On the Mechanism of Ti–TADDOLate-Catalyzed Asymmetric Diels–Alder Reactions

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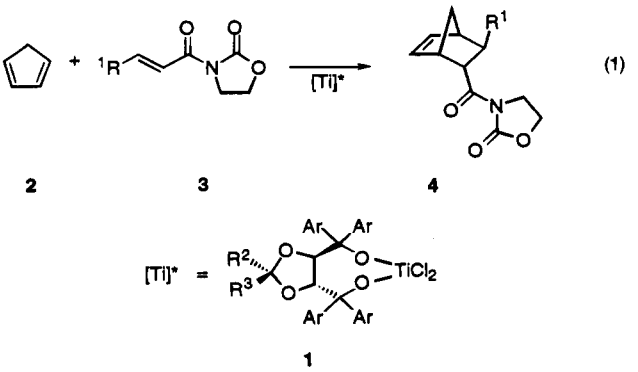
The mechanism of the diastereo- and enantioselective Diels–Alder reaction of cyclopentadiene with *N*-acyloxazolidinones catalyzed by titanium α,α,α′,α′-tetraaryl-1,3-dioxolane-4,5-dimethanolate (Ti–TADDOLate) complexes has been studied. On the basis of a series of experimental reactions catalyzed by a Ti–TADDOLate–*N*-cinnamoyloxazolidinone complex, which has been characterized by X-ray crystallography, it is found that both stoichiometric and catalytic reactions of this complex with cyclopentadiene lead to the same *endo*:*exo* ratio and enantiomeric excess of the Diels–Alder product as the Ti–TADDOLate-catalyzed reaction. The Diels–Alder reaction of different *N*-acyloxazolidinones with cyclopentadiene in the presence of modified Ti–TADDOLate complexes has also been investigated, and it is found that the *endo*:*exo* ratio is very dependent on chloride and tosylato ligands bound to the titanium atom. In the presence of chloride ligands attached to the titanium atom, the *endo* diastereomer of the Diels–Alder adduct is the major product formed, whereas a significant decrease in the amount of the *endo* Diels–Alder adduct is found when the more bulky tosylato ligands are bound to the titanium atom. The enantiomeric excess of the Diels–Alder product decreases also when the chloride ligands are exchanged with the tosylato ligands. On the basis of the experimental results, the mechanism of the Ti–TADDOLate-catalyzed Diels–Alder reaction of cyclopentadiene with *N*-acyloxazolidinones is discussed. It is proposed that the intermediate which accounts for the stereochemical outcome of the reaction is the one with the four oxygen atoms of the TADDOL and the *N*-acyloxazolidinone ligands bound to the titanium atom in the equatorial plane and the two axial positions occupied by the chloride or tosylato ligands.

Introduction

One of the most important reactions in organic chemistry for the formation of carbon–carbon bonds is the Diels–Alder reaction, and in recent years a great deal of effort has been devoted to the development of catalytic enantioselective reactions in this field.[1,2] The chiral titanium complexes **1** derived from α,α,α′,α′-tetraaryl-1,3-dioxolane-4,5-dimethanols (TADDOLs) have been found to catalyze and to induce high diastereo- and enantioselectivity in the Diels–Alder reaction of cyclopentadiene **2** with α,β-unsaturated *N*-acyloxazolidinones (eq 1).[3]



(1)

Compared with the numerous attempts to improve the diastereo- and enantioselectivity of the catalytic Diels–Alder reaction, relatively little effort has been devoted to understanding its mechanism.[4] For the Ti–TADDOLate-catalyzed Diels–Alder reaction, Narasaka *et al.*[5] have tried to characterize the chiral titanium reagent using NMR spectroscopy, and in an attempt to elucidate the origin of the high enantioselectivity observed in eq 1, Corey *et al.*[6] have investigated modified Ti–TADDOLate catalysts. It was proposed, based on a strong influence of the substituents in the meta position of the aromatic rings of the TADDOL ligand, that attractive π–π interactions between an aromatic group of the TADDOL ligand and the double bond of the dienophile

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(1) For a recent review about catalytic asymmetric Diels–Alder reactions, see *e.g.*: Kagan, H. B.; Riant O. *Chem. Rev.* **1992**, *92*, 1007.

(2) For other catalytic asymmetric Diels–Alder reactions, see *e.g.*: (a) Corey, E. J.; Imai, N.; Zhang, H.-Y. *J. Am. Chem. Soc.* **1991**, *113*, 728. (b) Corey, E. J.; Loh, T.-P. *J. Am. Chem. Soc.* **1991**, *113*, 8966. (c) Corey, E. J.; Loh, T.-P.; Roper, T. D.; Azimioara, M. D.; Noe, M. C. *J. Am. Chem. Soc.* **1992**, *114*, 8290. (d) Corey, E. J.; Ishihara, K. *Tetrahedron Lett.* **1992**, *33*, 6807. (e) Evans, D. A.; Lectka, T.; Miller, S. J. *Tetrahedron Lett.* **1993**, *34*, 7027. (f) Evans, D. A.; Miller, S. J.; Lectka, T. *J. Am. Chem. Soc.* **1993**, *115*, 6460. (g) Pikul, S.; Corey, E. J. *Org. Synth.* **1993**, *71*, 30. (h) Corey, E. J.; Roper, T. D.; Ishihara, K.; Sarakinos, G. *Tetrahedron Lett.* **1993**, *34*, 8399. (i) Waldmann, H. *Synthesis* **1994**, 535. (j) Kobayashi, S.; Ishitani, H.; Hachiya, I.; Araki, M. *Tetrahedron* **1994**, *50*, 11623. (k) Ishihara, K.; Yamamoto, H. *J. Am. Chem. Soc.* **1994**, *116*, 1561.

(3) (a) Narasaka, K.; Inoue, M.; Ojada, N. *Chem. Lett.* **1986**, 1109. (b) Narasaka, K.; Inoue, M.; Yamada, T. *Chem. Lett.* **1986**, 1967. (c) Narasaka, K.; Inoue, M.; Yamada, T.; Sigimori, J.; Iwasawa, N. *Chem. Lett.* **1987**, 2409. (d) Narasake, K.; Inoue, M.; Sugimori, J.; Kawase, Y.; Narasaka, K. *Chem. Lett.* **1989**, 1947. (g) Narasaka, K.; Iwasawa, N.; Inoue, M.; Yamada, T.; Narashima, M.; Sugimori, J. *J. Am. Chem. Soc.* **1989**, *111*, 5340.

(4) See *e.g.*: (a) Corey, E. J.; Sarshar, S.; Bordner, J. *J. Am. Chem. Soc.* **1992**, *114*, 7938. (b) Corey, E. J.; Loh, T.-P.; Roper, T. D.; Azimioara, M. D.; Noe, M. C. *J. Am. Chem. Soc.* **1992**, *114*, 8290. (c) Ishihara, K.; Gao, Q. Z.; Yamamoto, H. *J. Am. Chem. Soc.* **1992**, *114*, 10412. (d) Togni, A.; Rist, G.; Rish, G.; Schweiger, A. *J. Am. Chem. Soc.* **1993**, *115*, 1908. (e) Kobayashi, S.; Ishitani, H.; Araki, M.; Hachiya, I. *Tetrahedron Lett.* **1994**, *35*, 6325. (f) Boyle, T. J.; Eilerts, N. W.; Heppert, J. A.; Takusagawa, F. *Organometallics* **1994**, *13*, 2218.

(5) (a) Iwasawa, N.; Hayashi, Y.; Sakuri, H.; Narasaka, K. *Chem. Lett.* **1989**, 1581. (b) See also: Narasaka, K.; Tanaka, H.; Kanai, F. *Bull. Chem. Soc. Jpn.* **1991**, *64*, 387.

(6) Corey, E. J.; Matsumura, Y. *Tetrahedron Lett.* **1991**, *32*, 6289.

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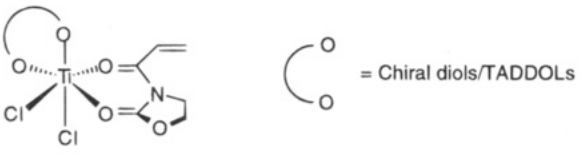
(in an *s-trans* geometry) and a *cis* orientation of the two chloride ligands at the titanium complex **5** protect one face and account for the high ee.[6]



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Very recently two new aspects concerning the mechansim of the Ti–TADDOLate-catalyzed Diels–Alder reaction have been published.[7,8] In the work by DiMare *et al.*,[7] the conclusion, with regard to the Ti–TADDOLate–alkene intermediate, was that the most abundant adduct has the oxygen atoms of the TADDOL and the *N*-acyloxazolidinone ligands in the equatorial plane of the octahedral titanium atom. Furthermore, it was concluded that the second most abundant adduct of the Ti–TADDOLate–*N*-acyloxazolidinone intermediate has only three of the four oxygen atoms in the equatorial plane and binds the *N*-acyloxazolidinone ligand proximal to one of the pseudoaxial TADDOL aryl residues.[7] On the basis of molecular mechanics calculations, it was proposed that the latter was responsible for the enantioselectivity in the Diels–Alder reaction as the former was lacking the close contact between the TADDOL aryl groups and the *N*-acyloxazolidinone and therefore would not be expected to have a strong shielding effect of the α-*si* side of **3**.[7] In the systematic work by Seebach *et al.*,[8] the influence of the mode of the catalyst, preparation, amount of catalyst, presence of molecular sieves, concentrations of the reactants, temperature, solvent, and TADDOL structures were studied. It was also proposed here that an intermediate having a *cis* arrangement of the two chloride ligands at the titanium atom probably was involved.

We have recently been able to obtain crystals upon treating $(i\text{-PrO})_2TiCl_2$ with (2*R*,3*R*)-2,3-*O*-(2-propylidene)-1,1,4,4-tetraphenyl-1,2,3,4-butanetetrol and 3-((*E*)-3-cinnamoyl)-1,3-oxazolidin-2-one (**3a**)[9] —the complex proposed to be the intermediate in the Ti–TADDOLate-catalyzed Diels–Alder reaction. The structure of this complex (**6**) was determined by X-ray diffraction and is shown in Figure 1.[9]

The X-ray structure of **6** consists of the TADDOLate and the *N*-cinnamoyloxazolidinone ligands in the equatorial plane and the two chloride ligands in the axial positions—*trans* to each other. The structure of the Ti–TADDOLate–*N*-cinnamoyloxazolidinone intermediate is thus in agreement with the one proposed to be the most abundant by DiMare *et al.*[7] However, compared with this structure, the X-ray structure of the Ti–TADDOLate–*N*-cinnamoyloxazolidinone intermediate differs in several ways. One of the aryl substituents of the TADDOLate ligand seems to block the upper α-*si* face of the alkene. This discrimination of the alkene is enhanced by the alkene plane of the dienophile being tilted 33° out of the plane containing the titanium atom and the four equatorial oxygen atoms toward one of the aryl groups, leading to a further shielding of the α-*si* face.[9] It was proposed

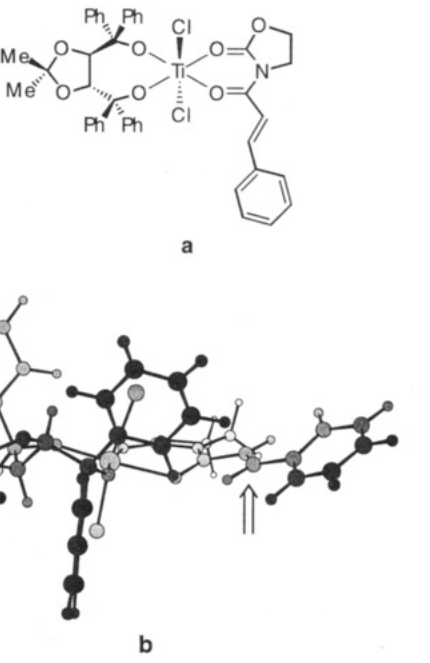


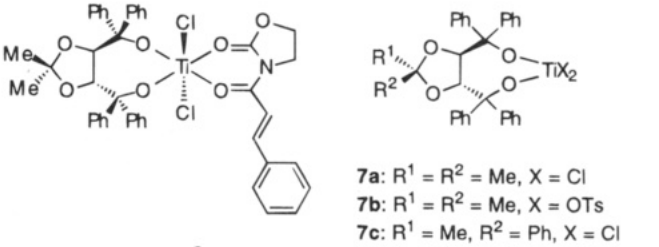
Figure 1. Two representations of the crystal structure of the Ti–TADDOLate–*N*-cinnamoyloxazolidinone intermediate **6**. (a) Schematic drawing of **6**. (b) Chem 3D representation.

that cyclopentadiene approaches the alkene in **6** from the less hindered face—α-*re* (as indicated by the arrow in Figure 1b)—placing the carbonyl group *endo* to optimize secondary orbital interactions.[9]

The contributions by DiMare *et al.*[7] and by Seebach *et al.*[8] and the structure of the Ti–TADDOLate–*N*-cinnamoyloxazolidinone complex **6**[9] stimulated us to present our experimental investigations of the mechanism of the Ti–TADDOLate-catalyzed Diels–Alder reaction.

Results and Discussion

The Diels–Alder reaction of cyclopentadiene (**2**) with **6** and modified Ti–TADDOLate **7a–d** catalyzed Diels–Alder reactions of **2** with *N*-acyloxazolidinones **3a,b** have been investigated. For further experimental details, see the Experimental Section.



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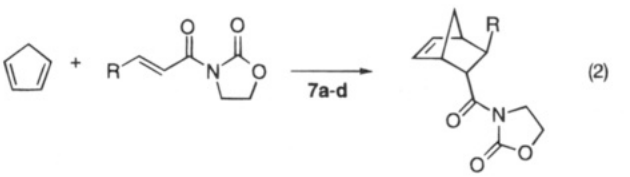
7a: $R^1 = R^2$ = Me, X = Cl
7b: $R^1 = R^2$ = Me, X = OTs
7c: R^1 = Me, R^2 = Ph, X = Cl
7d: R^1 = Me, R^2 = Ph, X = OTs



(2)

2 **3a**: R = Ph **3b**: R = Me **4a**: R = Ph **4b**: R = Me

The results for the different reactions performed are presented in Table 1. The absolute configurations of the

(7) Haase, C.; Sarko, C. R.; DiMare, M. *J. Org. Chem.* **1995**, *60*, 1777.
(8) Seebach, D.; Dahinden, R.; Marti, R. E.; Beck, A. K.; Plattner, D. A.; Kühnle, F. N. M. *J. Org. Chem.* **1995**, *60*, 1788.
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Table 1. Asymmetric Ti–TADDOLate-Catalyzed Diels–Alder Reactions of Cyclopentadiene (2) with *N*-Acyloxazolidinones 3a,b[a]

entry	alkene	catalyst/ amount (%)	product (*endo*:*exo*)[b]	ee (%) (*endo*)[c]	reaction temp (°C)	*endo*:*exo*[d]	ee (%) (*endo*)[d]
1		**6** (100)	**4a** (79:21)	45	0		
2	**3a**	**6** (10)	**4a** (79:21)	54	−20		
3	**3a**	**7a** (10)	**4a** (78:22)	49	0		
4	**3a**	**7b** (50)	**4a** (42:58)	37	−20		
5	**3a**	**7c** (10)	**4a** (83:17)	60	−20	88:12[3g]	64[3g]
6	**3a**	**7d** (50)	**4a** (53:47)	31	−20		
7	**3b**	**6** (10)	**4b** (86:14)	51	−20		
8	**3b**	**7a** (10)	**4b** (85:15)	42	−20	93:7[e]	55[e]
						83:17[8]	44[8]
9	**3b**	**7b** (50)	**4b** (76:34)	43	−20		
10	**3b**	**7c** (10)	**4b** (89:11)	86	−20	92:8[3g]	91[3g]
						87:13[8]	86[8]
11	**3b**	**7d** (50)	**4b** (67:33)	21	−20		

[a] The reactions were run on a 0.1 mmol scale in toluene for 48–72 h. For further details, see the Experimental Section. [b] The *endo*:*exo* ratio was determined by ^{1}H NMR spectroscopy on the crude product. [c] The ee was determined by HPLC on a Diacel Chiralpak AD column. [d] Results obtained by others for identical reactions. [e] The catalyst was applied in 100 mol %, see ref 3g.

major enantiomers *endo*-**4a** and *endo*-**4b** were determined by comparison of HPLC retention times.[10] In all entries in Table 1 the major isomer arises from attack of cyclopentadiene (**2**) to the α-*re* face of *N*-acyloxazolidinone, giving 2′(*R*)-*endo*-**4a** and 2′(*S*)-*endo*-**4b**.

The crystals of **6** can be prepared in a sufficient amount to be reacted with cyclopentadiene (**2**) in a stoichiometric reaction, and the result of this reaction is given as entry 1 in Table 1.[9] The Diels–Alder product **4a** is formed in an *endo*:*exo* ratio of 79:21 with 45% enantiomeric excess (ee) of the *endo* isomer. Reaction of **2** with **3a** in the presence of 10 mol % of **6** leads to the formation of **4a** in the same *endo*:*exo* ratio but with 54% ee (entry 2), similar to the results obtained for the reaction of a stoichiometric amount of **6** with **2**. The slightly higher ee in the latter case is probably due to the decrease in reaction temperature. The results obtained for both the stoichiometric and the catalytic reaction of **6** with **2** are in agreement with the catalytic reaction of **2** with **3a** in the presence of **7a** as a catalyst (entry 3). If **6** is the intermediate in the Ti–TADDOLate-catalyzed enantioselective Diels–Alder reaction and **2** approaches the α-*re* face of the alkene with **2** placed *endo* to the carbonyl group of the *N*-acyloxazolidinone ligand, an exchange of the chloride ligands with a more bulky ligand should be expected to alter the *endo*:*exo* ratio. We have therefore performed the reaction of **2** with **3a** in the presence of **7b** as the catalyst. The tosylato ligands are much more bulky than the chloride ligands in **6**, and placed *trans* to each other, the tosylato ligands might partly discriminate **2** in obtaining the secondary orbital interaction with the carbonyl group of the *N*-acyloxazolidinone coordinated to the Ti–TADDOLate complex. The reaction with **7b** as the catalyst proceeds much slower compared with **7a** and is probably due to both unfavorable steric and electronic factors for **2** in obtaining the optimal interaction with the alkene part of the *N*-acyloxazolidinone coordinated to the Ti–TADDOLate complex. We have therefore applied 50 mol % of the catalysts **7b** and **7d**. The results for this reaction (entry 4) show a change in the *endo*:*exo* ratio to 42:58 with an ee of 37% for the *endo* isomer. The change in the *endo*:*exo* ratio by the replacement of the chloride ligands with the tosylato ligands is relatively large, but a very significant change in the *endo*:*exo* ratio should probably not be expected as the sp^2-hybridized carbon atoms of **2** are not that different in space compared with the sp^3-hybridized carbon atom (*vide infra*).

In an attempt to investigate further the effect of the chloride and tosylato ligands, we have also studied the Diels–Alder reaction of **2** with **3a** catalyzed by **7c,d** (Table 1, entries 5 and 6). The trends for the diastereo- and enantioselectivities found for the catalysts **7c,d** are very similar to those obtained for **7a,b** as the former catalysts also show a decrease in the *endo*:*exo* ratio when the chloride ligands are exchanged with the more bulky tosylato ligands. For the reaction using **7c** as the catalyst the *endo*:*exo* ratio is 83:17 (entry 5), and this ratio changes to 53:47 when the tosylato ligand is bound to the titanium atom (entry 6). The change in *endo*:*exo* ratio is accompanied by a significant lowering in the ee (entries 5 and 6).

The reaction of *N*-acyloxazolidinone **3b** with cyclopentadiene (**2**) in the presence of **6** and **7a–d** has also been studied. The reasons for choosing **3b** are (i) to investigate if ligand **3a** can be exchanged from **6** leading to the Diels–Alder product **4b**, (ii) to determine if similar trends are observed for **3b** as the alkene as for **3a**, and (iii) to compare these results with the results obtained by others as **3b** is the most common dienophile applied in these reactions.[3g,6,8] The results for the reaction of **3b** with **2** in the presence of **6** (10 mol %) are given as entry 7 in Table 1. It appears from the results in entry 7 that **3a** is exchanged with **3b** during the reaction course and that the latter reacts with **2** to give **4b** with a slightly better diastereo- and enantioselectivity compared with **3a** as the alkene. The *endo*:*exo* ratios and enantioselectivities for the reaction of **3b** with **2** catalyzed by **7a–d** are presented as entries 8–11 in Table 1. The reaction of **3b** with **2** in the presence of **7a** as the catalyst leads to **4b** with an *endo*:*exo* ratio of 85:15 and with an ee of 42% of the *endo* isomer. A similar reaction with **7b** as the catalyst gives **4b** and the expected reduction of the *endo*:*exo* ratio to 76:34 is obtained (entry 9), supporting the idea that the bulkiness of the axial ligands in the catalyst affects the *endo*:*exo* ratio of the Diels–Alder product. However, the ee of the *endo* isomer for this particular reaction is not affected by the presence of the tosylato ligand (entry 9). Changing the catalysts to **7c** or **7d** for the reaction of **3b** with **2** leads to the same trends for the *endo*:*exo* ratio as those obtained when then reaction is catalyzed by **7a,b**, as the *endo*:*exo* ratio decreases from

(10) Kobayashi, S.; Ishitani, H.; Hachiya, I.; Araki, M. *Tetrahedron* **1994**, *50*, 11632.

89:11 (entry 10) to 67:33 (entry 11) when the chloride ligands are exchanged with the tosylato ligands. The results obtained in entry 10 are close to those obtained by Seebach *et al.*,[8] but slightly lower than the results found by Narasaka *et al.*[3g] Compared with the use of the catalysts **7a**,**b**, the enantioselectivities of the Diels–Alder product **4b** in the latter reactions are much more dependent on the chloride or tosylato ligand attached to the titanium atom, as the ee decreases from 86% when **7c** is the catalyst (entry 10) to 21% with **7d** as the catalyst (entry 11).

The experimental results presented in Table 1 and the structural knowledge of complex **6** allow us to begin to understand the Ti–TADDOLate-catalyzed Diels–Alder reaction of cyclopentadiene (**2**) with *N*-acyloxazolidinones. The diastereo- and enantiomeric outcome of the reaction can be accounted for by the assumption that the structure of the intermediate in solution is similar to **6**. A similar structure was also the one which DiMare *et al.*[7] proposed to be the most abundant complex in solution. On the basis of the structure of **6** presented in Figure 1b, it appears that **2** can approach the alkene in **6** from the less hindered face—α-*re*—as indicated. From the results in Table 1, **2** reacts with both a stoichiometric amount of **6** with **3a** in the presence of **6** in a catalytic amount (10 mol %) and with **3a** in the presence of **7a** as a catalyst to give nearly identical results with respect to diastereo- and enantioselectivity. These results can be accounted for by the approach of **2** to **6** as outlined in Figure 2. This reaction path allows maximum secondary orbital interaction with the carbonyl group of the *N*-cinnamoyloxazolidinone. The diastereoselectivity of the reaction changes when the chloride ligands are exchanged with tosylato ligands. To account for this change, we have optimized using MM2 calculations[11] the structure of the intermediate where **3a** is coordinated to catalyst **7b** with the assumption that the Ti–TADDOLate–*N*-cinnamoyloxazolidinone part of the complex has the same structure as this part in **6**. We are fully aware of the fact that this is a significant constraint of the intermediate, but it allows us to a certain extent to compare **6** with this new intermediate. The optimized structure of this intermediate is shown in Figure 2b. In Figure 2b is also included the *endo* reaction path of **2** to the alkene part of the intermediate. The presence of the tosylato ligand in the axial position below the Ti–TADDOLate–*N*-cinnamoyloxazolidinone plane causes an increase in the steric bulk of this part of the intermediate as the two oxygen atoms of the tosylato group are pointing toward **2**. Comparing the approach of **2** to the alkene part of the intermediate shown in Figure 2a with that in Figure 2b might account for the experimental results. The reaction path of **2** with **6** in Figure 2a is in agreement with the experimental results in Table 1. The change in diastereo- and enantioselectivity using **7b** as a catalyst can be accounted for in Figure 2b as the *endo* approach of **2** to the alkene part of the catalytic intermediate will lead to steric repulsion between **2** and the tosylato ligand as indicated in the figure. Changing the reaction path from *endo* to *exo* will minimize this steric repulsion on behalf of the proposed favorable secondary orbital interaction of **2** with the carbonyl group of the *N*-acyloxazolidinone.

Moving further to the reaction of **2** with the different *N*-acyloxazolidinones in the presence of the other catalysts is, based on the approach of **2** to the catalytic intermediates presented in Figure 2, parts a and b, proposed to lead to similar trends for the diastereo- and enantioselectivities of the Ti–TADDOLate-catalyzed Diels–Alder reaction as those discussed above. We thus propose that the isolated and characterized intermediate **6** can account for the stereochemical outcome of the Ti–TADDOLate-catalyzed Diels–Alder reaction, but we can of course not exclude that other intermediates might be involved in the Ti–TADDOLate-catalyzed Diels–Alder reaction.

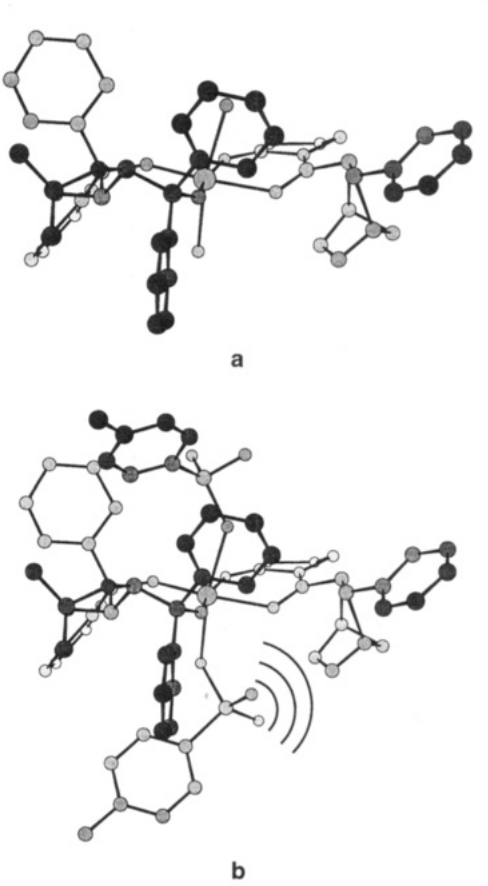

Figure 2. (a) Proposed approach of cyclopentadiene (**2**) to the Ti–TADDOLate–*N*-acyloxazolidinone intermediate. (a) The proposed *endo* reaction path of **2** with the alkene part of Ti–TADDOLate–*N*-cinnamoyl oxazolidinone intermediate **6** (C–C bond lengths between the alkene in **6** and **2** are 2.0 Å and hydrogen atoms are omitted for clarity). (b) The proposed *endo* approach of **2** to the intermediate formed by reaction of catalyst **7b** with *N*-cinnamoyloxazolidinone showing the steric repulsion between the tosylato ligand and the sp^2-hybridized carbon atoms of **2** (C–C bond lengths between the alkene part of the intermediate and **2** are 2.0 Å and hydrogen atoms are omitted for clarity).

Experimental Section

General Methods. ^{1}H NMR spectra were recorded at 300 MHz using $CDCl_3$ as the solvent and are reported in ppm downfield from TMS. HPLC was performed using a 4.6 mm × 25 cm Diacel Chiralpak AD column. Preparative thin layer chromatography (TLC) was performed on 200 × 200 × 1.8 mm silica gel ($PF_{254+366}$ Art. 7748, Merck) on glass plates. Solvents were dried using standard procedures. Powdered molecular sieves (4 Å) were activated by being heated to 250 °C for 3 h under high vacuum. All glass equipment was dried in an oven before use.

Materials. The starting materials 3-((*E*)-cinnamoyl)-1,3-oxazolidin-2-one (**3a**),[3g] 3-((*E*)-2′-butenoyl)-1,3-oxazolidin-2-one

(11) Burkert, U.; Allinger, N. L. *Molecular Mechanics*; American Chemical Society: Washington, DC, 1982; p 1.

(**3b**),[3g] the TADDOLs,[3g,12] $(i\text{-PrO})_2TiCl_2$,[13] and the Ti–TADDOLate–*N*-cinnamoyloxazolidinone complex **6**[9] were synthesized according to the literature. Cyclopentadiene (**2**) was cracked from dicyclopentadiene prior to use. Silver *p*-toluenesulfonate was received from Fluka and used without further purification. Powdered molecular sieves (4 Å) were received from Aldrich. Millex filter units 45 μm pore size were received from Millipore.

Preparation of TADDOL–$TiCl_2$ Catalysts 7a and 7c. To the TADDOL (0.11 mmol) placed in a 5 mL flask with a magnetic stirring bar under N_2 was added a 0.1 M toluene solution of $(i\text{-PrO})_2TiCl_2$ (0.10 mmol) *via* syringe. After 0.5 h of stirring at room temperature (rt), the catalyst was ready for use.

Preparation of TADDOL–$Ti(OTos)_2$ Catalysts 7b and 7d. To silver *p*-toluenesulfonate (83.7 mg, 0.3 mmol) placed in a 5 mL flask with a magnetic stirring bar under N_2 was added a 0.1 M toluene solution of $(i\text{-PrO})_2TiCl_2$ (0.10 mmol) *via* syringe. After 48 h of stirring at rt, the suspension was transfered to a syringe and filtered through a Millex filter unit into a 5 mL flask containing TADDOL (0.11 mmol), a magnetic stirring bar, and an N_2 atmosphere. The mixture was stirred 0.5 h prior to use.

Procedure for the Asymmetric Diels–Alder Reaction (Table 1, entries 2–11). To a toluene suspension (1 mL) of the 3-acyloxazolidinone **3** (0.1 mmol) and 50 mg of 4 Å powdered molecular sieves in a 5 mL flask with a magnetic stirring bar under N_2 was added the catalyst **7a** or **7c** (0.1 mL, 0.01 mmol), **7b** or **7c** (0.5 mL, 0.05 mmol) *via* syringe, or **6** (8 mg, 0.01 mmol). The reaction mixture was cooled to −20 ° C on an ice/NaCl bath (or 0 °C on an ice bath). After 15 min, **2** (200 μL, 2.0 mmol) was added *via* syringe. The reaction mixture was stirred for 48 h during which the temperature was allowed to rise to rt. The reaction mixture was stirred with 1 mL of 5% MeOH in CH_2Cl_2 and filtered through a 20 mm layer of silica gel. After the silica gel layer was washed with another 2 mL of 5% MeOH in CH_2Cl_2, the solvent was evaporated *in vacuo*. The crude material was purified by preparative TLC (silica gel, Et_2O/petroleum ether, 2:1) to give the single diastereomers of **4**.

3-(((1′*S*,2′*R*,3′*R*,4′*R*)-3′-Phenylbicyclo[2.2.1]hept-5′-en-2′-yl)carbonyl)-1,3-oxazolidinone (*endo*-4a). Conversions for the reactions described in entries 1–6 in Table 1 are >50%. The ^1H NMR spectra were identical to the literature data.[10] HPLC (Diacel Chiralpak AD, hexane/*i*-PrOH = 19/1, flow rate = 1.0 mL/min): t_R = 16 min (minor), t_R = 31 min (major in all entries).[10,14]

3-(((1′*S*,2′*S*,3′*R*,4′*R*)-3′-Methylbicyclo[2.2.1]hept-5′-en-2′-yl)carbonyl)-1,3-oxazolidinone (*endo*-4b). Conversions for the reaction described in entries 7–11 in Table 1 are >70%. ^1H NMR spectra were identical to the literature data.[10] HPLC (Diacel Chiralpak AD, hexane/*i*-PrOH = 19/1, flow rate = 1.0 mL/min): t_R = 11 min (major), t_R = 13 min (minor in all entries).[10,14]

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(14) The absolute configurations of *endo*-**4a** and *endo*-**4b** were determined by comparison with the HPLC analysis performed in ref 10.