Hz, 1 H), 6.48 (d, *J* = 15.4 Hz, 1 H), 6.40 (d, *J* = 11.3 Hz, 1 H).

(*E*)-**13**: IR (neat) 1593, 1493, 1446, 986 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.75 (dd, *J* = 15.7, 10.2 Hz, 1 H), 6.48 (d, *J* = 15.7 Hz, 1 H), 6.15 (dd, *J* = 10.2, 15.4 Hz, 1 H), 5.86 (d, *J* = 15.4 Hz, 1 H), 1.08 (s, 9 H). Anal. ($C_{14}H_{18}$) C, H for the mixture of (*E*)- and (*Z*)-**13**.

(*Z*)-**13**: IR (neat) 1605, 1494, 1448, 733 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.42–7.16 (m, 6 H), 6.44 (d, *J* = 15.4 Hz, 1 H), 6.00 (dd, *J* = 11.9, 12.6 Hz, 1 H), 5.49 (d, *J* = 11.9 Hz, 1 H), 1.23 (s, 9 H).

(*E*)-**14**: IR (neat) 1597, 1495, 1447, 985 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.44–7.15 (m, 5 H), 6.75 (d, *J* = 10.5, 15.6 Hz, 1 H), 6.45 (d, *J* = 15.6 Hz, 1 H), 6.18 (dd, *J* = 10.5, 15.3 Hz, 1 H), 5.79 (d, *J* = 15.3, 7.0 Hz, 1 H), 2.06 (br m, 1 H), 1.82–1.60 (br m, 4 H), 1.45–1.05 (br m, 6 H). Anal. ($C_{16}H_{20}$) C, H for the mixture of (*E*)- and (*Z*)-**14**.

(*Z*)-**14**: IR (neat) 1595, 1495, 1446, 735 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.44–7.15 (m, 5 H), 7.05 (dd, *J* = 15.4, 10.2 Hz, 1 H), 6.52 (d, *J* = 15.4 Hz, 1 H), 6.05 (dd, *J* = 10.2 Hz, 1 H), 5.38 (dd, *J* = 10.2 Hz, 1 H), 2.58 (br m, 1 H), 1.82–1.60 (br m, 4 H), 1.45–1.05 (br m, 6 H).

(*E*)-**15**: IR (neat) 1595, 1493, 1450, 955 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.47–7.11 (m, 5 H), 6.99 (dd, *J* = 10.9, 15.4 Hz, 1 H), 6.39 (d, *J* = 15.4 Hz, 1 H), 6.00 (d, *J* = 10.9 Hz, 1 H), 1.83 (s, 6 H). Anal. ($C_{12}H_{14}$) C, H for the mixture of (*E*)- and (*Z*)-**15**.

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(*Z*)-**15**: IR (neat) 1595, 1492, 1452, 732 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 7.40–7.20 (m, 5 H), 6.44 (dd, J = 11.0, 11.1 Hz, 1 H), 6.36 (d, J = 11.0 Hz, 1 H), 6.32 (d, J = 11.1 Hz, 1 H), 1.82 (s, 6 H).

(*E*)-**16**: IR (neat) 964 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.17 (dd, J = 10.6, 15.0 Hz, 1 H), 5.77 (d, J = 10.6 Hz, 1 H), 5.60 (d, J = 15.0 Hz, 1 H), 1.74 (s, 6 H), 1.04 (s, 9 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 143.3, 132.9, 127.0, 125.5, 33.2, 29.9, 26.0, 18.3; mass spectrum, m/e 138.1 (P).

(*Z*)-**16**: IR (neat) 734 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.21 (dd, J = 11.4, 11.9 Hz, 1 H), 5.91 (d, J = 11.9 Hz, 1 H), 5.27 (d, J = 11.4 Hz, 1 H), 1.80 (s, 3 H), 1.72 (s, 3 H), 1.16 (s, 9 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 139.2, 135.1, 123.2, 121.4, 33.5, 31.5, 26.6, 17.6. Anal. ($C_{10}H_{18}$) C, H.

(*E*)-**17**: IR (neat) 958 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.19 (dd, J = 10.8, 15.2 Hz, 1 H), 5.78 (d, J = 10.8 Hz, 1 H), 5.51 (dd, J = 15.2, 6.9 Hz, 1 H), 2.00 (br m, 1 H), 1.78–1.60 (br, 4 H), 1.74 (s, 6 H), 1.40–1.00 (br, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 138.0, 132.8, 125.5, 124.2, 41.1, 33.3, 26.3, 26.2, 18.2. Anal. ($C_{12}H_{20}$) C, H for the mixture of (*E*)- and (*Z*)-**17**.

(*Z*)-**17**: IR (neat) 734 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.10–6.01 (m, 2 H), 5.17 (m, 1 H), 2.43 (br m, 1 H), 1.81 (s, 6 H), 1.78–1.60 (br, 4 H), 1.40–1.00 (br, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 135.7, 134.9, 122.9, 120.7, 36.6, 33.5, 26.1, 26.0, 18.1.

18: see ref 4 and 17.

(*E*)-**19**: IR (neat) 965 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.18 (dd, J = 10.7, 15.4 Hz, 1 H), 5.80 (d, J = 10.7 Hz, 1 H), 5.63 (d, J = 15.4 Hz, 1 H), 5.10 (br m, 1 H), 2.18–1.95 (br m, 4 H), 1.76 (s, 3 H), 1.68 (s, 3 H), 1.60 (s, 3 H), 1.03 (s, 9 H). Anal. ($C_{15}H_{26}$) C, H for the mixture of (*E*)- and (*Z*)-**19**.

(*Z*)-**19**: IR (neat) 737 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.28 (d, J = 11.8 Hz, 1 H), 6.01 (dd, J = 11.8, 11.9 Hz, 1 H), 5.31 (d, J = 11.8 Hz, 1 H), 5.10 (br m, 1 H), 1.72 (s, 3 H), 1.68 (s, 3 H), 1.60 (s, 3 H), 1.16 (s, 9 H).

(*E*)-**20**: IR (neat) 961 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.21 (dd, J = 10.7, 15.2 Hz, 1 H), 5.79 (d, J = 10.7 Hz, 1 H), 5.54 (dd, J = 7.1, 15.2 Hz, 1 H), 5.10 (br m, 1 H), 2.27 (br m, 1 H), 2.20–1.94 (br m, 4 H), 1.74 (s, 3 H), 1.69 (s, 3 H), 1.61 (s, 3 H), 1.40–1.12 (br m, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 138.5, 136.5, 131.5, 125.0, 124.3, 124.2, 41.2, 40.0, 33.3, 26.8, 26.3, 26.2, 25.7, 17.7, 16.7. Anal. ($C_{17}H_{28}$) C, H for the mixture of (*E*)- and (*Z*)-**20**.

(*Z*)-**20**: IR (neat) 737 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.20 (m, 1 H), 6.08 (d, J = 5.4 Hz, 1 H), 5.19 (br m, 1 H), 5.10 (br m, 1 H), 2.40 (br m, 1 H), 1.78–1.55 (br, 4 H), 1.75 (s, 3 H), 1.70 (s, 3 H), 1.62 (s, 3 H), 1.40–1.12 (br m, 6 H).

(*E*)-**21**: IR (neat) 961 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.49–7.00 (br m, 5 H), 6.87 (d, J = 15.8 Hz, 1 H), 6.49 (d, J = 15.8 Hz, 1 H), 5.09 (br, 2 H), 1.96 (s, 3 H). Anal. ($C_{11}H_{12}$) C, H for the mixture of (*E*)- and (*Z*)-**21**.

(*Z*)-**21**: IR (neat) 729 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.49–7.00 (br m, 5 H), 6.40 (d, J = 12.3 Hz, 1 H), 6.11 (d, J = 12.3 Hz, 1 H), 4.98 (br, 2 H), 1.70 (s, 3 H).

(*E*)-**22**: IR (neat) 1605, 1495, 1454, 964, 908 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.19 (d, J = 15.8 Hz, 1 H), 5.66 (dt, J = 15.8, 6.1 Hz, 1 H), 4.86 (br, 2 H), 2.87–2.56 (br m, 2 H), 2.56–2.21 (br m, 2 H), 1.82 (s, 3 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 142.2, 141.9, 133.5, 129.9, 128.5, 128.4, 125.9, 114.6. Anal. ($C_{13}H_{16}$) C, H for the mixture of (*E*)- and (*Z*)-**22**.

(*Z*)-**22**: ^1H NMR (90 MHz, $CDCl_3$) δ 5.86 (d, J = 11.6 Hz, 1 H), 5.41 (dt, J = 11.6, 6.4 Hz, 1 H), 4.80 (br, 2 H) for the olefin protons.

(*E*)-**23**: IR (neat) 967, 909 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 6.11 (d, J = 15.8 Hz, 1 H), 5.57 (dd, J = 15.8, 6.6 Hz, 1 H), 4.86 (br, 2 H), 2.23–1.91 (br m, 1 H), 1.91–1.43 (br, 4 H), 1.82 (s, 3 H), 1.43–1.00 (br, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 142.4, 136.7, 130.3, 114.2, 40.9, 33.1, 26.3, 26.1, 18.7. Anal. ($C_{11}H_{18}$) C, H.

(*Z*)-**23**: ^1H NMR (90 MHz, $CDCl_3$) δ 5.74 (d, J = 11.5 Hz, 1 H), 5.20 (dd, J = 11.5, 9.7 Hz, 1 H), 4.93 (br, 3 H) for the olefin protons.

24: IR (neat) 853 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 5.77 (br, 1 H), 5.43 (br, 1 H), 2.67–2.20 (br, 6 H), 2.20–1.99 (br, 2 H), 1.99–1.74 (m, 2 H), 1.71–1.37 (br, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 141.8, 141.7, 129.4, 119.0, 38.2, 35.5, 32.1, 30.2, 28.9, 28.1, 26.8, 24.2. Anal. ($C_{12}H_{18}$) C, H.

(*E*)- **and** (*Z*)-**25**: IR (neat) 1600, 1493, 1442 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.49–7.00 (m, 5 H), 6.37 (br, 1 H) [6.23 (br, 1 H) for (*Z*)-**25**], 5.63 (br, 1 H) [5.43 (br, 1 H) for (*Z*)-**25**], 2.81–2.49 (br, 2 H), 2.49–2.16 (br, 2 H), 2.23 (s, 3 H) [2.06 (s, 3 H) for (*Z*)-**25**], 2.11–1.80 (m, 2 H). Anal. ($C_{14}H_{16}$) for the mixture of (*E*)- and (*Z*)-**25**.

(*E*)-**28**: IR (neat) 1604, 1496, 1454, 963 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.20 (br, 5 H), 6.06 (d, J = 15.8 Hz, 1 H), 5.63 (br, 1 H), 5.51 (dt, J = 15.8, 5.1 Hz, 1 H), 2.86–2.54 (br m, 2 H), 2.54–2.26 (br m, 2 H), 2.26–1.91 (br, 4 H), 1.83–1.40 (br, 4 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 142.2, 135.7, 134.1, 128.5, 128.3, 127.6, 125.9, 125.7, 36.4, 34.8, 25.9, 24.8, 22.8, 22.7. Anal. ($C_{16}H_{20}$) C, H.

(*E*)-**29**: IR (neat) 1604, 1495, 1453, 965 cm^{-1}; ^1H NMR (90 MHz, $CDCl_3$) δ 7.20 (br, 5 H), 6.06 (d, J = 15.4 Hz, 1 H), 5.77 (t, J = 6.6 Hz, 1 H), 5.57 (dt, J = 15.4, 6.6 Hz, 1 H), 2.89–2.57 (br m, 2 H), 2.57–2.00 (br m, 6 H), 1.91–1.29 (br m, 6 H); ^{13}C NMR (22.5 MHz, $CDCl_3$) δ 142.9, 142.2, 134.8, 132.1, 128.5, 128.3, 125.9, 125.6, 36.4, 34.9, 32.3, 28.6, 27.6, 27.0, 26.4. Anal. ($C_{17}H_{22}$) C, H.

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Transmetalation and Reverse Transmetalation on Ortho-Activated Aromatic Compounds: A Direct Route to *o,o'*-Disubstituted Benzenes

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Mercury substitution ortho to appropriately activated benzenes was achieved by using the reagent lithium tetramethylpiperidide (LiTMP)/mercuric chloride. LiTMP provides for lithiation ortho to the activating group; $HgCl_2$ functions as an in situ trap effecting mercury-for-lithium transmetalation. Ortho,ortho'-dimercuration was also observed; this occurs by iteration of the transmetalation process. The effects of major variables on these reactions were studied by using primarily *N,N*-diethylbenzamide as the activated substrate. Isopropyl benzoate, 2-phenyl-4,4-dimethyloxazoline, etc. were found to behave similarly. The mercurated aromatics could be converted to the corresponding haloaromatics in excellent yield, providing, for example, a good synthesis of *o,o'*-diiodo-*N,N*-diethylbenzamide, otherwise difficultly accessible. Reverse transmetalation methodology was employed to prepare *o,o'*-dilithiated-*N,N*-diethylbenzamide, which was characterized by its reactions with electrophiles.

Amide activation for ortho-lithiation of aromatic compounds is very well-known.[1] Recently we showed that this phenomenon also occurs on strained systems like cubane and cyclopropane which use orbitals high in s character

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