VOLUME 119, NUMBER 15
APRIL 16, 1997

JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Highly Efficient Ring Closure of Aromatic Dialdehydes to Macrocyclic Allenes

Marcus S. Brody, Robin M. Williams, and M. G. Finn*

Contribution from the Department of Chemistry, University of Virginia, Charlottesville, Virginia 22901

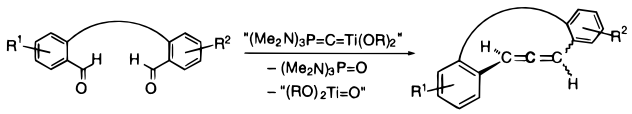
Received August 15, 1996[⊗]

Abstract: The one-pot double deoxygenation of simple alkyl- and polyether-tethered aromatic dialdehydes to give macrocyclic allenes has been accomplished in extraordinarily high yield without the need for slow-addition techniques, using a Ti(IV)-substituted ylide reagent and bis(trimethylsilyl)amide bases. Diastereoselective allene formation occurs when a binaphthyl unit is present in the substrate backbone, and the resulting cyclic allene is characterized by X-ray diffraction. Highly efficient cyclization is proposed to be the result of a combination of preorganization about the amide base counterion and a low concentration of the immediate precursor to Wittig-style olefination ring closure.

We have recently developed a family of Ti(IV)-substituted phosphorus methylides as "doubly oxophilic" reagents for the convenient condensation of nonenolizable aldehydes to 1,3-disubstituted allenes.[1−4] An obvious extension of this methodology is the synthesis of cyclic compounds from dicarbonyl precursors (Scheme 1). Here we report several remarkably efficient examples of such a process, along with a preliminary exploration of the reaction scope and a discussion of its important mechanistic features. Of particular interest are the diastereoselective synthesis of a binaphthyl-tethered allene and the preparation of several polyoxygenated macrocyclic allenes.

The most widely-used approaches to the closure of large rings[5−9] include the construction of ester,[10−12] amide,[13,14]

Scheme 1



vinylogous carbon−carbon,[15−17] and polyether[18,19] bonds, invariably in dilute solution. The conversion of dicarbonyl compounds to large-ring cyclic olefins (defined here as having ring sizes >10) has received somewhat less attention, most

[⊗] Abstract published in *Advance ACS Abstracts*, March 15, 1997.

(1) Hughes, K. A.; Dopico, P. G.; Sabat, M.; Finn, M. G. *Angew. Chem. Int., Ed. Engl.* **1993**, *32*, 554−555.
(2) Reynolds, K. A.; Dopico, P. G.; Sundermann, M. J.; Hughes, K. A.; Finn, M. G. *J. Org. Chem.* **1993**, *58*, 1298−1299.
(3) Reynolds, K. A.; Dopico, P. G.; Brody, M. S.; Finn, M. G. *J. Org. Chem.* In press.
(4) Reynolds, K. A.; Finn, M. G. *J. Org. Chem.* In press.
(5) Stille, J. K.; Tanaka, M. *J. Am. Chem. Soc.* **1987**, *109*, 3785−3786.
(6) Fujita, E. *Pure Appl. Chem.* **1981**, *53*, 1141−1154.
(7) Nicolaou, K. C. *Tetrahedron* **1977**, *33*, 683−710.
(8) Meng, Q.; Hesse, M. *Topics in Current Chemistry: Ring Closure Methods in the Synthesis of Natural Products*; Springer-Verlag: Berlin, 1991.
(9) McQuillin, F. J.; Baird, M. S. *Alicyclic Chemistry*, 2nd ed.; Cambridge University Press: Cambridge, 1983.
(10) Inanaga, J.; Hirata, K.; Saeki, H.; Katsuki, T.; Yamaguchi, M. *Bull. Chem. Soc. Jpn.* **1979**, *52*, 1989−1994.
(11) Lee, J. Y.; Kim, B. H. *Tetrahedron* **1996**, *52*, 571−588.
(12) Sharma, A.; Sankaranarayanan, S.; Chattopadhyay, S. *J. Org. Chem.* **1996**, *61*, 1814−1816.
(13) Rodgers, S. J.; Ng, C. Y.; Raymond, K. N. *J. Am. Chem. Soc.* **1985**, *107*, 4095−4096.
(14) Schwartz, E.; Gottlieb, H. E.; Frolow, F.; Shanzer, A. *J. Org. Chem.* **1985**, *50*, 5469−5476.
(15) Ma, S.; Negishi, E. *J. Am. Chem. Soc.* **1995**, *117*, 6345−6357.
(16) Stille, J. K.; Su, H.; Hill, D. H.; Schnieder, P.; Tanaka, M.; Morrison, D. L.; Hegedus, L. S. *Organometallics* **1991**, *10*, 1993−2000.
(17) Johnson, E. P.; Chen, G.-P.; Fales, K. R.; Lenk, B. E.; Szendroi, R. J.; Wang, X.-J.; Carlson, J. A. *J. Org. Chem.* **1995**, *60*, 6595−6598.
(18) Patterson, I.; Mansuri, M. M. *Tetrahedron* **1985**, *41*, 3569−3624.
(19) Karin, M. R.; Sampson, P. *J. Org. Chem.* **1990**, *55*, 598−605.

S0002-7863(96)02868-5 CCC: $14.00

Scheme 2

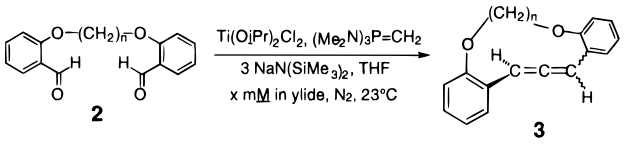


Table 1. Isolated Yields (with respect to ylide) of Macrocyclic Allenes **2** from Dialdehydes **1**

			% yield vs ylide concentration	
n	allene	ring size	5.0 mM	1.41 mM
2	3a	11	25	45
4	3b	13	32	80
5	3c	14	34	85
6	3d	15	34	90
8	3e	17	44	87,[a] 87,[b] 40,[c] 70[d]
10	3f	19	27	20,[a] 40,[b] 0[c]

[a] Using $NaN(SiMe_3)_2$. [b] Using $KN(SiMe_3)_2$. [c] Using $KN(SiMe_3)_2$ and 18-crown-6. [d] Using $NaN(SiMe_3)_2$ and 18-crown-6.

attempts involving reductive coupling, but some Wittig chemistry has been employed.[20−23] The yields for these reactions may be quite good (40−70% for 13- to 15-membered rings), but the use of both high dilution (ca. 1 mM) and slow addition techniques is required.

The double olefination methodology used here is a variation of the simple, "one-pot" allene condensation procedure first reported.[1] Later work[4] has identified the active reagent as a combination of the titanium-substituted ylide species $(Me_2N)_3P{=}C(H)TiCl(OiPr)_2$ (**1**) and the hindered base $NaN(SiMe_3)_2$. The reactions are performed at room temperature under an inert atmosphere without concern for slow addition. Thus, macrocyclic allenes are obtained in one step from convenient starting materials, avoiding the multistep procedures that characterize most allene syntheses.[24−28]

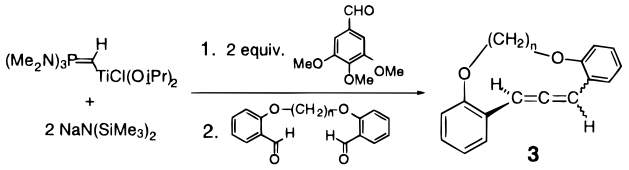
Results and Discussion

To explore the conformational and entropic requirements of the ring-closure process, the alkyl-tethered *ortho*-salicylaldehyde derivatives **2** were prepared by standard methods. As shown in Scheme 2, treatment of a dilute solution of freshly-prepared Ti-substituted ylide **1** and $NaN(SiMe_3)_2$ in THF with a solution of each dialdehyde, followed by extractive workup and column chromatography, provides macrocyclic allenes **3** in yields shown in Table 1. The yields are remarkably high for 13- to 17-membered-ring sizes, especially since the *n*-alkyl tether is highly flexible. Yields are lower for the 11-membered- and 19-membered-ring allenes, presumably due to torsional strain in the former product and entropic barriers to cyclization in the latter case.

Several important aspects of the process are noted below.

(1) Since the titanated ylide has been found to decompose within 1 h at room temperature to methylphosphonium salt, no benefit can be derived from slow addition of the dialdehyde.[29] Fortunately, yields improve dramatically upon dilution of the reaction mixture from 5.0 mM in ylide to 1.4 mM, especially for intermediate chain lengths (Table 1).

Scheme 3



(2) A standard procedure based on the intermolecular variation of the process[1] was employed for reactions summarized in Table 1, involving the addition of 4 molar equiv of the dialdehyde to the phosphorus ylide solution. The excess dialdehyde is easily recovered from the reaction mixture by column chromatography. Alternatively, 2 equiv of a monoaldehyde may be introduced initially, followed immediately by 1.5 molar equiv of the desired dialdehyde substrate (all relative concentrations are noted with respect to starting methylide; Scheme 3). The only allenes observed in such cases derive from the dialdehyde precursors, consistent with similar observations made for intermolecular condensation reactions.[1,3] The origin of this selective incorporation of the third and fourth aldehyde equivalents introduced into the reaction mixture has been described in detail elsewhere.[30] Yields of cyclic allenes obtained by this alternative procedure are generally 10−20% lower with respect to ylide than for reactions shown in Table 1,[31] but are obviously more efficient with respect to dialdehyde if unreacted starting material is not recovered.

(3) In general, macrocyclic allenes are the only organic products observed; no dimeric or oligomeric compounds are detected even from reactions done at 5 mM ylide. The presence of substantial quantities of vinylphosphonium salts, produced as stable intermediates (see below), is ruled out by treatment of the aqueous phase obtained from workup of the reaction mixtures with $NaBPh_4$, which we have found in other studies to be an effective precipitating agent for alkyl- and vinylphosphonium salts of this kind. No such compounds were obtained.

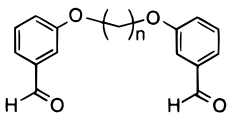
The ring closure reaction proved to be much more sensitive to the aromatic substitution pattern than to the length of the alkyl tether. In contrast to substrates **2**, *meta*-substituted dialdehydes **4a**−**d** under identical conditions afforded little (<10%) allene at 5 mM ylide and no allene at 1.41 mM, demonstrating that the conformational bias toward cyclization provided by an *ortho* aromatic substitution pattern is required for high yields. Surprisingly, allenes derived from intermolecular aldehyde coupling were not detected, even at fairly high concentrations, and macrocyclic allene yields were not increased for substrates **4** at reduced concentration. Therefore, it appears likely that decomposition of a reaction intermediate occurs in preference to dialdehyde cross coupling. An exception

(20) McMurry, J. E. *Acc. Chem. Res.* **1983**, *16*, 405−411.
(21) Becker, K. B. *Tetrahedron* **1980**, *36*, 1717−1745.
(22) Nicolaou, K. C.; Seitz, S. P.; Pavia, M. R.; Petasis, N. A. *J. Org. Chem.* **1979**, *44*, 4011−4013.
(23) Vollhardt, K. P. C. *Synthesis* **1975**, *0*, 765−780.
(24) Schuster, H. F.; Coppola, G. M. *Allenes in Organic Synthesis*; John Wiley & Sons: New York, 1984.
(25) Patai, S., Ed. *The Chemistry of Ketenes, Allenes, and Related Compounds, Parts 1 and 2*; Wiley-Interscience: Chichester, 1980.
(26) Pasto, D. J. *Tetrahedron* **1984**, *40*, 2805−2827.
(27) Marshall, J. A.; Wang, X. *J. Org. Chem.* **1992**, *57*, 3387−3396.
(28) Okamura, W. H.; Aurrecoechea, J. M.; Gibbs, R. A.; Norman, A. W. *J. Org. Chem.* **1989**, *54*, 4072−4083.

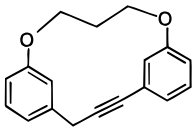
(29) It does not prove to be advantageous to drop the temperature of one-pot double olefination reactions.[3] We have proposed that this is due to an unfortunate decrease in the rate of an important deprotonation process that must be fast in order to effectively compete with a decomposition pathway.[4]

(30) Briefly, this effect arises from the complexation of aromatic aldehydes by the two excess equivalents of $NaN(SiMe_3)_2$ present in the titanated ylide mixture. The resulting α-amino alkoxide adducts provide necessary basicity but remove those aldehyde equivalents from the olefination process. See ref 3 for a complete discussion.

(31) For example, allene **3d** is isolated in 75−85% yield if 2 equiv of 3,4,5-trimethoxybenzaldehyde are added to the Ti-substituted ylide mixture (1.41 mM), followed by 1.5 equiv of dialdehyde **2d**. Allene **3c** is obtained in 78% yield, **3e** in 65% yield, and **9** in 49% yield (at room temperature) by this method. The choice of "blocking" monoaldehyde may be made to facilitate chromatographic separation.



4a n = 3 **4c** n = 8
4b n = 5 **4d** n = 10



5

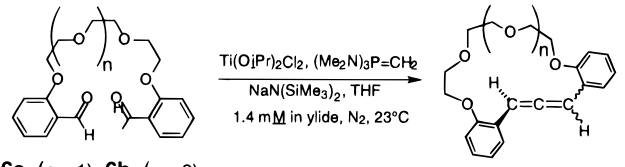
is dialdehyde **4a** ($n = 3$), which gave a 33% yield of the cyclized alkyne **5**, instead of the expected allene. It is possible that the alkyne arises from an intermediate allene by base-induced isomerization, driven by a release of ring strain. This may be compared to the case of the corresponding *ortho*-substituted dialdehyde **3a** ($n = 2$), which was converted to the cyclic allene with no indication of the alkyne isomer.

A possible explanation for the high yields of cyclic allenes from dialdehydes **2** and the absence of dimeric or oligomeric byproducts is a preorganization of the substrate or intermediate about the Lewis acidic cation of the bis(trimethylsilyl)amide base. A similar type of template effect has been described in macrolactonizations[14] and is a mainstay of crown ether synthesis. In that event, the reaction outcome should depend upon the identity of the cation. Indeed, when the cyclization of dialdehyde **2f** is conducted in the presence of $KN(SiMe_3)_2$ instead of the usual $NaN(SiMe_3)_2$, the yield of allene **3f** increases from 20% to 40% (Table 1). In contrast, standard intermolecular allene condensations are either unaffected or less efficient when $KN(SiMe_3)_2$ is employed.[1,3] Furthermore, no cyclic allene is formed from **2f** if $KN(SiMe_3)_2$ is used in the presence of an equimolar amount of the potassium-selective complexing agent 18-crown-6. A similar effect is observed for the better substrate **2e**, which is converted to allene in 87% yield using either $NaN(SiMe_3)_2$ or $KN(SiMe_3)_2$, 70% yield when the crown ether is added to the sodium-containing reaction, but only 40% when the crown ether is used in the presence of $KN(SiMe_3)_2$.

The reaction scope also extends to polyether-tethered dialdehydes **6a**,**b**, which give cyclic polyethers **7a**,**b** of comparable ring size to the hydrocarbons **3** (Scheme 4). An upper limit to the tether length was reached with **6c**, which could not be converted to the corresponding 23-membered cyclic allene. The allenes **7a** and **7b** do not function as crown ethers toward potassium ion when tested in a standard extractive assay.[32]

Lastly, the influence of a chiral moiety in the tether unit was tested by examining the ring closure of binaphthyl dialdehyde **8**, which afforded allene **9** in 79% yield at room temperature (Scheme 5). A diastereomer ratio of 5:1 was measured by both integration of the ^{1}H NMR peaks of the allenic C−H units [6.35 (minor) and 6.05 ppm (major)] and the ^{13}C NMR signals of the central allene carbons [211.2 (minor) and 210.5 ppm (major)]. When the condensation reaction is performed at 0 °C, the diastereomeric ratio is improved to 10:1, although total yield is diminished (35%). A small amount of the pure major diastereomer as a THF solvate was isolated by repeated column chromatography of **9**, prepared from enantiomerically pure (+)-(*R*)-**8**, followed by recrystallization from THF/heptane. The optical rotation of this compound was found to be $[\alpha]_D^{23}$ +411° ($c = 0.180$, dry THF), and its absolute configuration was established by X-ray crystallography as the (*R*)-binaphthyl-(*S*)-allene structure, as shown in Figure 1 and Table 2. This is consistent with the observed optical rotation, assuming that the large value characteristic of 1,3-diarylallenes ($[\alpha]_D^{25} \geq +459°$ for 1,3-diphenylallene)[33] overcomes the chiroptical contribution of the binaphthyl unit, and that the absolute configuration correlation of a (+)-rotation with the (*S*)-allene enantiomer,

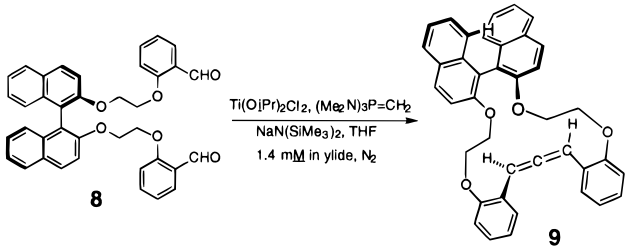
Scheme 4



6a (n = 1), **6b** (n = 2)
6c (n = 3)

	n	ring size	yield
7a	1	17	67%
7b	2	20	23%

Scheme 5



8 **9**

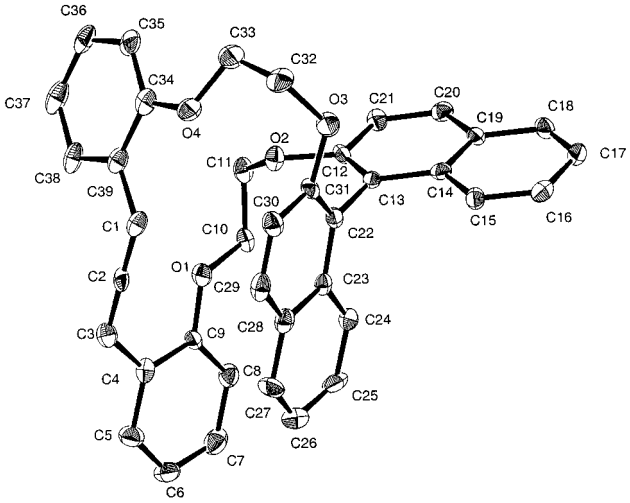


Figure 1. ORTEP drawing of the solid state structure of **9** showing 30% probability ellipsoids with atom numbering scheme. H atoms are omitted for clarity. Pertinent dihedral angles: C2−C1−C39−C38 9.2(7)°, C2−C3−C4−C9 −15.5(8)°; C12−C13−C22n-C31 −96.6(5)°; C39−C1−C3−C4 91.6°.

Table 2

empirical formula	$C_{43}H_{38}O_5$
formula weight	634.77
crystal color and habit	colorless block
crystal system	monoclinic
lattice parameters	$a = 8.572(2)$ Å
	$b = 13.050(4)$ Å
	$c = 14.752(5)$ Å
	$\beta = 93.94(2)°$
	$V = 1646(2)$ Å^3
space group	$P2_1$ (No. 4)
Z	2
residuals R; R_w	0.048; 0.061
goodness of fit	1.64

(32) Koenig, K. E.; Lein, G. M.; Stuckler, P.; Kaneda, T.; Cram, D. J. *J. Am. Chem. Soc.* **1979**, *101*, 3553−3566.

(33) Walbrick, J. M.; Wilson, J. W., Jr.; Jones, W. M. *J. Am. Chem. Soc.* **1968**, *90*, 2895−2901. In this paper, the optical rotation of 1,3-diphenylallene prepared from an enantiomerically pure cyclopropane precursor is reported as $[\alpha]_D^{25}$ +459° in hexane. Recrystallization is reported to give a compound with $[\alpha]_D^{25}$ +1020°, measured in ethanol. It is

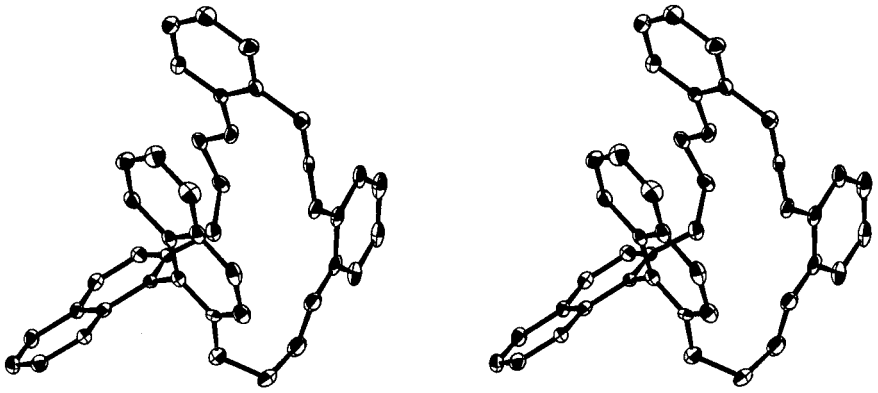
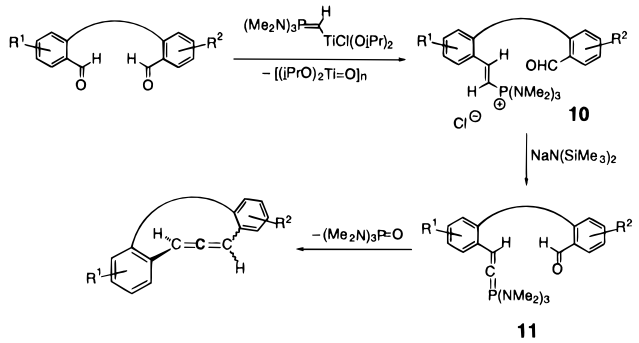


Figure 2. Stereoscopic ORTEP drawing of the solid state structure of **9**.

Scheme 6



reported for 1,3-diphenylallene and supported by theoretical studies,[34,35] is valid with respect to compound **9**.

A stereo representation of the solid-state structure of (+)-**9** is shown in Figure 2. The allene unit appears to be unstrained, with each *ortho*-substituted aromatic group aligned substantially in the sp^2-plane of its adjacent allenic carbon. This allows for overlap of the allene and aromatic π-orbitals, as is usual for these systems and expected on the basis of the optical rotation data. A cleft is formed between one naphthyl ring and the allene, which are parallel to one another, although these units do not appear to undergo a strong π-stacking interaction as judged by the appearance of coincident ^{1}H and ^{13}C resonances for the C1 and C3 positions in the NMR spectra. (The closest contact is between the hydrogen on C1 and C30, 2.63 Å.) The induction of *S*-allene stereochemistry by an *R*-binaphthyl tether supports the prediction made on the basis of the calculated energy differences between the two diastereomers. Molecular mechanics analysis[36] shows that the *R*-binol/*S*-allene diastereomer is approximately 2.0 kcal/mol lower in energy than the *R*-binol/*R*-allene diastereomer.

In conjunction with the results of a study of the intermolecular allene-forming process, the reaction mechanism is proposed to involve the conversion of dialdehyde to vinylphosphonium salt **10**, followed by deprotonation by excess base (Scheme 6). The resulting allenic phosphorane unit of **11**, if analogous to derivatives of simple benzaldehydes that we have previously examined,[4] is unstable toward decomposition at room temperature and is a competent Wittig reagent. Intramolecular condensation with the pendant aldehyde group affords the cyclic product (Scheme 6). The success of the cyclization process results from the fortunate matching of the rates of two important steps: the starting Ti-substituted ylide is rapidly consumed in the selective formation of mono-vinylphosphonium salt **10**, and then **10** is deprotonated slowly by the hindered amide base. Under these conditions, the steady-state concentration of allenic phosphorane **11** is low, thus maximizing the chances for intramolecular allene formation relative to intermolecular condensation. In effect, the reaction mechanism manages its own "slow addition" of phosphorus ylide to intramolecular aldehyde in dilute solution.

Experimental Section

General Methods. THF and hexane were purified by distillation from Na benzophenone ketyl. Ti(O*i*Pr)$_4$ was vacuum distilled and stored under nitrogen. All other reagents were purchased from commerical suppliers and used as recieved. NaN(SiMe$_3$)$_2$ was obtained either as a solid or in THF solution from Lancaster Chemical Co. or Aldrich Chemical Co. $(Me_2N)_3P{=}CH_2$ was prepared as previously described[3] from P(NMe$_2$)$_3$ and CH$_3$I; when desired, $^{13}CH_3I$ is used to provide a label at the central allene carbon. TiCl$_2$(O*i*Pr)$_2$ was prepared by mixing equimolar hexane solutions of TiCl$_4$ and Ti(O*i*Pr)$_4$. Dialdehydes were prepared by reaction of the appropriate α,ω-dibromide with 10 equiv of the appropriate salicylaldehyde and K$_2$CO$_3$ in DMF and purified by column chromatography; characterization data are reported as Supporting Information. All manipulations involving ylide species were conducted under dry nitrogen atmosphere. Reported yields are the average of at least two independent runs, with an observed variation of ±5%. The cyclic allenes reported here are unstable upon standing at room temperature in ambient light for more than 12 h but may be stored for long periods in frozen benzene solution. In spite of repeated attempts, we were unable to obtain satisfactory elemental analyses for most of the reported allenes, which by NMR spectroscopy appear to be pure. High-resolution mass spectrometry (HRMS) was performed at the Department of Chemistry and Biochemistry, University of Texas at Austin.

General Procedure for Cyclic Allene Synthesis. One equivalent of $(Me_2N)_3P{=}CH_2$ is added to 1.4 equiv of TiCl$_2$(O*i*Pr)$_2$ in 10 mL of THF. The resulting yellow-orange solution is treated immediately with 3 equiv of a THF solution of NaN(SiMe$_3$)$_2$, producing an immediate color change to red-brown. THF is added to adjust the ylide concentration to the desired value, followed immediately by the rapid addition with stirring of the dialdehyde in 1 mL of THF solution. The reaction mixture is allowed to stir at room temperature for 7−10 h, and then the solvent is removed by rotary evaporation. The residue is dissolved in CH_2Cl_2, filtered through a pad of Celite to remove insoluble titanium byproducts, and purified by column chromatography (silica gel, 7:1 light petroleum ether:CH_2Cl_2). After isolation of the allene,

not clear if the increase in optical rotation is due to an enrichment in enantiomeric purity or to the change in solvent. Later theoretical papers[34,35] show a match between calculations of optical rotation of 1,3-diphenylallene and the lower of these two experimental values.

(34) Ruch, E.; Runge, W.; Kresze, G. *Angew. Chem., Int. Ed. Engl.* **1973**, *12*, 20−25.

(35) Runge, W.; Kresze, G. *J. Am. Chem. Soc.* **1977**, *99*, 5597−5603.

(36) Geometry minimization was performed using the MM2 force field as implemented in Macromodel versions 4.0 and 4.5. Bond rotation about the binaphthyl C−C single bond was not constrained in the calculation, and so both diastereomers (composed of a single allene "epimer" and both possible binaphthyl structures) were evaluated in a single Monte Carlo conformational search of 15 000 starting structures, generating ten or more duplicates of the minimum-energy conformation of each diastereomer.

which usually comprises the least polar material in the mixture, excess aldehyde may be recovered by elution with higher concentrations of CH_2Cl_2.

3a: ^{1}H NMR ($CDCl_3$) δ 7.2 (m, 4H), 7.1 (m, 4H), 6.3 (s, 2H), 4.3 (d, J = 9.2 Hz, 2H), 4.0 (d, J = 9.2 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 212.8, 157.6, 129.9, 128.0, 127.6, 123.9, 121.0, 89.4, 73.6; IR (CH_2Cl_2) 1932; UV−vis (CH_2Cl_2, nm) 225, 260 cm^{-1}; mp 142−144 °C. Anal. Calcd for $C_{17}H_{14}O_2$: C, 81.58; H, 5.64. Found: C, 81.78; H, 6.00.

3b: ^{1}H NMR ($CDCl_3$) δ 7.7 (m, 4H), 6.9 (m, 4H), 6.5 (s, 2H), 4.1 (t, 4H), 1.4 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 211.2, 156.3, 139.1, 127.7, 125.3, 121.3 115.0, 91.3, 70.4, 26.3; IR ($CDCl_3$) 1934 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260 nm; mp 148−149 °C (sample recrystallized from CH_2Cl_2/EtOH); HRMS (chemical ionization): calcd for [M + 1] $C_{19}H_{19}O_2$, 279.1384, obsd 279.1385.

3c: ^{1}H NMR ($CDCl_3$) δ 7.24 (d, J = 7.7 Hz, 2H), 7.1 (t, J = 6.2 Hz, 2H), 6.9 (m, 4H), 6.6 (s, 2H), 4.2 (m, 2H), 3.9 (m, 2H), 1.8 (m, 2H), 1.7 (m, 2H), 1.6 (m, 2H); ^{13}C NMR ($CDCl_3$) δ 210.1, 157.0, 129.4, 127.9, 124.2, 120.9, 113.5, 91.2, 68.9, 28.5, 22.3; IR (CH_2Cl_2) 1945 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260, 295 nm; mp 136−138 °C (sample recrystallized from CH_2Cl_2/EtOH); HRMS (chemical ionization): calcd for [M + 1] $C_{20}H_{21}O_2$ 293.1540, obsd 293.1536.

3d: ^{1}H NMR ($CDCl_3$) δ 7.3 (m, 6H), 6.9 (m, 2H), 6.6 (2, 2H), 4.1 (m, 4H), 1.8 (m, 4H), 1.5 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 209.4, 129.3, 127.5, 125.2, 120.7, 113.1, 90.4, 63.5, 29.2, 27.2, 21.9; IR ($CDCl_3$) 2921, 2867, 1942 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260 nm; mp 111−112 °C (sample recrystallized from CH_2Cl_2/EtOH); HRMS (chemical ionization): calcd for [M + 1] $C_{21}H_{23}O_2$ 307.1697, obsd 307.1697.

3e: ^{1}H NMR ($CDCl_3$) δ 7.1 (m, 8H), 6.7 (s, 2H), 4.1 (t, J = 11.4 Hz, 4H), 1.5 (m, 12H); ^{13}C NMR ($CDCl_3$) δ 210.3, 155.8, 128.9, 127.6, 122.9, 120.2, 111.6, 91.1, 68.2, 29.0 28.9, 25.8; IR ($CDCl_3$) 1943 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260, 310 nm; isolated as an oil; HRMS: calcd for $C_{23}H_{26}O_2$ 334.1931, obsd 334.1916.

3f: ^{1}H NMR ($CDCl_3$) δ 7.1 (m, 8H), 6.7 (s, 2H) 4.0 (m, 4H); 1.1 (m, 16H); ^{13}C NMR ($CDCl_3$) δ 211.4, 156.7, 129.6, 128.2, 123.4, 120.6, 114.6, 111.5, 91.6, 67.5, 29.2, 27.5, 26.6, 25.6; IR ($CDCl_3$) 1960 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260, 310 nm; mp 84−85 °C (sample recrystallized from CH_2Cl_2/EtOH); HRMS (chemical ionization): calcd for [M + 1] $C_{25}H_{31}O_2$ 363.2322, obsd 363.2310.

5: ^{1}H NMR ($CDCl_3$) δ 7.3 (m, 6H), 7.01 (m, 2H), 4.5 (t, J = 5.4 Hz, 2H), 4.4 (t, J = 5.4 Hz, 2H), 3.8 (s, 2H), 2.3 (p, J = 5.4 Hz, 2H); ^{13}C NMR ($CDCl_3$) δ 132.4, 130.4, 129.5, 128.4, 126.5, 123.4, 121.9, 121.4, 121.1, 120.2, 115.7, 95.3, 90.5, 70.6, 68.3, 65.0, 29.6, 23.9; IR ($CDCl_3$) 3053, 2879, 1936, 1599 cm^{-1}. HRMS (chemical ionization): calcd for [M] $C_{18}H_{16}O_2$, 264.1150, obsd 264.1145.

7a: ^{1}H NMR ($CDCl_3$) δ 7.3 (dd, J = 7.7, 1.5 Hz, 2H), 7.2 (dt, J = 8.1, 1.8 Hz, 2H), 6.9 (t, J = 7.3 Hz, 2H), 6.8 (d, J = 8.1 Hz, 2H), 6.8 (s, 2H), 3.8 (m, 12H), 1.2 (s, 4H); ^{13}C NMR ($CDCl_3$) δ 211.0, 158.0, 129.1, 127.7, 120.8, 112.1, 91.1, 71.2, 69.6, 68.1; IR ($CDCl_3$) 1938 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260, 300 nm; HRMS (chemical ionization): calcd for [M + 1] $C_{21}H_{23}O_4$ 339.1595, obsd 339.1596.

7b: ^{1}H NMR ($CDCl_3$) δ 7.4 (d, J = 7.5 Hz, 2H), 7.2 (t, J = 6.9 Hz, 2H), 6.9 (m, 4H), 6.8 (s, 2H), 4.3 (m, 4H), 4.1 (m, 4H), 3.8 (m, 4H), 3.7 (s, 4H); ^{13}C NMR ($CDCl_3$) δ 211.2, 156.5, 129.5, 128.2, 123.9, 121.3, 112.4, 91.7, 71.6, 71.1, 69.9, 68.7; IR ($CDCl_3$) 1940 cm^{-1}; UV−vis (CH_2Cl_2) 225, 260, 300 nm; isolated as an oil; HRMS (chemical ionization): calcd for [M + 1] $C_{23}H_{27}O_5$ 383.1856, obsd 383.1851.

For **9**, the major diasteromer may be purified by column chromatography or by recrystallization by diffusion of heptane into a THF solution of the allene. Characterization data (major diastereomer): ^{1}H NMR ($CDCl_3$) δ 7.9 (d, J = 8.8 Hz, 2H), 7.8 (d, J = 8.1 Hz, 2H), 7.4 (d, J = 9.2 Hz, 2H), 7.2, (m, 3H), 7.7 (m, 3H), 6.8 (t, J = 6.6 Hz, 2H), 6.5 (d, J = 8.1 Hz, 2H), 6.1 (s, 2H), 4.1 (m, 4H), 3.9 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 210.7, 155.8, 154.0, 134.1, 129.4, 128.6, 127.6, 127.3, 126.1, 125.0, 123.5, 123.4, 121.2, 120.4, 116.1, 111.3, 90.5, 68.0, 67.2; UV−vis (MeOH) 204, 228; UV−vis (CH_2Cl_2) 206 ($\epsilon = 7.3 \times 10^4$), 230 ($\epsilon = 9.9 \times 10^4$), 262 (shoulder, $\epsilon = 2.2 \times 10^4$), 294 (shoulder, $\epsilon = 1.3 \times 10^4$), 334 (shoulder, $\epsilon = 3.8 \times 10^3$); HRMS: calcd for $C_{39}H_{30}O_4$ 562.2142, obsd 562.2128. Optical rotation was measured on the same sample of the pure major diastereomer used for crystallographic analysis, $[\alpha]^{23}_D$ +411° (c = 0.180, dry THF), and for a 2.35:1 ratio of diastereomers, $[\alpha]^{23}_D$ +206° (c = 12.9, THF). The minor diastereomer shows an analogous set of ^{1}H NMR peaks, with the greatest differences being the appearance of the allenic C−H at 6.3 ppm (vs 6.1 ppm), and a doublet at 6.7 (J = 8.1 Hz, 2H; vs 6.5 ppm).[37]

X-ray Crystallography. X-ray measurements were carried out on a Rigaku AFC6S diffractometer using Mo Kα radiation (λ = 0.71069 Å). Calculations were performed on a VAXstation 3500 computer using the TEXSAN 5.0 software[38] and in the later stages on a Silicon Graphics Personal Iris 4D35 computer with the teXsan 1.7 package.[39] Relevant crystallographic data are listed in Table 2. Unit cell dimensions were determined by applying the setting angles of 25 high-angle reflections. Three standard reflections were monitored during the data collection showing no significant variance. The structure was solved by direct methods in SIR88.[40] Full-matrix least-squares refinement with anisotropic displacement parameters for all non-hydrogen atoms yielded the final R of 0.048 (R_w = 0.061). All hydrogen atoms were found in difference Fourier maps and included in calculations without further refinement. The final difference map was essentially featureless with the highest peak of 0.2 e/A^3. The results of the refinement are presented in Table 2.

Acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this research (27397-AC1). Support from the National Science Foundation (CHE 93-13746) and Cambridge Isotope Laboratories (for a generous grant of $^{13}CH_3I$ through the CIL Research Grant Program) is gratefully acknowledged. We thank Dr. Michal Sabat for X-ray crystallography of allene **9**.

Supporting Information Available: Characterization data for dialdehydes **2**, **6**, and **8**, and X-ray crystal structure data for allene **9** (11 pages). See any current masthead page for ordering and Internet access instructions.

JA962868O

(37) From the value obtained for the pure diastereomer, one would expect an optical rotation of approximately 166° for a 2.35:1 diastereomeric mixture, if the allene moiety was the sole contributor. A comparison with the observed value shows that the contribution of the binaphthyl fragment is of similar magnitude to the optical rotation of the binaphthyl dialdehyde precursor **8**, as expected. Circular dichroism (THF, 5.78 μM) of the pure major diastereomer showed a negative Cotton effect, with extrema at 225 ($\Delta\epsilon$ = 18.9 mdeg) and 237 nm ($\Delta\epsilon$ = −22.8 mdeg), matching that of the binaphthyl aldehyde **8**. The CD spectra of diarylallenes have been shown to strongly resemble those of binaphthyls in this frequency range [Mason, S. F.; Vane, G. W. *Tetrahedron Lett.* **1965**, 1593−1597]. In addition, a region of negative $\Delta\epsilon$ extends from 250 to 266 nm ($\Delta\epsilon$ = ca. 5−8 mdeg) that is not exhibited by compound **8**.

(38) TEXSAN 5.0: Single Crystal Structure Analysis Software. Molecular Structure Corp.: The Woodlands, TX 77381, 1989.

(39) teXsan 1.7: Single Crystal Sructure Analysis Software. Molecular Structure Corp.: The Woodlands, TX 77381, 1995.

(40) Burla, M. C.; Camalli, M.; Cascarano, G.; Giacovazzo, C.; Polidori, G.; Spagna, R.; Viterbo, D. *J. Appl. Crystallogr.* **1989**, *22*, 389.