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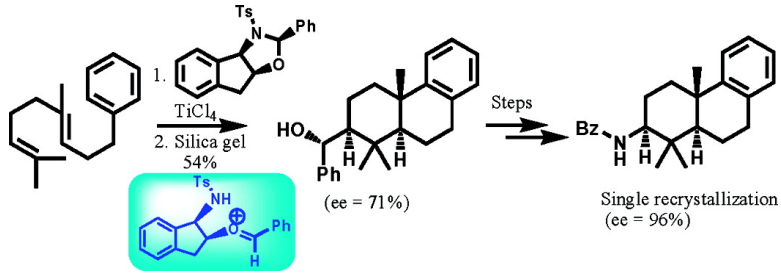
J. Am. Chem. Soc., **2008**, 130 (30), 10024-10029 • DOI: 10.1021/ja802896n • Publication Date (Web): 08 July 2008



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Bioinspired Polyene Cyclization Promoted by Intermolecular Chiral Acetal-$SnCl_4$ or Chiral *N*-Acetal-$TiCl_4$: Investigation of the Mechanism and Identification of the Key Intermediates

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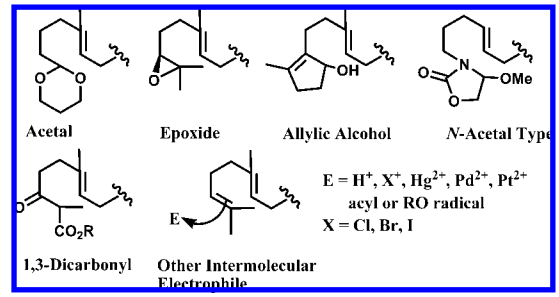
Abstract: New strategies using chiral acetal or chiral mixed-acetal in the presence of Lewis acids ($SnCl_4$ or $TiCl_4$) to promote polyene cyclization reaction are described. Acetal-promoted and mixed-acetal-promoted polyene cyclization products are very versatile and can easily be converted into various optically active tricyclic and tetracyclic terpenoids. One of the derivatives of the cyclization products was obtained up to 96% ee after a single recrystallization. In addition, an oxocarbenium intermediate was found to be responsible for the good asymmetric selectivity for this type of reaction.

Introduction

Although the fundamental works of biomimetic polyene cyclization have been established as early as the 1960s by Stork and Eschenmoser,[1] this state of the art reaction is still inspiring the passion and creativity of modern chemists. The key to a successful polyene cyclization is to have good *initiators*. Johnson,[2,3] van Tamelene,[4] Corey,[5] Overman,[6] Nishizawa,[7] and others[8] have contributed tremendously to the vast development of 20th century's cationic polyene cyclization chemistry using different initiators (Scheme 1). These initiators include acetal, allylic alcohol, epoxide, Hg(II), etc., which have been successfully applied to the syntheses of many complex molecules. Shortly after Johnson's acetal protocol, Speckamp[9] reported the first intramolecular *N*-acetal-promoted polyene cyclization. The acyl iminium was the active species that is responsible for the initiation of this cyclization. In addition, transition metals such as Pt(II) and Pd(II)[10] have also been developed as practical initiators for this type of cationic transformation.

Scheme 1



Another important initiator is proton, which was recognized as good initiator for polyene cyclization by Stork and Eschenmoser. However, the asymmetric version was only

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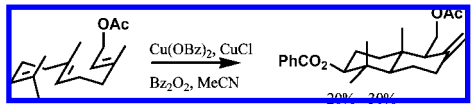
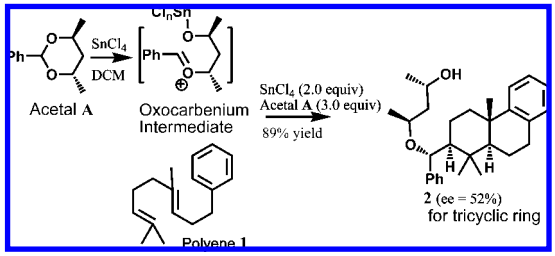
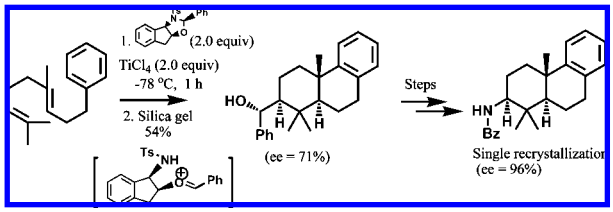
Scheme 2



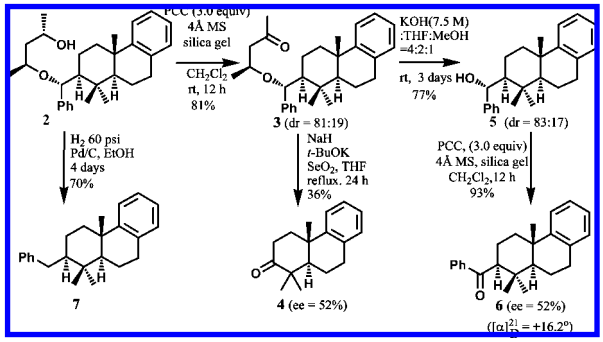
Scheme 3



Scheme 4



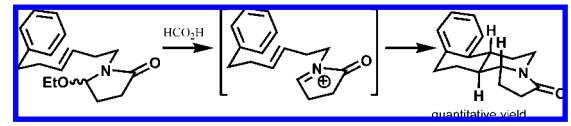
Scheme 5. Functionalization of Acetal-Initiated Cyclization Products to Various Terpenoids



established recently by Yamamoto[11] who demonstrated that *chiral LBA catalysts* could be used to construct multiple rings with high enantioselectivities. In addition, Ishihara has also elegantly established a highly enantioselective polyene cyclization reaction promoted by chiral electrophilic halogen atom.[12]

In addition to cationic polyene cyclization, Breslow[13] in 1968 demonstrated that oxygen radical was also a promising initiator for polyene cyclization (Scheme 2).

Scheme 6



Later, several carbo-radical-initiated polyene cyclization reactions were reported. Snider,[14] Demuth,[15] Pattenden,[16] and Yang[17] developed three new protocols, namely, using 1,3-dicarbonyl radical, photochemically generated radical, and acyl radical as initiators. Very recently, radical generated from reductively opening of epoxide was also successfully used as initiator for polyene cyclization by Oltra.[18]

Although many successes had been accomplished, biomimetic cationic polyene cyclizations with high asymmetric selectivities and high efficiency are still challenging problems in both academia and industries.[19] To tackle this problem, we reported an asymmetric acetal-initiated intermolecular polyene cyclization (Scheme 3).[20]

In this paper, we investigated the reaction using *N*-acetals (Scheme 4). One of the derivatives of the cyclization products was obtained in moderate yield with up to 96% ee after a single recrystallization. In addition, an oxocarbenium intermediate was found to be responsible for the good asymmetric selectivity for this type of reaction.

Results

Treatment of polyene **1** with chiral acetal **A** in the presence of $SnCl_4$ afforded the tricyclic product **2** in 89% yield with

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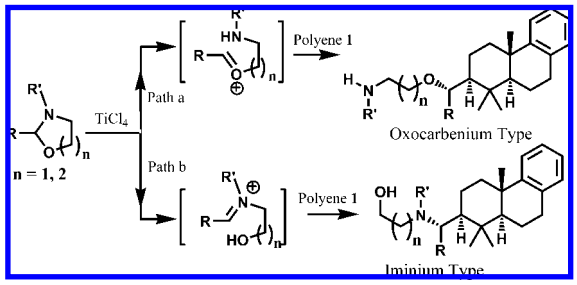


Figure 1. Two possible pathways for mixed-acetal (*N*-acetal)-initiated polyene cyclization.[20,22,23]

moderate diastereoselectivities (dr = 66:18:16, 52% ee for tricycle) (Scheme 3).[20a] In addition, acetal-initiated cyclization products are very versatile and can be easily converted into various optically active tricyclic terpene compounds (Scheme 5). Oxidation of the cyclization product **2** provided ketones **4** and **6**. Hydrogenation of **2** afforded terpenoid **7** in 70% yield.

Since the *chiral* oxocarbenium generated from 1,3-dioxane **A** was believed to be responsible for the good asymmetric selectivity, we decided to carry out the study of *mixed acetal* (*N*-acetal) with the hope of generating the chiral iminium intermediate to obtain the aza-polycyclic compounds.

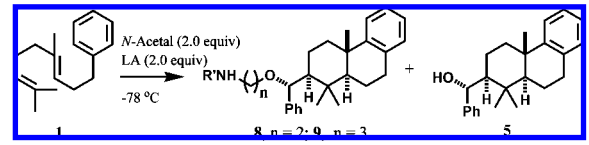
Previously, *N*-acetal-initiated polyene cyclizations have been demonstrated by Speckamp,[9] Kano,[21] and Grieco,[22] and the iminium intermediate, which was preferentially formed, promoted the intramolecular polyene cyclization successfully (Scheme 6).[9]

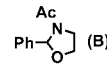
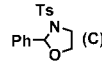
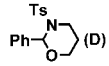
It is interesting to note that, by using *N*-acetal, the reaction can proceed through two possible pathways (Figure 1), one through the oxocarbenium[20] and the other via the iminium[22,23] intermediate. Hence, in the case of *intermolecular N*-acetal-promoted polyene cyclization, it is not clear whether iminium or oxocarbenium will be the active species responsible for the cyclization.

Our initial focus was to find proper *N*-acetal initiators to react with polyene **1** (Table 1). Therefore, polyene **1** was subjected to cyclization using various *N*-acetals in the presence of different Lewis acids. No reaction occurred when **1** was treated with mixed acetal **B** in the presence of $SnCl_4$ (Table 1, entry 1). When acyl substituent on the acetal was replaced by a tosyl group, cyclization fortunately proceeded to afford the tricyclic product **8** in 30% yield together with 9% yield of the alcohol **5** (Table 1, entry 2). The best yield (62% yield) was obtained when $TiCl_4$ was used instead of $SnCl_4$ (Table 1, entry 3). On the other hand, when *N*-acetal **D** was used, the cyclization product **9** was isolated in 64% yield which was contaminated with monocyclized isomer (entry 4). In a summarizing note, the optimal reaction condition was to use 2.0 equiv of $TiCl_4$ and 2.0 equiv of five-membered *N*-acetal **C**.

With the optimized reaction conditions in hand, cyclization of various polyenes with different benzene ring analogues was carried out and the results are summarized in Table 2. In all cases, the products were obtained in moderate yields with good diastereoselectivities.

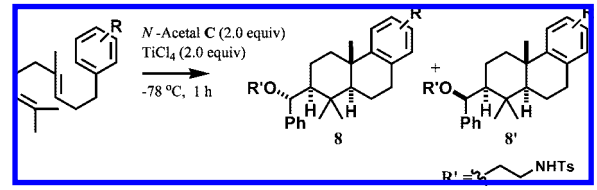
Table 1. *N*-Acetal-$TiCl_4$-Promoted Polyene Cyclization



Entry	*N*-Acetal	Lewis Acid	Time (h)	Product	Yield(%)[a]	Yield(%)[a] 5
1	 (B)	$SnCl_4$	24	—	0	0
2	 (C)	$SnCl_4$	1	**8**	30	9
3	(C)	$TiCl_4$	1	**8**	**62**	**9**
4	 (D)	$TiCl_4$	1	**9**	64[b]	Trace

[a] Isolated yield. [b] Monocyclized isomers were isolated together with the desired tricylic products in a mixture of 74:26 (based on ^{1}H NMR).

Table 2. *N*-Acetal-$TiCl_4$-Promoted Polyene Cyclization with Various Substrates



Entry	R	Substrate	Product[a]	Yield (%)[b] **8** + **8′**	dr[c] (**8**:**8′**)
1	–	**1**	**8** + **8′**	62	89:11
2	4-Me	**1a**	**8a** + **8a′**	51	89:11
3	3-Me	**1b**	**8b** + **8b′**	50	93:7
4	2-Me	**1c**	**8c** + **8c′**	62	90:10
5	4-OMe	**1d**	**8d** + **8d′**	50	88:12

[a] Side-chain-cleaved products **5** were also isolated in 5−9% yield. [b] Isolated yield. [c] The isomers of benzylic chiral center were observed. The values of dr were determined based on ^{1}H NMR integration of benzylic CH.

Subsequently, we extended this method to the asymmetric version of chiral *N*-acetal[24]-promoted polyene cyclization (Table 3). Various chiral *N*-acetals were subjected to the reaction with polyene **1** under the optimized conditions. The results are shown in Table 3. In all cases, good yields of cyclization products **5** were obtained. It was worthy to note that side-chain-cleaved chloride product **10** was the only observed product. Stirring of the chloride product **10** in silica gel in mixed wet solvent of dichloromethane and hexane (1:1) for 24 h afforded the corresponding alcohol **5**/**5′** in good yields. In addition, we found that the chirality of oxygenated carbon in the chiral *N*-acetal is important for the achievement of high diastereoselectivities. Without a chiral environment on oxygenated carbon, no selectivity was observed (Table 3, entry 1).

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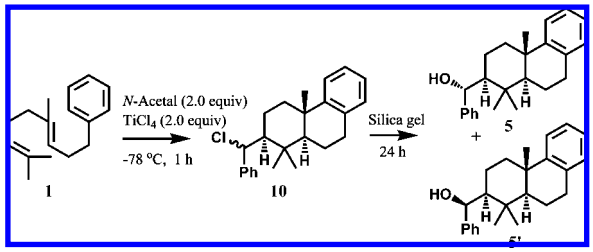
(24) The chiral *N*-acetal was synthesized from optical pure 1,2-hydroxy amine using the modified Didier's procedure: (a) Didier, E.; Fouque, E.; Taillepied, I.; Commercon, A. *Tetrahedron Lett.* **1994**, *35*, 2349–2352. (b) Agami, C.; Couty, F.; Mathieu, H. *Tetrahedron Lett.* **1996**, *37*, 4001–4002. (c) Commercon, A.; Bézarf., D.; Bernard, F.; Bourzat, J. D. *Tetrahedron Lett.* **1992**, *33*, 5185–5188. (d) Hajji, C.; Zaballos-García, E.; Sepúlveda-Arques, J. *Synth. Commun.* **2003**, *33*, 4347–4354. (e) Grieco, P. A.; Fobare, W. F. *J. Chem. Soc., Chem. Commun.* **1987**, 185–186.
(25) For structure detail of ketone **13**, see Supporting Information.

Table 3. Screen for Different Chiral *N*-Acetals as Initiators



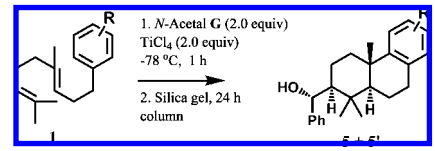
Entry	*N*-Acetal	Porduct[a]	Yield (%)[b]	ee (%)[c]
1	(E)	5+5'	62	0
2	(F)	5+5'	41	15
3	(G)	5+5'	**54**	**71**
4	(H)	5+5'	30	73
5	(I)	5+5'	30	57
6	(J)	5+5'	50	58
7	(K)	5+5'	40	63
8	(L)	5+5'	54	0

[a] The possible formation of the other enantiomer of **5′** cannot be ruled out. [b] Isolated yield. [c] Alcohol was oxidized into ketone to destroy benzylic chiral center; ee values were determined by HPLC analysis of corresponding isolated pure ketone.

The best result we obtained was 54% yield and 71% ee when *N*-acetal **G** was used as the initiator for the cyclization (Table 3, entry 3). When mesyl group was used instead of the tosyl group (Table 3, entry 4), better ee (73%) was obtained but the yield was lower (30%). Generally, other aromatic sulfonyl groups also gave respectable yields and moderate enantioselectivities. Surprisingly, the mesityl group diminished the asymmetric induction of the polyene cyclization reaction (0% ee, Table 3, entry 8).

Using this optimized conditions, we screened various polyene substrates and the results are summarized in Table 4. In all cases, the products were obtained in good yields and good ee.

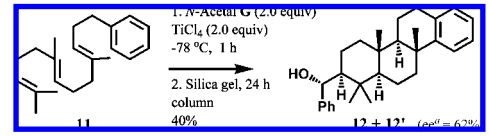
Table 4. *N*-Acetal-Promoted Asymmetric Polyene Cyclization Using Various Substrates



Entry	R	Polyene	Product[a]	Yield[b] (%)	dr	ee[c] (%)
1	–	**1**	**5** + **5′**	54	93:7	71
2	4-Me	**1a**	**5a** + **5a′**	56	93:7	62
3	3-Me	**1b**	**5b** + **5b′**	55	92:8	60
4	2-Me	**1c**	**5c** + **5c′**	58	91:9	60
5	4-OMe	**1d**	**5d** + **5d′**	41	90:10	71

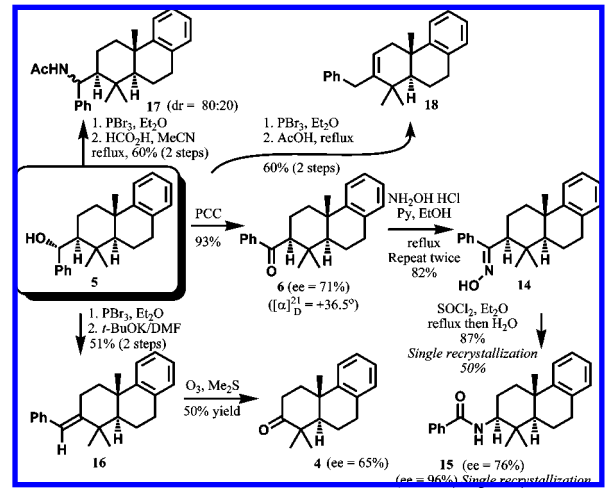
[a] Only structures of **5** are shown. [b] Isolated yield. [c] Alcohols were oxidized into corresponding ketones **6** to remove benzylic chiral centers; ee values were determined by chiral HPLC analysis of ketones **6**.

Scheme 7



[a] Only the structure of **12** is shown. Diastereomeric ratio = 93:7. Alcohols were oxidized into corresponding ketone **13**[25] to remove benzylic chiral centers; ee value was determined by chiral HPLC analysis of ketone **13**.

Scheme 8



It is worthy to note that even tetracyclic terpenoid could be obtained efficiently in good ee (62%) and moderate yield (40%) (Scheme 7).

The products of *N*-acetal-promoted polyene cyclization were very versatile and could be readily converted into diverse terpenoid compounds (Scheme 8). Oxidation of alcohol **5** provided ketone **6** in 93% yield with 71% ee.

Beckmann rearrangement protocol[26] was applied to the ketone **6**, and amide **15** was obtained in 50% yield with up to 96% ee after a single recrystallization (Scheme 8). Alcohol **5** could be converted to alkene **16**, and upon ozonolysis, ketone **4** was obtained in 62% ee and 25% yield over three steps. In addition,

(26) For review about Beckmann rearrangement, see: (a) Beckmann, E. *Ber. Dstch. Chem. Ges.* **1886**, *19*, 998. (b) Gawley, R. E. *Org. React.* John Wiley and Sons, Inc.: New York, 1988; Vol. 35, p 9. (c) *Comprehensive Organic Synthesis*; Trost, B. M., Ed.; Pergamon Press: Oxford, 1991; Chapter 1.9, p 341.

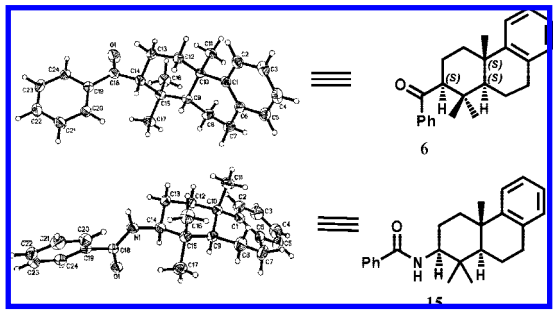
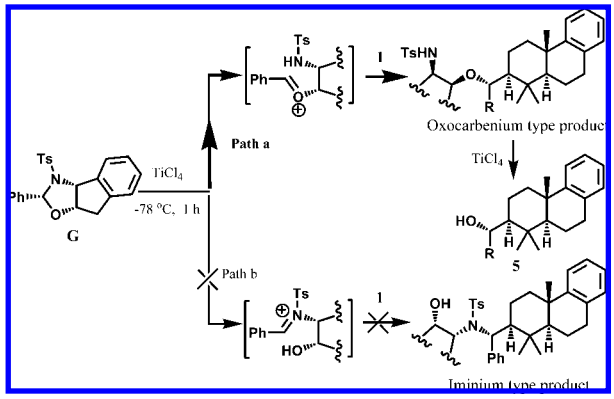
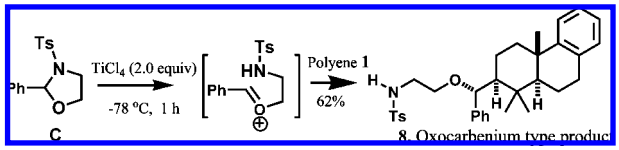


Figure 2. X-ray crystallography structures of **6** and **15**, 50% probability was chosen for the ellipsoids.

Scheme 9



Scheme 10



acid-promoted elimination of brominated **5** provided benzylic carbocation, which underwent proton shift to afford alkene **18**. Moreover, intermolecular trapping of benzylic carbocation afforded amide **17**.

The absolute stereochemistry of polyene cyclization adducts **6** ($[\alpha]^{21}_D = +36.5$, 71% ee) promoted by chiral *N*-acetal was determined by comparison of its optical rotation with that of ketone **6** ($[\alpha]^{21}_D = +16.2$, 52% ee) (obtained from chiral acetal-promoted polyene cyclization).[21] The stereochemistry of **6** was further verified by X-ray crystallography (Figure 2) and chiral HPLC analyses.

Discussion

While these new findings showed encouraging results, the actual cyclization mechanism was found to be different from previously reported *N*-acetal-promoted polyene cyclization reactions. Instead of an iminium intermediate, an oxocarbenium intermediate was most likely generated when *N*-acetal was exposed to $TiCl_4$ (Path a, Scheme 9).

Such a conclusion was based on the following findings:

(1) In the case of racemic studies using *N*-acetal **C**, we observed only the oxocarbenium type product **8** without detection of iminium type product (Scheme 10 and Figure 3).

(2) In the case of chiral *N*-acetal **E** derived from *primary* alcohol, we isolated 53% asymmetric cyclization product **19** as *O*-benzyl ether without side chain cleavage in the presence of $TiCl_4$ (1.0 equiv) (Scheme 11). These results suggested that not

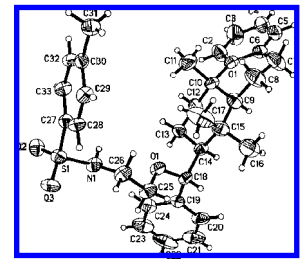
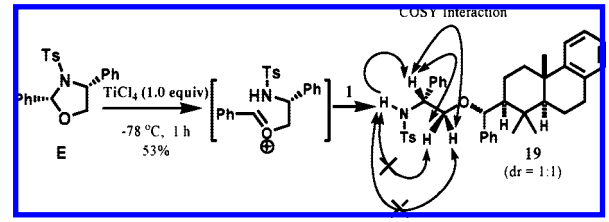


Figure 3. X-ray structure of **8**, 50% probability was chosen for the ellipsoids.

Scheme 11



only achiral *N*-acetal but also chiral *N*-acetal underwent oxocarbenium pathway to initiate polyene cyclization.

The following transition states (Figure 4) were proposed to account for the observed stereochemistries. Initial step involved the selective cleavage of the oxazolidine ring of *N*-acetal **G** to afford an active oxocarbenium intermediate. The active oxocarbenium intermediate was subsequently attacked from the less hindered *Re* face by the polyene **1** via antiperiplanar, open-chain transition states (paths a and b).[27] The favored path b was proposed to be much less sterically demanding and lower in energy compared to path a, thereby affording the major enantiomer of **6**. Cyclization through unfavorable path a provided the minor enantiomer of **6**.

Conclusion

In summary, we have developed an asymmetric Lewis acid mediated intermolecular acetal or *N*-acetal-initiated cationic polyene cyclization to form tricyclic and tetracyclic terpenoids. Diverse optically active terpenoids were readily synthesized in few steps via simple modification sequences. In addition, an oxocarbenium intermediate was found to be responsible for the good asymmetric selectivity for this type of reaction. Optimizations of this chiral *N*-acetal-$TiCl_4$ system are in progress in order to achieve higher enantioselectivities.

Experimental Section

General procedure for preparation of chiral *N*-acetal: To a 50 mL round-bottom flask with a magnetic stirring bar were added aminoindanol (0.745 g, 5.0 mmol, 1.0 equiv), THF (20 mL), and water (20 mL). Triethyl amine (1.01 g, 10.0 mmol, 2.0 equiv) was then added via syringe. The solution was cooled to 0 °C prior to addition of TsCl (0.953 g, 5.0 mmol, 1.0 equiv). The reaction mixture was allowed to proceed at room temperature for another 12 h before quenching with ice water (30 mL). The aqueous layer was extracted with ethyl acetate (2 × 40 mL), and the combined organic extracts were washed with water (30 mL) and brine (30 mL) and dried over anhydrous sodium sulfate, filtered, and concentrated in vacuo. The residual crude product was purified by column chromatography to afford the desired product

(27) (a) Loh, T. P.; Hu, Q. Y.; Ma, L. T. *J. Am. Chem. Soc.* **2000**, *123*, 2450–2451. (b) Loh, T. P.; Hu, Q. Y.; Tan, K. T.; Cheng, H. S. *Org. Lett.* **2001**, *3*, 2669–2672. (c) Hayashi, T.; Konishi, M.; Kumada, M. *J. Am. Chem. Soc.* **1982**, *104*, 4963–4965. (d) Denmark, S. E.; Weber, E. J. *J. Am. Chem. Soc.* **1984**, *106*, 7970–7971.

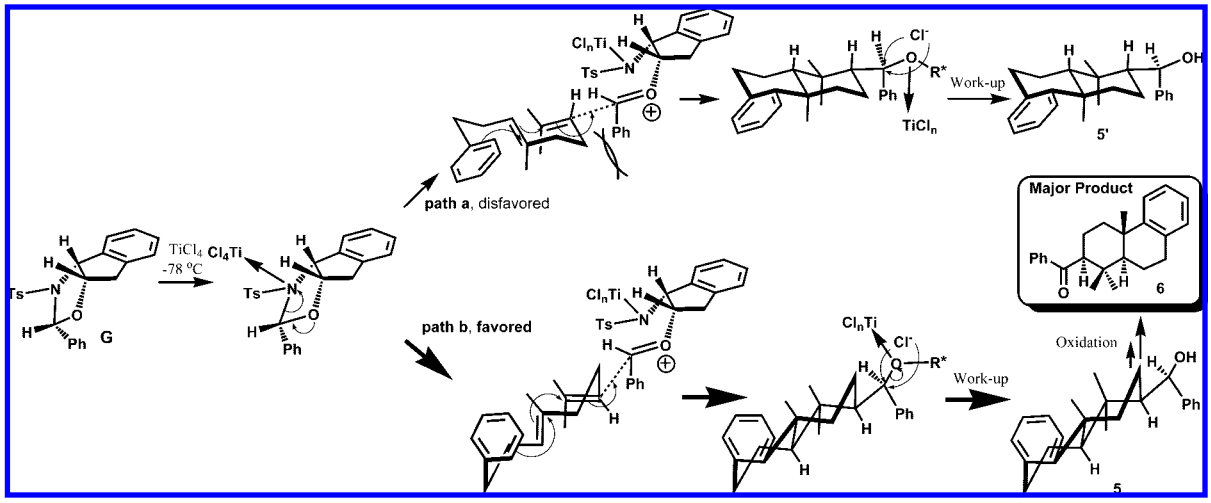


Figure 4. Proposed mechanism for *N*-acetal-promoted polyene cyclization.

as a white solid. The white solid was then placed in a 50 mL dry round-bottom flask with a magnetic stirring bar. $ClCH_2CH_2Cl$ (30 mL) and $PhCH(OMe)_2$ (1.52 g, 10.0 mmol, 2.0 equiv) were added via syringe. The reaction mixture was stirred at room temperature, and camphorsulfonic acid (CSA) (116 mg, 0.5 mmol, 0.1 equiv) was added in one portion. The reaction mixture was heated at 70 °C for 12 h before quenching with $NaHCO_3$ (50 mL) at room temperature. The aqueous layer was extracted with CH_2Cl_2 (2 × 40 mL). The combined organic extracts were washed with water (30 mL) and brine (30 mL) and dried over anhydrous sodium sulfate, filtered, and concentrated in vacuo. The residual crude product was purified by column chromatography to afford the desired product as a white solid: mp 151−153 °C; 90% yield over two steps; $[\alpha]^{20}_D = +35.7$ ($c = 2.64$, $CHCl_3$); R_f 0.50 (hexane/ethyl acetate = 4:1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.75−7.72 (m, 2H), 7.44−7.37 (m, 1H), 7.31−7.25 (m, 2H), 7.18−7.10 (m, 2H), 7.10−6.97 (m, 6H), 6.05 (s, 1H), 5.38 (d, J = 5.50 Hz, 1H), 4.41 (td, J = 5.26, 0.73 Hz, 1H), 3.03 (d, J = 17.16 Hz, 1H), 2.95 (dd, J = 17.42, 4.83 Hz, 1H), 2.40 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 144.3, 140.0, 139.7, 138.4, 135.0, 129.9, 128.7, 128.5, 128.0, 127.9, 126.9, 126.2, 125.1, 93.3, 81.9, 67.8, 37.4, 21.6; HRMS (EI) m/z calcd for $C_{23}H_{21}NO_3S$ $[M]^+$ 391.1242, found 391.1243; FTIR (NaCl) ν 3421, 1579, 1458, 1423, 1350, 1288, 1165 cm^{-1}.

General procedure for *N*-acetal-$TiCl_4$-promoted asymmetric polyenel cyclization reactions: To a 10 mL round-bottom flask with a magnetic stirring bar were added *N*-acetal **G** (78 mg, 0.2 mmol, 2.0 equiv) and CH_2Cl_2 (1.5 mL) at room temperature. The solution was cooled to −78 °C prior to addition of $TiCl_4$ (1.0 M in CH_2Cl_2, 0.2 mL, 2.0 equiv). CH_2Cl_2 (0.5 mL) solution of polyene **1** (23 mg, 0.1 mmol, 1.0 equiv) was added via syringe. The reaction was stirred at −78 °C for 1 h before quenching with saturated $NaHCO_3$ aqueous solution (5 mL). The mixture was gradually warmed to room temperature and was stirred for another 0.5 h. The aqueous layer was extracted with CH_2Cl_2 (3 × 20 mL), and the combined organic layers were washed with water (20 mL) and brine (20 mL), dried over anhydrous Na_2SO_4, filtered, and concentrated in vacuo. To the residual crude product in a 25 mL round-bottom flask were added silica gel (10 g), hexane (10 mL), CH_2Cl_2 (10 mL), and water (1 mL). The mixture was stirred for 24 h at room temperature. The mixture was then purified by flash column chromatography. Alcohol **5** was obtained in 54% yield as a colorless oil: $[\alpha]^{21}_D = +14.7$ (c = 4.0, $CHCl_3$); R_f 0.75 (hexane/ethyl acetate = 4:1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.01−7.38 (m, 9H), 5.21 (d, J = 3.87 Hz, 1H), 2.97 (ddd, J = 17.42, 6.62, 1.74 Hz, 1H), 2.83 (ddd, J = 17.42, 11.50, 6.96 Hz, 1H), 2.30 (dt, J = 12.54, 3.14 Hz, 1H), 2.01−1.91 (m, 1H), 1.87 (dd, J = 13.45, 2.94 Hz, 1H), 1.84−1.70 (m, 2H), 1.66−1.58 (m, 1H), 1.43−1.26 (m, 2H), 1.25 (s, 3H), 1.24 (s, 3H), 1.11 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 149.6, 146.1, 135.0, 128.8, 128.0, 126.5, 125.6, 125.3, 125.2, 124.5, 72.1, 55.5, 51.9, 38.4, 38.0, 37.3, 30.9, 30.0, 24.8, 19.4, 18.7, 16.1; HRMS (EI) m/z calcd for $C_{24}H_{30}O$ $[M]^+$ 334.2297, found 334.2293; FTIR (KBr) ν 3342, 2966, 2914, 1487, 1448, 1377, 1215, 1051, 756, 700 cm^{-1}.

General procedure for oxidation of cyclization product **5** to ketone **6**: To an oven-dried 25 mL round-bottom flask equipped with a magnetic stirring bar were added PCC (0.129 g, 0.6 mmol, 12.0 equiv), 4 Å molecular sieve (0.3 g, oven-dried over 48 h), silica gel (0.3 g, oven-dried over 48 h), and CH_2Cl_2 (10 mL). The mixture was cooled to 0 °C, and alcohol **5** (19 mg, 0.05 mmol, 1.0 equiv) in CH_2Cl_2 (1 mL) was added dropwise. The reaction was gradually warmed to room temperature and was stirred for another 12 h. The mixture was filtered through a pad of silica gel and flushed with 200 mL of CH_2Cl_2. The solution was concentrated in vacuo. The residual crude product was purified by flash column chromatography to afford the ketone **6** as a colorless solid: mp 73−75 °C; yield 93%, ee 71%; $[\alpha]^{21}_D = +36.9$ (c = 0.98, $CHCl_3$); R_f 0.70 (hexane/ethyl acetate = 4:1); ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.0−7.97 (m, 1H), 7.54−7.45 (m, 2H), 7.27−7.09 (m, 6H), 3.42 (dd, J = 12.56, 2.45 Hz, 1H), 2.99 (dd, J = 17.17, 6.11 Hz, 1H), 2.88 (ddd, J = 17.50, 11.07, 7.01 Hz, 1H), 2.45 (dt, J = 13.04, 2.97 Hz, 1H), 2.40−2.15 (m, 1H), 1.93 (dd, J = 13.71, 6.27 Hz, 1H), 1.92−1.50 (m, 4H), 1.29 (s, 3H), 1.06 (s, 3H), 0.95 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 204.3, 149.4, 139.1, 134.9, 132.7, 129.0, 128.5, 128.2, 125.8, 125.4, 124.5, 54.3, 52.2, 38.5, 38.0, 37.0, 31.4, 30.7, 25.2, 23.3, 18.5, 18.2; HRMS (EI) m/z calcd for $C_{24}H_{28}O$ $[M]^+$ 332.2140, found 332.2134; FTIR (KBr) ν 3070, 2868, 1670, 1653, 1629, 1377, 1288, 1120, 1001, 873, 759, 723 cm^{-1}.

Acknowledgment. This paper is dedicated to Professor Elias J. Corey (Harvard University) on the occasion of his 80th birthday. We thank Dr. Yong-Xin Li (Nanyang Technological University) for X-ray analyses. We gratefully acknowledge the Nanyang Technological University and the Singapore Ministry of Education Academic Research Fund Tier 2 (No. T206B1221) for the financial support of this research.

Supporting Information Available: Experimental procedures, spectroscopic data for new compounds, chiral HPLC traces of **4**, **6**, **6a**−**6d**, **13**, and **15** and cif files for **E**, **G**, **H**, **6**, **8**, and **15**. This material is available free of charge via the Internet at http://pubs.acs.org.

JA802896N