Mechanism of Lithium Perchlorate/Diethyl Ether-Catalyzed Rearrangement of α- and *β-endo*- and *-exo*-Dicyclopentadienyl Vinyl Ethers: Use of Deuterium Labeling and a Chiral Probe

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Lithium perchlorate/diethyl ether (LPDE) mediated rearrangement of α- and *β-endo*-dicyclopentadienyl vinyl ethers **5** and **6** resulted in the formation of the aldehyde **8**, indicating that the mechanism is nonconcerted and the recombination of the ion pair occurs at the dissociated stage and not the intimate ion-pair stage. Proof of this came from deuterium-labeling studies and the use of an optically pure starting material. Furthermore, that the ionic intermediate formed must be symmetrical resulting in enantiomeric aldehydes from both normal and allylic attack corresponding to products of formal 1,3 and 3,3 shifts was seen in the chiral analysis of the benzoate derivative of the aldehydes formed from the optically pure vinyl ether.

Introduction

The stereochemical and regiochemical control of carbon−carbon bond formation offered by the Claisen rearrangement[1] has made this sigmatropic rearrangement a powerful synthetic tool. Many variations[2] of this fundamental reaction have been developed to include heteroatoms, lower temperature conditions, and better stereochemical control in the bond-forming step. We wanted to exploit the Claisen rearrangement methodolgy for the stereospecific generation of new chiral centers in the synthesis of linear triquinanes. Linear triquinanes are an important class of sesquiterpene natural products possessing the fused *cis-anti-cis*-[6.3.0.$0^{2,6}$]undecane carbon skeleton. Some of these compounds have antitumor and antibiotic properties[3] and hence there are many reports on their synthesis.[4]

As one of our approaches to synthesize the linear triquinane frameworks, *cis-anti-cis*-**1** and *cis-syn-cis*-**2** (Figure 1), we sought to use the literature known *endo*-tricyclo[5.2.1.$0^{2,6}$]deca-4,8-dien-*endo*-3-ol, and *endo*-tricyclo[5.2.1.$0^{2,6}$]deca-4,8-dien-*exo*-3-ol (henceforth referred to as 1α and 1*β*-dicyclopentadienols) **3** and **4**,[5a] respectively, as the starting materials. Even though

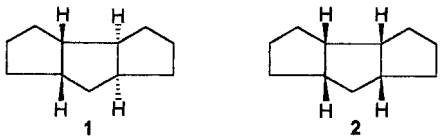

Figure 1.

many approaches have been described in the literature for triquinane systems, the attractive template motif offered by the epimeric endodicyclopentadien-1-ols has not been exploited very much except for two reports.[6]

By retaining the two syn fused cyclopentane rings of the endodicyclopentadienol and by making use of the Claisen rearrangement or one of its variants, the third cyclopentane ring could be annulated in a stereocontrolled manner (Scheme 1).

Oxidative cleavage of the norbornene double bond in the final stage would release the assembly of triquinane with useful functionality for further elaboration. This approach can also be extended to the dihydro-*endo*-dicyclopentadienol and *exo*-dicyclopentadienol since these substrates are readily obtained from *endo*-dicyclopentadiene.[7] Claisen rearrangement of 1α and 1*β endo*-dicyclopentadienyl vinyl ethers **5** and **6**, respectively, has not been reported. Hence, it was important to study the thermal behavior of these ethers, which on Claisen rearrangement should give rise to the respective *γ,δ*-unsaturated aldehydes with retention of stereochemistry. It turned out that while 1*β*-vinyl ether **6** underwent a thermal 3,3-sigmatropic Claisen rearrangement to furnish aldehyde **8**, the thermal behavior of 1α-vinyl ether **5** took a different course, viz. a 3,3-sigmatropic Cope rearrangement to give the *anti*-vinyl ether **7** (Scheme 2).

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(1) Claisen, L. *Ber.* **1912**, *45*, 3157. Wipf, P. In *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Paquette, L. A., Eds.; Pergamon Press: Oxford, 1991; Vol. V, pp 827.

(2) Carroll, M. F. *J. Chem. Soc.* **1940**, 704; **1940**, 1266; **1941**, 507. Kinel, W.; Cope, A. C. *J. Am. Chem. Soc.* **1943**, *65*, 1992. Wick, A. E.; Felix, D.; Schwend, K. G.; Steen, K.; Eischen Moscher, A. *Helv. Chim. Acta* **1969**, *52*, 1030. Ireland, R. E.; Mueller, R. H.; Willard, A. K. *J. Am. Chem. Soc.* **1976**, *98*, 2868. Denmark, S. E.; Harmat, M. A. *Tetrahedron Lett.* **1984**, *25*, 1543.

(3) Paquette, L. A. The Development of Polyquinane Chemistry. *Topics in Current Chemistry*; Springer-Verlag: Berlin, 1979.

(4) Paquette, L. A.; Doherty, A. M. *Polyquinane Chemistry: Synthesis and Reactions*; Springer-Verlag: Berlin, 1989. Hudlicky, T.; Sinai-Zingde, G.; Natchus, M. G.; Ranu, B. C.; Papadapolous, P. *Tetrahedron* **1987**, *45*, 5685 and references therein under hirsutene, capnellene, and coriolin.

(5) (a) See Woodward, R. B.; Katz, T. J. *Tetrahedron* **1959**, *5*, 70 for a reversal in the nomenclature. (b) Suri, S. C. *Tetrahedron Lett.* **1988**, *29*, 4031.

(6) Dawson, B. A.; Gosh, A. K.; Jurlina, J. C.; Stothers, J. R. *J. Chem. Soc., Chem. Commun.* **1983**, 204. Ito, T.; Tomiyoshi, N.; Nakamura, K.; Ajuma, S.; Izewa, M.; Maruyama, F.; Yanagiya, M.; Shirahama, H.; Matsumoto, T. *Tetrahedron Lett.* **1982**, 1721.

(7) (a) Nelson, G. L.; Chaiw-Liangkuo, K. *Synthesis* **1975**, 105. (b) Fiaud, J. C.; Legros J. Y. *J. Org. Chem.* **1987**, *52*, 1907. Also see ref 13. (c) Brown, C. A.; Ahuja, V. K. *J. Org. Chem.* **1973**, *38*, 2226. Brown, C. A.; Ahuja, V. K. *J. Chem. Soc., Chem. Commun.* **1973**, 553. Brown, C. A.; Ahuja, V. K. *J. Am. Chem. Soc.* **1963**, *85*, 1003.

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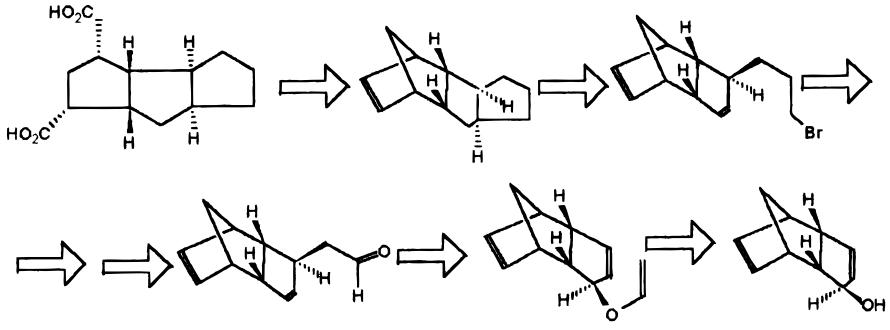
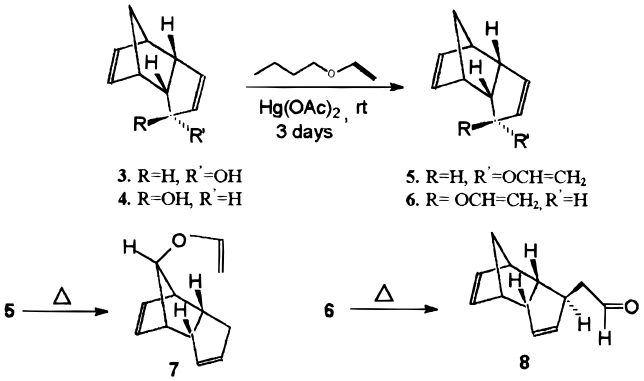
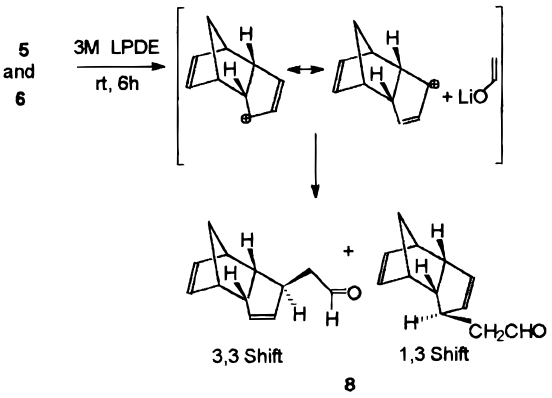
Scheme 1



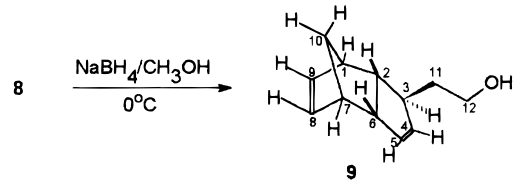
Scheme 2



Scheme 3



Scheme 4



In this context, the work of Grieco et al.[8] on LPDE-mediated 1,3-sigmatropic rearrangement of allyl vinyl ethers led us to investigate the behavior of the epimeric ethers **5** and **6** in LPDE medium. Both **5** and **6** in LPDE gave the aldehyde **8**. The Claisen substrates that have been studied in LPDE medium so far are disubstituted at the γ-carbon of the allyl moiety.[8] To avoid the steric crowding at the γ-carbon, the recombination of ions is preferentially directed to the less crowded α-carbon resulting in the formation of product of formal 1,3-shift.

In the vinyl ether substrates **5** and **6**, however, there is no substituent on the γ-carbon making the two ends of the allyl π-system indistinguishable; these ethers therefore appeared to be the right candidates to get more insight into the mechanism of the LPDE-mediated 1,3-Claisen rearrangement. It was not possible to differentiate between the nonconcerted 1,3 and 3,3 processes from the products since the molecules under study are racemic and the structures of the products are indistinguishable. The ionic intermediates involved in the nonconcerted process are symmetrical. Hence, the nonconcerted 1,3 shift could not be differentiated from the nonconcerted 3,3 shift on the basis of the resulting product (Scheme 3).

This problem can be overcome by resorting to one of the following techniques: (i) cross-over experiments, (ii) using a deuterium labeled substrate, and (iii) a chiral probe, i.e., an optically active vinyl ether. The cross-over experiments have been successfully employed by Grieco et al.[8] We have used deuterium labeling and a chiral probe to ascertain which of the two allylic carbon atoms is involved in the recombination of the enolate ion and the carbocation formed. This approach has not been reported previously. This paper reports the results of our study.

(8) Grieco, P. A.; Clark, J. D.; Jague, C. T. *J. Am. Chem. Soc.* **1991**, *113*, 5488.

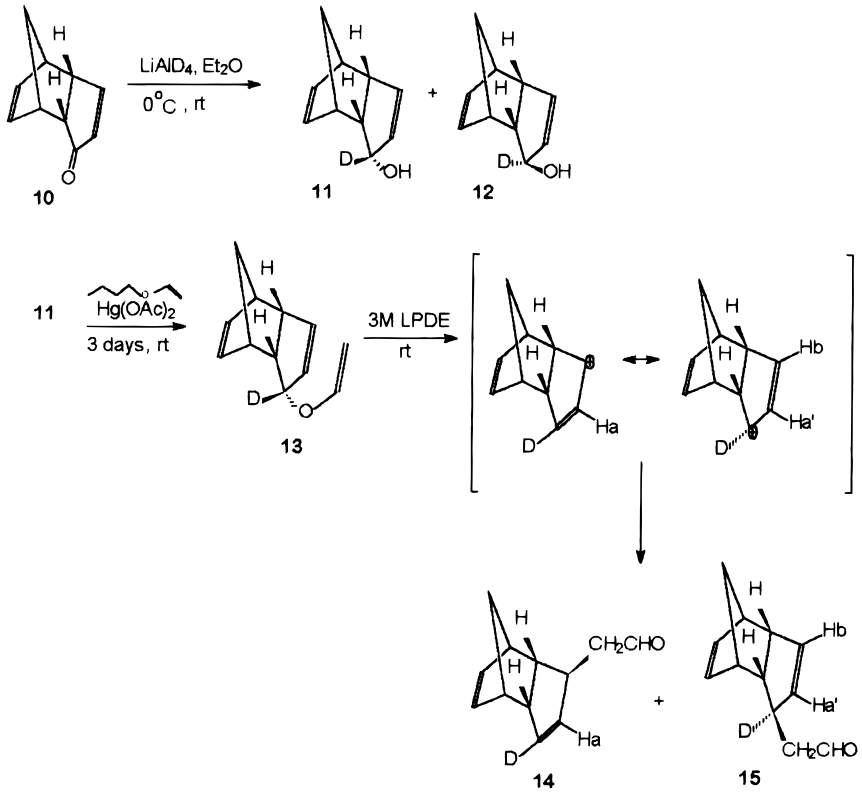
Results and Discussion

When racemic 1α vinyl ether **5** was treated with 3 M LPDE at rt, it furnished the aldehyde **8** in 55% yield. This product was found to be identical in all respects with that obtained from the thermal Claisen rearrangement of racemic 1β-vinyl ether **6**. Under the above LPDE conditions, the racemic 1β-vinyl ether **6** furnished a single aldehydic product that was also found to be identical in all respects with **8** (Scheme 3). The structure of the aldehyde was based on its spectroscopic data and its 2,4-DNP derivative. The configuration of its acetaldehyde chain was based on literature reports on the supra-supra migration in the thermal Claisen rearrangement. This was confirmed by NOE experiments on the alcohol **9** (Scheme 4).

When the signal due to H_6 at δ 3.2 was irradiated, there was enhancement in intensity of the signals at δ 2.7 (H_7), 2.3 (H_2), and 1.2 (H_{10}), showing that these are on the same side. Intensity for the signal due to H_3 did not increase. Upon irradiation of the signal at δ 2.3, the intensity of the signals at δ 1.2 (H_{10}), 1.5 (H_{11}), 2.85 (H_1), and 3.2 (H_6) was enhanced, and the enhancement seen for H_3 was marginal, showing that H_3 is not on the same side as H_2.

Since both α- as well as β-vinyl ethers yield the same product, viz. **8** (with inversion of configuration) in LPDE, it is evident that **5** and **6** undergo prior ionization

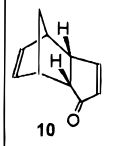
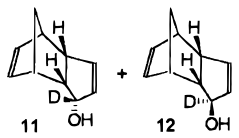
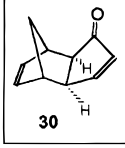
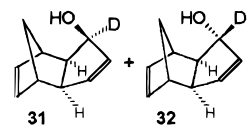
Scheme 5



followed by attack of the lithium enolate from the less hindered face of the allyl cation as envisaged in Scheme 3. While the nonconcerted nature of these transformations is clearly evident, these findings do not provide any insight into the question as to whether the recombination of the ion pair occurs at the intimate ion-pair stage or at the dissociated stage. Ion-pair recombination at the intimate ion pair stage giving rise to attack at the allylic end from the opposite face of the allyl P system is geometrically precluded, while attack from the same side can lead to ipso substitution with inversion or retention of stereochemistry. Recombination of ion pair after complete dissociation can lead to both attacks, viz. ipso and allylic from the opposite face of the P system, which is less hindered. From the products obtained, it is not possible to discern the actual mechanism of this transformation. The question of which of the two allylic carbon atoms is involved in the recombination step was answered by the following two experimental approaches:

(i) Deuterium-Labeling Experiment.[9] In previously reported examples, the γ-carbon of the allyl moiety of the allyl vinyl ether is disubstituted, making it obvious from the structure whether the product is due to formal 1,3 or 3,3 shift. In the case of **5** and **6**, the γ-carbon of the allylic framework is not disubstituted and the dicyclopentadienyl vinyl ethers used for this study are racemic. The deuterated 1α- and 1β-*endo*-cyclopentadienol compounds were prepared from their corresponding ketones and converted to the vinyl ethers, which on treatment with LPDE gave the aldehydes (Scheme 5). Thus, *endo*-ketone **10** gave the deuterated α- and β-hydroxy compounds (9:1) **11** and **12**, respectively, on reduction with $LiAlD_4$ (Table 1). The α-alcohol **11** was used to make the β-deuterio-α-vinyl ether **13**, which on treatment with LPDE gave a mixture of the deuterated aldehydes **14** and **15**.

Table 1. $LiAlD_4$ Reduction of Endo- and Exo-dicyclopentadienones

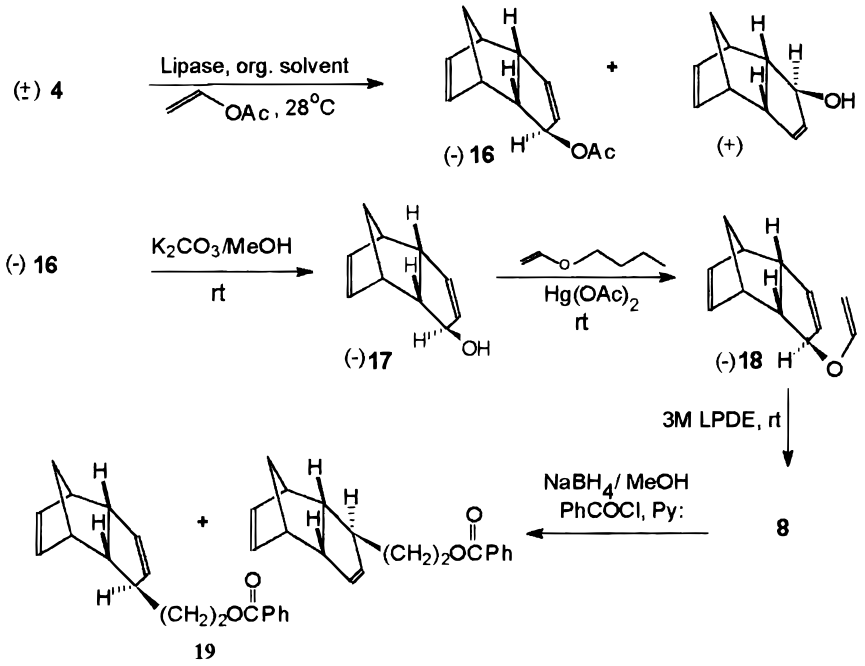
Enone	Products	Ratio	Yield
 **10**	 **11** + **12**	9:1	55
 **30**	 **31** + **32**	9:1	55

The deuterated aldehydes **14** and **15** were formed in a 1:1 ratio as inferred from the ^{1}H NMR spectrum by comparing the integration of the olefinic protons at δ 5.4 (H_a and $H_{a'}$) and δ 5.58 (H_b) of **14** and **15**, respectively. Recombination of the acetaldehyde enolate ion exclusively at the α carbon of the allyl cation should lead to **15**, whereas the recombination at the allylic end would yield only **14**. In both cases, the attack of the enolate would be from the less-hindered side, viz. β-face.

As deuterium is found to be scrambled, and **14** and **15** are formed in a ratio of 1:1, it is amply clear that the mechanism is nonconcerted and the enolate anion attacks the original α-carbon and the γ-carbon of the allyl cation with equal probability. The lack of regioselectivity in the recombination step in systems where the γ-carbon is not disubstituted as revealed by deuterium-labeling experiments is noteworthy and indicates that the ion-pair recombination does not occur at the intimate ion-pair stage.

(ii) Use of a Chiral Probe. The *endo*-dicyclopentadien-*exo*-3-ol, **4**, used in the above investigation was

Scheme 6



racemic. In light of the findings from the deuterium-labeling studies described above, the optically pure vinyl ether **18** on LPDE treatment should give racemic **8** (Scheme 6) as the intermediate allyl cation (Scheme 3) is symmetrical. This was the rationale on which the experiment was based.

The racemic 1β-dicyclopentadienol **4** was resolved by a transesterification reaction using a lipase[10] to get the (−) acetate **16** and the (+)-alcohol (Scheme 6). The optically pure alcohol **17**, $[\alpha]^{25}_D = -70.5$ (*c* 2, $CHCl_3$) [lit.[10] $[\alpha]^{25}_D = -73.9$ (*c* 0.9, $CHCl_3$)] obtained from the acetate was used for the trans etherification reaction resulting in the formation of optically active vinyl ether **18**, $[\alpha]^{25}_D = -39.6$ (*c* 2, $CHCl_3$).

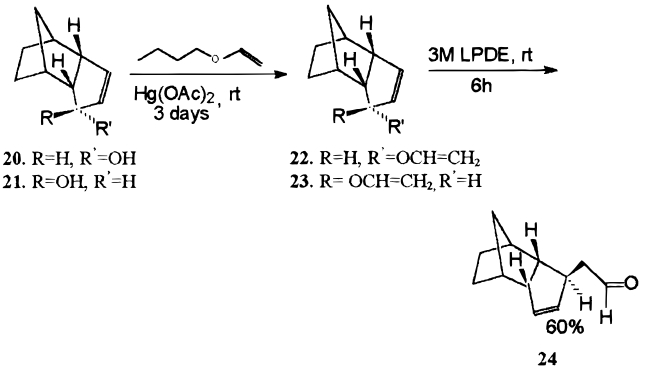
Exposure of the optically active 1β- vinyl ether **18** at rt to LPDE afforded the racemic aldehyde **8** (1:1), whose optical purity was established by chiral HPLC analysis of the benzoate derivatives **19** using a Chiracel OD column.

This establishes unequivocally that the mechanism of the LPDE-catalyzed rearrangement of these dicyclopentadienyl vinyl ethers is nonconcerted, the recombination of the ion pair does not occur at the intimate ion-pair stage, and the carbocation formed is attacked with equal probabiliy at both the α- and the γ-position.

The related compounds, racemic dihydro-*endo*-dicyclopentadienyl vinyl ethers **20** and **21** (Scheme 7), and the racemic exocyclopentadienyl vinyl ethers **25**[13] and **26** (Scheme 8) were also studied in LPDE medium.

In both the cases, i.e., the α- and β-vinyl ethers of the two series, viz. the dihydro series, **22** and **23** and the *exo*-dicyclopentadiene system, **27** and **28** afforded the corresponding single racemic aldehydic products **24** and **29**,

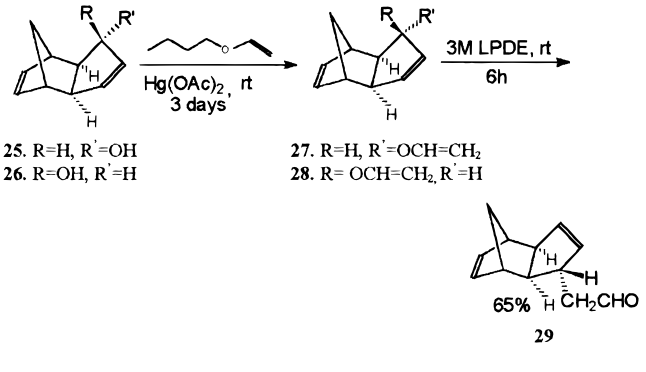
Scheme 7



20. R=H, R'=OH
21. R=OH, R'=H
22. R=H, R'=OCH=CH$_2$
23. R= OCH=CH$_2$, R'=H

24

Scheme 8



25. R=H, R'=OH
26. R=OH, R'=H
27. R=H, R'=OCH=CH$_2$
28. R= OCH=CH$_2$, R'=H

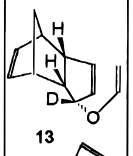
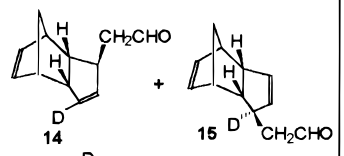
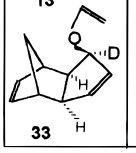
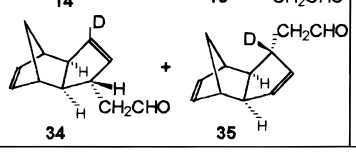
29

respectively, when treated with 3 M LPDE at room temperature.

Treatment of racemic 1α-deuterio-*exo*-dicycclopentadienyl-1β-vinyl ether **33**, prepared from the 1α-deuterio-1β-ol **31**, with LPDE furnished a mixture of the two aldehydes **34** and **35** in a 1:1 ratio (Table 2) again revealing that the recombination of the enolate anion occurs at both ends of the allylic cation in this nonconcerted process. The recombination of the ion pair occurs from the less hindered α-face.

(9) (a) Palani, N.; Balasubramanian, K. K. *Tetrahedron Lett.* **1993**, *34*, 5001. (b) Dilling, W. L.; Pilpus, R. A. *J. Org. Chem.* **1970**, *35*, 2971.
(10) Takano, S.; Inomata, K.; Takahashi, M.; Ogasawara, K. *Synlett* **1991**, 636.
(11) Reetz, M. T.; Gansauer, A. *Tetrahedron* **1993**, *49*, 6025.
(12) Palani, N. Ph.D. Thesis, IIT, Madras, India, 1996.
(13) Cookson, R. C.; Isaac, N. S.; Szelke, M. *Tetrahedron* **1964**, *20*, 714.

Table 2. LPDE Assisted Rearrangement of Deuterated Vinyl Ethers

Vinyl Ether	Products	Ratio	Yield %
 **13**	 **14** + **15**	1:1	55
 **33**	 **34** + **35**	1:1	60

Summary

1α- and 1β-vinyl ethers **5** and **6** of *endo*-dicyclopentadienol on treatment with LPDE furnished a single aldehyde **8**. The mechanism was established by (a) deuterium-labeling studies by subjecting the deuterated vinyl ether **13** to LPDE conditions (NMR of the isolated product confirmed it to be a 1:1 mixture of the aldehydes resulting from a 1,3 shift and a 3,3 shift) and (b) by the use of a chiral probe or the optically active vinyl ether **18** under LPDE conditions, which resulted in the formation of racemic aldehyde **8** as evidenced by the chiral HPLC analysis of its benzoate derivative **19**, thus proving that the enolate anion attacks the original α-carbon and the allylic-end γ-carbon with equal probability in this nonconcerted mechanism.

Similarly, the 1α- and 1β-vinyl ethers **22** and **23** of dihydro-*endo*-dicyclopentadienol gave a single aldehyde **24** as did the 1α- and 1β-vinyl ethers **27** and **28** of *exo*-dicyclopentadienol, which gave the aldehyde **29**, indicating the mechanism to be nonconcerted in all these cases. Furthermore, deuterium-labeling studies in the *exo*-dicyclopentadienol vinyl ether **33** revealed a 1:1 mixture of aldehydes on LPDE treatment **34** and **35**.

This study, for the first time, establishes the mechanism of lithium perchlorate/diethyl ether (LPDE)-catalyzed rearrangement of α- and *β-endo-* and *-exo*-dicyclopentadienyl vinyl ethers by using deuterium-labeling studies and a chiral probe as nonconcerted, and the recombination of the ion pair formed must occur at the dissociated stage and not the intimate ion-pair stage, such that the enolate ion recombines with both the α- and γ-carbons (either of the allylic carbocations) with equal probability. The remarkable difference in the behavior of the 1α ether toward thermal conditions and toward LPDE is noteworthy, the former resulting in Cope rearrangement and the latter leading to Claisen products by nonconcerted 1,3 and 3,3 shifts.

Experimental Section

^{1}H NMR spectra were recorded at 400 MHz except where indicated at 600 MHz. The ^{13}C NMR were recorded at 100.5 MHz except where indicated otherwise. The chemical shifts of all the NMR spectra are reported in parts per million relative to tetramethylsilane.

Preparation of Lithium Perchlorate. Lithium hydroxide was neutralized with 70% aqueous perchloric acid under cooling (ice bath 5−10 °C). The precipitated lithium perchlorate was filtered and air-dried. Anhydrous lithium perchlorate was made by drying the hydrated salt at 140 °C/0.1 mm for 6 h. The salt was then dissolved in dry diethyl ether to make a 3 M solution.

CAUTION:[11] Care has to be taken in drying lithium perchlorate. The thermal stability of lithium perchlorate (up to and above its melting point of 247 °C) holds only in the absence of oxidizable organic substrates. A violent explosion was reported after mixing 1 g each of cyclooctatetraene (COT) and dimethylacetylene dicarboxylate in 9.5 mL of dry ether containing 5 g of lithium perchlorate. It is likely that COT was oxidized, initiating the explosion.

General Procedure for LPDE-Assisted Rearrangements. All reactions were conducted at ambient temperature employing a 0.2 M solution of the allyl vinyl ether in 3 M LPDE. The reaction time varied from 3 to 6 h.

(a) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*endo*-3-ol, 3.[5b] This compound (1α-hydroxy-*endo*-dicyclopentadienol) was prepared as follows: To a cooled, stirred solution of the enone (1 g, 6.9 mmol) in methanol (30 mL) was added cerous chloride heptahydrate (2.5 g, 6.8 mmol), followed by $NaBH_4$ (0.25 g, 6.84 mmol). The mixture was stirred at 0 °C for 3 h, poured into crushed ice, and extracted with hexane−dichloromethane (4:1). The organic layers were combined, dried over sodium sulfate, filtered, and concentrated under reduced pressure. Flash column chromatography of the crude product gave the alcohol and its epimer (fluffy solid): yield 0.75 g; epimer, 0.1 g; mp 82 °C; IR (CCl_4, cm^{-1}) 3620, 3500, 1625,1585; ^{1}H NMR ($CDCl_3$) δ 6.2 (dd, J = 5.6, 3.3 Hz, 1H), 5.82 (dd, J = 5.6, 3.3 Hz, 1H), 5.6 (m, 2H), 4.6 (dd = t, J = 8.2 Hz, 1H), 3.3 (dd, J = 7.27, 4.5 Hz, 1H), 2.9−3 (m, 3H), 1.8 (br s, 1H), 1.58 (dt, J = 8 Hz, 1H), 1.45 (d, J = 8 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 135.23 (d), 135.15 (d), 134.65 (d), 133.41 (d), 75.88 (d), 54.02 (d), 52.55 (t), 47.00 (d), 46.86 (d), 44.69 (d); HRMS calcd 148.088 81 for $C_{10}H_{12}O$, found 148.085 51.

(b) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3-ol, 4 (1β-hydroxy-*endo*-dicyclopentadienol), was prepared according to the method described previously.[5a]

(c) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*endo*-3-yl Vinyl Ether, 5. A mixture of alcohol **3** (1 g, 67 mmol), *n*-butyl vinyl ether (5 mL), and mercuric acetate (100 mg, 0.3 mmol) was shaken well at room temperature for 3 days. The excess butyl vinyl ether was removed under reduced pressure. The pure liquid was obtained in 45% yield; IR (neat, cm^{-1}) 1635, 1620; ^{1}H NMR (C_6D_6) δ 6.32 (dd, J = 14.16, 6.35 Hz, 1H), 6.21 (dd, J = 5.37, 2.93 Hz, 1H), 5.7 (dd, J = 5.37, 2.93 Hz, 1H), 5.58 (dt, J = 5.86, 1.95 Hz, 1H), 5.4 (dt, J = 5.86, 1.95 Hz, 1H), 4.6 (d, J = 10 Hz,1H), 4.25 (dd, J = 14.16, 2.1 Hz, 1H), 4.0 (dd, J = 6.35, 2.1 Hz, 1H), 3.0 (m, 1H), 2.9 (br s, 1H), 2.55−2.7 (m, 2H), 1.5 (d, J = 8.8 Hz, 1H), 1.15 (d, J = 8.3 Hz, 1H); ^{13}C NMR (75 MHz, C_6D_6) δ 151.48 (d), 135.67 (d), 134.80 (d), 131.81 (d), 131.73 (d), 86.89 (t), 53.65 (d), 51.06 (t), 46.45 (d), 45.40 (d), 44.75 (t).

(d) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3-yl Vinyl Ether, 6. The vinyl ether **6** was prepared following the procedure adopted for the preparation of **5**. The crude material was chromatographed over basic alumina using hexane as eluent to get a pure liquid: yield 0.8 g, 68%; IR (neat, cm^{-1}) 1630, 1605; ^{1}H NMR (C_6D_6) δ 6.40 (dd, J = 14.89, 6.38 Hz, 1H), 5.8 (dd, J = 6.3, 3.1 Hz, 1H), 5.75 (dd, 1H), 5.65 (ddd = dt, J = 5.79, 3.6 Hz, 1H), 5.58 (ddd, 1H), 4.4 (dd, J = 14.89, 2.1 Hz, 1H), 4.2 (br s, 1H), 4.1 (dd, J = 6.38, 2.1 Hz, 1H), 3.2 (m, 1H), 2.8 (br s,1H), 2.7 (br s, 1H), 2.5 (m, 1H), 1.5 (dt, J = 8.2, 1.8 Hz, 1H), 1.2 (d, J = 8.2 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 150.56 (d), 139.73 (d), 135.88 (d), 132.25 (d), 131.25 (d), 88.13 (t), 85.35 (d), 54.99 (d), 51.65 (t), 50.10 (d), 45.17 (d), 44.98 (d); HRMS calcd 174.104 47 for $C_{12}H_{14}O$, found 174.104 29.

(e) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*anti*-10-yl Vinyl Ether, 7. A solution of the ether **5** (0.25 g, 1.4 mmol) in toluene (5 mL) was refluxed under nitrogen for 6 h. Toluene was evaporated under reduced pressure, and the crude product was chromatographed using a column (basic alumina, eluted with hexane) to afford the anti ether in 50% yield along with the unreacted starting material: ^{1}H NMR (C_6D_6) δ 6.2 (dd, J = 6.84, 14.16 Hz, 1H), 5.78 (ddd, J = 0.98, 3.42, 6.38 Hz, 1H), 5.73 (ddd, J = 0.98, 3.42, 6.38 Hz, 1H), 5.51 (m, 2H), 4.31 (dd, J = 1.46, 14.16 Hz, 1H), 4.01 (dd, J = 1.46, 6.84 Hz, 1H), 3.81(dd, J = 1.95 Hz, 1H), 3.53 (m, 1H), 3.01 (m, 1H), 2.77 (br m, 1H), 2.69 (br m, 1H), 2.15 (m, 1H), 1.58 (m, 1H); ^{13}C NMR

($CDCl_3$) δ 150.26 (d), 134.34 (d), 132.67 (d), 130.89 (d), 130.67 (d), 90.70 (d), 88.47 (t), 52.42 (d), 48.23 (d), 42.14 (d), 38.85 (d), 34.19 (t).

(f) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dienyl-3-*exo*-acetaldehyde, 8. The β-ether **6**, (0.31 g, 1.78 mmol) was treated with 3 M LPDE (9 mL) at room temperature under nitrogen. The contents were shaken well, and the reaction was monitored by TLC. On completion, the reaction turned yellowish green. The reaction mixture was poured into crushed ice and extracted with dichloromethane−hexane 1:4. The organic extracts were combined, washed with brine, dried over anhydrous sodium sulfate, and filtered, and the solvent was removed under reduced pressure. The crude aldehyde product was purified by flash column chromatography to yield 0.18 g (58%) of the pure aldehyde: IR (neat, cm^{-1}) 2720, 1710, 1630; ^1H NMR ($CDCl_3$) δ 9.78 (t, J = 1.47 Hz, 1H), 6.02 (dd, J = 5.86, 2.93 Hz, 1H), 5.94 (dd, J = 5.86, 2.93 Hz, 1H), 5.57 (ddd = dt, J = 5.36, 1.95 Hz, 1H), 5.42 (ddd = dt, J = 5.36, 1.95 Hz, 1H), 3.25 (m, 1H), 3.00 (br s, 1H), 2.8 (br s, 1H), 2.47 (ddd, J = 19.0, 10.25 Hz, J = 1.48 Hz, 1H), 2.41 (m, 2H), 2.31 (ddd = dt, J = 10.25, 3.91 Hz, 1H), 1.5 (ddd = dt, J = 8.3, 1.95 Hz, 1H), 1.28 (d, J = 8.3 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 202.56 (d), 135.94 (d), 134.55 (d), 133.44 (d), 132.76 (d), 54.78 (d), 50.76 (t), 50.35 (t), 49.14 (d), 45.89 (d), 45.02 (d), 42.00 (d); HRMS calcd 174.104 47 for $C_{12}H_{14}O$ found 174.106 71.

2,4-DNP derivative of 8: mp 139 °C; ^1H NMR (600 MHz, $CDCl_3$) δ 11.1 (br s, 1H), 9.13 (d, J = 2.57 Hz, 1H), 8.33 (dd, J = 9.5, 2.5 Hz, 1H), 7.9 (d, J = 9.5 Hz, 1H), 7.5 (t, J = 5.38 Hz, 1H), 6 (dd, J = 5.6, 2.9 Hz, 1H), 5.9 (dd, J = 5.6, 2.9 Hz, 1H), 5.6 (dt, J = 5.4, 2.4 Hz, 1H), 5.48 (dt, J = 5.6, 2.8 Hz, 1H), 3.3 (m, 1H), 2.9 (br s, 1H), 2.8 (br s, 1H), 2.5 (m, 3H), 2.3 (m, 1H), 1.5 (d, J = 8 Hz, 1H), 1.3 (d, J = 8 Hz, 1H); HRMS calcd 354.132 81 for $C_{18}H_{18}N_4O_4$, found 354.129 95.

(g) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3-ylethanol, 9. A mixture of the aldehyde **7** (0.1 g, 0.57 mmol), methanol (5 mL), and sodium borohydride (40 mg, 1 mmol) was stirred at 0 °C for 3 h. Excess methanol was removed, and the crude product was poured into crushed ice and extracted with ether. The organic layers were combined, dried over anhydrous sodium sulfate, concentrated, and purified by column chromatography to yield the alcohol (liquid): 80 mg, 80% yield; IR (neat, cm^{-1}) 3450, 1620, 1550; ^1H NMR ($CDCl_3$) δ 5.9 (dd, J = 5.5, 2.75 Hz, 1H), 5.87 (dd, J = 5.5, 2.75 Hz, 1H), 5.47 (dt, J = 5.5, 1.6 Hz, 1H), 5.37 (dt, J = 5.5, 1.6 Hz, 1H), 3.8 (m, 2H), 3.2 (m, 2H), 2.85 (br s, 1H), 2.7 (br s, 1H), 2.3 (m, 1H), 1.95 (m, 1H), 1.45−1.56 (m, 3H), 1.4 (dt, J = 8.4, 1.4 Hz, 1H), 1.2 (dt, J = 8.4, 1.4 Hz, 1H); ^{13}C NMR ($CDCl_3$) δ 136.08 (d), 135.88 (d), 132.95 (d), 132.53 (d), 61.73 (t), 54.76 (d), 50.42 (t), 49.13 (d), 46.217 (d), 45.03 (d), 44.64 (d), 39.84 (t).

(h) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3D-*endo*-3-ol, 11. This compound was prepared according to the reported procedure[9b] using lithium aluminum deutride in dry ether and the dienone **10**. The crude material, a mixture of *endo*-**11** and *exo*-**12**, was purified by flash chromatography to yield pure *endo*-**11** and pure *exo*-**12** in a ratio of 9:1. The yield of pure endo alcohol **11** was 55%: IR (neat, cm^{-1}) 3600, 1630; ^1H NMR ($CDCl_3$) δ 6.18 (dd, J = 5.8, 2.9 Hz, 1H), 5.8 (dd, J = 5.8, 2.9 Hz, 1H), 5.6 (m, 2H), 3.3 (dd, J = 7.5, 2.9 Hz, 1H), 2.9 (m, 2H), 1.65 (dt, J = 8.3, 1.4 Hz, 1H), 1.45 (dt, J = 8.3 Hz, 1H), 1.3 (br s, 1H); ^{13}C NMR ($CDCl_3$) δ 137.89 (d), 135.34 (d), 134.47 (d), 132.29 (d), 54.52, 53.26 (d), 51.18 (t), 44.67 (d), 44.55 (d); HRMS calcd 149.095 09 for $C_{10}H_{11}OD$, found 149.097 96.

(i) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3D-*endo*-3-yl Vinyl Ether, 13. This was prepared by the procedure given in section c above. The pure liquid was obtained in 50% yield: IR (neat, cm^{-1}) 1640, 1580; ^1H NMR (C_6D_6) δ 6.43 (dd, J = 6.35, 14.16 Hz, 1H), 6.03 (dd, J = 2.93, 5.86 Hz, 1H), 5.71 (dd, J = 2.93, 5.86 Hz, 1H), 5.66 (dd, J = 1.46, 5.86 Hz, 1H), 5.6 (dd, J = 1.46, 5.86 Hz, 1H), 4.26 (dd, J = 1.47, 14.16 Hz, 1H), 4.03 (dd, J = 1.47, 6.35 Hz, 1H), 3.28 (m, 1H), 2.98 (dd, J = 4.4, 7.82 Hz, 1H), 2.92 (br s, 1H), 2.87 (m, 1H), 1.49 (ddd = dt, J = 1.46, 8.3 Hz, 1H), 1.39 (J = 8.3 Hz, 1H); ^{13}C NMR (C_6D_6) δ 151.27 (d), 136.69 (d), 134.78 (d), 131.98 (d), 131.39 (d), 87.23 (t), 53.92 (d), 51.34 (t), 46.20 (d), 45.42 (d), 44.54 (d).

(j) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dienylacetaldehyde, 14 and 15, were prepared as reported in section f and obtained in 55% yield: ^1H NMR ($CDCl_3$) δ 9.78 (t, J = 2 Hz, 1H), 6.05 (dd, J = 5.62, 2.5 Hz, 1H), 5.9 (dd, J = 5.62, 2.5 Hz, 1H), 5.58 (dd, J = 6.25, 2.5 Hz, 1H), 5.4 (m, 2H), 3.3 (m, 1H), 3 (s, 1H), 2.8 (s, 1H), 2.2−2.5 (m, 4H), 1.5 (dt, J = 8.1, 1.4 Hz, 2H), 1.2 (d, J = 8.1 Hz, 1H).

(k) Resolution of *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3-ol, 4, To Give 16 and 17. The reported procedure[10] was followed except for minor changes. To a stirred solution of (±)-**4** (485 mg, 3.28 mmol), vinyl acetate (15 mL, 1.9 mmol), and *tert*-BuOMe (10 mL) was added lipase PS (Amano, 100 mg). Two other enzymes, porcine pancreatic lipase (PPL) and *Candida cylindracea* lipase (CCL), were also tried and found to be very slow. The suspension was stirred at 37 °C, and the conversion was monitored by GC on a 10% OV-17 column. The reaction was stopped at 50% conversion (48 h). The mixture was filtered through Celite, and the filtrate was evaporated under reduced pressure. The residue was chromatographed (silice gel, EtOAc/hexane 1:20) to give optically active (−)-acetate **16**, which was hydrolyzed to yield the optically active alcohol (−)-**17**: $[\alpha]^{25}_D = -70.5$ (*c* 2, $CHCl_3$).

(l) *endo*-Tricyclo[5.2.1.0^{2,6}]deca-4,8-dien-*exo*-3-yl Vinyl Ether, 18. This was prepared from optically active alcohol **17** by the procedure reported in section c: $[\alpha]^{25}_D = -39.6$ (*c* 2, $CHCl_3$).

(m) *endo*-Tricyclo[5.2.1.0^{2,6}]dec-4-en-*endo*-3-ol, 20.[7b] This was prepared from the corresponding dihydro enone[12] by the procedure given in section a above. The isomeric alcohols were formed in a ratio of 9:1. Flash chromatography yielded the pure solid endo alcohol **20**: 1.2 g (80%); IR (CCl_4, cm^{-1}) 3610, 3410; ^1H NMR ($CDCl_3$) δ 5.8 (dt, J = 6, 2 Hz, 1H), 5.75 (dt, J = 6, 2 Hz, 1H), 4.85 (dd, J = 10, 2.2 Hz, 1H), 2.85 (m, 1H), 2.6 (m, 1H), 2.38 (m, 2H), 1.95 (br s, 1H, OH), 1.2−1.6 (m, 6H); ^{13}C NMR ($CDCl_3$) δ 134.71 (d), 133.79 (d), 76.38 (d), 51.06 (d), 47.71 (d), 41.41 (t), 41.05 (d), 38.84 (d), 24.88 (t), 24.26 (t); HRMS calcd 150.1087 for $C_{10}H_{14}O$, found 150.10772.

(n) *endo*-Tricyclo[5.2.1.0^{2,6}]dec-4-en-*exo*-3-ol, 21.[7b,7c] To a mixture of nickel acetate (0.15 g, 0.6 mmol) in dry ethanol (10 mL) was added sodium borohydride (0.025 g, 0.6 mmol). The reaction mixture became black. Hydrogen gas was flushed into the flask. Alcohol **4** (0.7 g, 4.73 mmol) was added and connected to a hydrogen bubbler. The reaction was stopped after intake of the theoretically required volume of hydrogen, and the contents were filtered through a silica gel pad. Ethanol was evaporated under reduced pressure. Water (10 mL) was added, the residue was extracted with diethyl ether, and the organic layers were combined, washed with brine, dried over anhydrous sodium sulfate, and filtered. Removal of the solvent followed by flash chromatography yielded pure **21**: 0.55 g; IR (neat, cm^{-1}) 3450, 1630; ^1H NMR ($CDCl_3$) δ 5.82 (ddd = dt, J = 5.5, 1.9 Hz, 1H), 5.7 (ddd = dt, J = 5.5, 1.9 Hz, 1H), 4.68 (br s, 1H), 3.15 (m, 1H), 2.35 (dd = t, J = 1.5 Hz, 1H), 2.25 (dd = t, J = 1.5 Hz, 1H), 2.15−2.2 (m, 1H), 1.0−1.6 (m, 7H); ^{13}C NMR ($CDCl_3$) δ 139.54 (d), 133.25 (d), 77.93 (d), 54.55 (d), 52.23 (d), 41.75 (t), 39.87 (d), 39.28 (d), 25.06 (t), 23.48 (t); HRMS calcd 150.1087 for $C_{10}H_{14}O$, found 150.107 57.

Supporting Information Available: ^1H NMR spectra for all new compounds and experimental data for **22**−**29**, **31**, and **33**−**35** (22 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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