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Asymmetric Diels–Alder reaction of (*S*)-α-*p*-tolylsulfinyl α,β-unsaturated esters: the role of the sulfinyl group in asymmetric Diels–Alder reactions of vinylsulfoxides

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Abstract: The mechanistic models so far proposed to explain the behavior of vinylsulfoxides as dienophiles in asymmetric Diels–Alder reactions are revised on the basis of the results obtained in the reactions of (*S*)-benzyl 2-*p*-tolylsulfinylacrylate **3** with cyclopentadiene, Dane's diene and furan under different conditions, as well as other results previously reported, concerning sulfinylacrylates, sulfinylmaleates and trialkoxycarbonyl sulfinyl ethenes. The moderate reactivity of sulfinylacrylates and the scarce influence that the incorporation of additional alkoxycarbonyl groups exerts on their reactivity is explained by assuming a variable electronic influence of the sulfinyl group on the double bond, acting as withdrawing and donating electron group depending on the substitution at the double bond. In the reactions with cyclopentadiene, both reactivity and stereoselectivity raised in the presence of ZnX_2 as catalysts (ZnI_2>$ZnBr_2$>$ZnCl_2$), but $TiCl_4$ was found to be the most efficient catalyst allowing the reactions to take place at low temperatures. With cyclopentadiene and furan, steric and electronic interactions between the CH_2 and O, respectively, and the substituent at sulfur on the *s-cis* conformation of the vinylsulfoxide must be considered to predict the favored stereochemical course. © 1997 Elsevier Science Ltd

The asymmetric Diels–Alder reaction using enantiopure vinylsulfoxides as chiral dienophiles has gained wide attention in recent years[1] due to the ability of the sulfinyl group to control the π-facial selectivity. However, in order to take advantage of such ability an electron-withdrawing group must be incorporated on the dienophilic double bond, which increases the reactivity (unsubstituted vinylsulfoxides are very poor dienophiles) and restricts the conformational mobility around the C–S bond (when they are placed at geminal or *cis* positions with respect to the sulfinyl group). In this sense, several activating groups, like nitro,[1g] carbonyl,[2] or sulfone[3] have been attached to the double bond, but no doubt the most studied is the ester group.

From the pioneering study of the reaction of methyl 2-*p*-tolylsulfinyl acrylate **1** with cyclopentadiene under thermal and $ZnCl_2$ catalyzed conditions,[4] many interesting sulfinylacrylates have been studied for several authors,[2] although the contribution of Koizumi in this field is clearly the most significant.[5] The π-facial selectivity could be satisfactorily controlled with the combined use of these monoactivated vinylsulfoxides and Lewis acids like $ZnCl_2$. However, the control of the *endo/exo* selectivity (it was efficient only in particular cases) and the moderate or low reactivity (determining that the majority of the studies only concern to cyclopentadiene) were the two main problems restricting the general synthetic usefulness of these dienophiles. In order to overcome these limitations, recently we have studied the asymmetric Diels–Alder reactions of benzyl methyl 2-*p*-tolylsulfinyl maleates **2**.[1i,j] We reasoned that its reactivity as well as its *endo* selectivity should be presumably higher than those of the acrylates. Nevertheless, the second ester group does not confer the expected effect to dienophiles and thus the reactivity of the maleates is scarcely modified and their *endo* selectivity was only slightly improved

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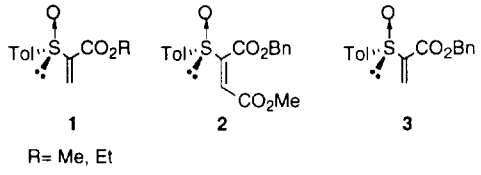
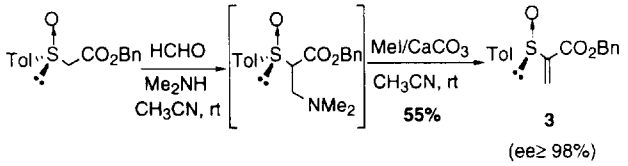
with respect to those of the acrylates. The two main contributions of these studies were the strong increase of the reactivity in the presence of $TiCl_4$ and the fact that the *endo* selectivity was substantially improved in reactions with acyclic dienes.[6] Taking into account that the Diels–Alder reactions of enantiopure α-sulfinylacrylates have been scarcely studied and never under $TiCl_4$ catalysis, in this paper we describe the cycloadditions of (*S*)-benzyl 2-*p*-tolylsulfinyl acrylate **3**[7] with cyclopentadiene, Dane's diene and furan under different conditions. Otherwise, from the results obtained in this study, we discuss the models so far proposed to explain the reactivity and stereoselectivity of the cycloadditions of both α-sulfinyl acrylates and α-sulfinyl maleates (Scheme 1).



Scheme 1.

The (*S*)-benzyl 2-*p*-tolylsulfinyl acrylate (**3** ee≥98%) was readily prepared from benzyl (*R*)-*p*-tolylsulfinyl acetate in a single one pot experimental procedure as previously described by us[7] (Scheme 2). The procedure is based on a Mannich condensation and further *in situ* nitrogen quaternization.



Scheme 2.

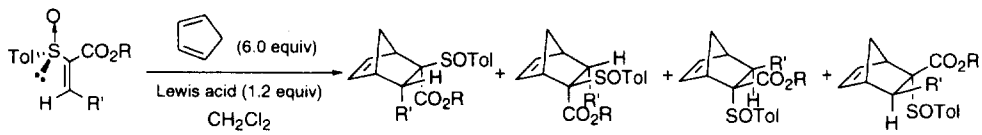
Table 1 summarizes the stereochemical results obtained in the Diels–Alder reactions of **1–3** with cyclopentadiene.[8] Data dealing with dienophiles **1** and **2** have been taken from references 1i,j and 4 respectively. The adducts **6** were obtained in 75–95% yield after chromatography and their stereochemical assignment was established by ^{1}H-NMR[9] analysis and by comparison with the data reported by Koizumi for the cycloaddition of **1** with those of very similar adducts (Scheme 3).[4]

As expected, the results obtained from dienophile **3** were almost identical to those from **1** (compare the pairs of entries 1/3 and 2/4). The significant π-facial selectivity observed in the reaction of these dienophiles and its complete inversion in the presence of the zinc halides, described firstly by Koizumi in 1985,[4] are the most remarkable findings of their behavior. On the other hand, from Table 1 can be deduced that changes in the zinc halides used as catalysts has significant influence in the reactivity and mainly in the *endo/exo* selectivity, which became higher with ZnI_2 (entry 5). This fact could be a consequence that this Lewis acid has a higher solubility and a better ability to form chelated species than the other zinc halides.[10] The incorporation of a second ester group to the dienophile reinforces the *endo* selectivity observed in reactions from dienophile **2** but, surprisingly, its influence on the reactivity is little or none (compare entries 8 with 1 and 3 as well as 9 with 2 and 4). This fact might be explained by assuming that the sulfinyl group shows a variable electronic influence on the double bond, acting as withdrawing (due to its -I and maybe its -M character if it is assumed the participation of the empty d orbitals) or donating (due to its +M character associated to its lone electron pair at sulfur) electron group depending on the other substituents of the double bond. In the case of the maleates **2**, the donating character of the sulfinyl group must be higher than that of the acrylates **1** and **3**, and thus compensates the decreasing of the electronic density produced by the second ester group. The fact that reactions of trialkoxycarbonyl sulfinylethylenes with cyclopentadiene required 72 h at

Table 1. Diels–Alder reaction of dienophiles **1–3** with cyclopentadiene

		Cycloaddition conditions				Isomer ratio[a]	Stereoselectivity	
Entry	Dienophile	Catalyst (1.2 equiv)	T (°C)	t (h)	Adduct	*endo*-**A**/*endo*-**B**/*exo*-**A**/*exo*-**B**	*endo*/*exo*[b]	**A**/**B**[c]
1	**1**[d]	---	20	6	**4**	64/11/23/2	3.0	6.7
2	**1**[d]	$ZnCl_2$	0	3	**4**	2/77/2/19	3.8	0.04
3	**3**	---	20	8	**6**	62/11/25/2	2.7	6.7
4	**3**	$ZnBr_2$	0	1.5	**6**	--/78/--/22	3.5	<0.04
5	**3**	ZnI_2	-20	1	**6**	--/87/--/13	6.7	<0.04
6	**3**	$Eu(fod)_3$	0	1.5	**6**	32/20/38/10	1.3	2.3
7	**3**	$TiCl_4$	-78	0.5	**6**	4/58/9/29	1.6	0.15
8	**2**[e]	---	20	10	**5**	73/8/19/--	4.3	11.5
9	**2**[e]	$ZnBr_2$	-20	6	**5**	7/88/5/--	19.0	0.14
10	**2**[e]	$Eu(fod)_3$	-20	2	**5**	66/3/31/--	2.2	32.3
11	**2**[e]	$TiCl_4$	-78	2	**5**	83/13/4/--	24.0	6.7

[a]Determined by ^1H NMR on the crude mixtures. [b] Endoselectivity. [c]π-facial selectivity. [d]Data taken from reference 4. [e]Data taken from reference 1i,j.



1: R= Me, R'= H

2: R= Bn, R'= CO_2Me

3: R: Bn, R'= H

Scheme 3.

rt to completion[1d] revealed that these dienophiles exhibited a lower reactivity than maleates (despite the additional ester group existing in this triester), which reinforces the assumption that sulfinyl group could act as a modulator of the electronic density (and therefore its dienophilic reactivity) of the double bond.[11]

The highest amount of the *exo* adducts **6** was observed in reactions catalyzed by $Eu(fod)_3$ (the *exo*-**A** adduct is the major one in these conditions), being this result similar to that obtained starting from maleates **2** (see entries 6 and 10). Nevertheless, the π-facial selectivity is quite different depending on the dienophile (2.3 and 32.3 respectively for the *endo* approaches of acrylate **3** and maleate **2**)

Other interesting point concerns to the use of $TiCl_4$ as catalyst. Its effect increasing the reactivity of dienophile **3** is much higher than from the other Lewis acids which agrees with the results obtained from maleate **2**. Nevertheless, its effect on the π-facial selectivity is the opposite in maleates and acrylates. Thus, in the case of maleates **2**, the favored *endo* adduct is just the same that obtained in the absence of catalyst (see entries 8 and 11), whereas for acrylate **3** the favored adducts in the presence of $TiCl_4$, *endo*-**6B** and *exo*-**6B** (entry 7), are obtained as minor in the absence of catalyst (entry 3). These results indicates that the influence of $TiCl_4$ on the π-facial selectivity is identical to that of $ZnBr_2$ for acrylates (compare entries 4 or 5 with 7), but the opposite one for maleates (compare entries 9 and 11).

Changes in the π-facial selectivity of the acrylates have been usually explained by assuming the chelating ability of the catalysts, according to the original explanation formulated by Koizumi.[4] In the

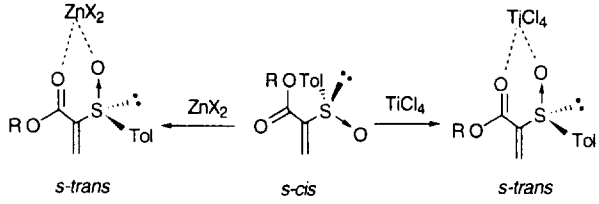


Figure 1.

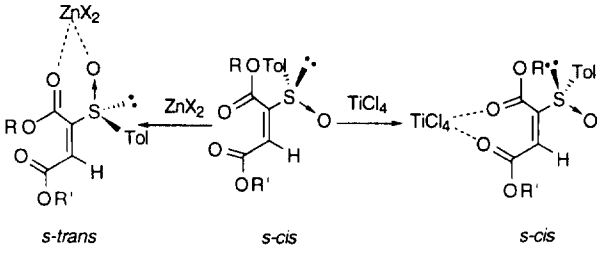


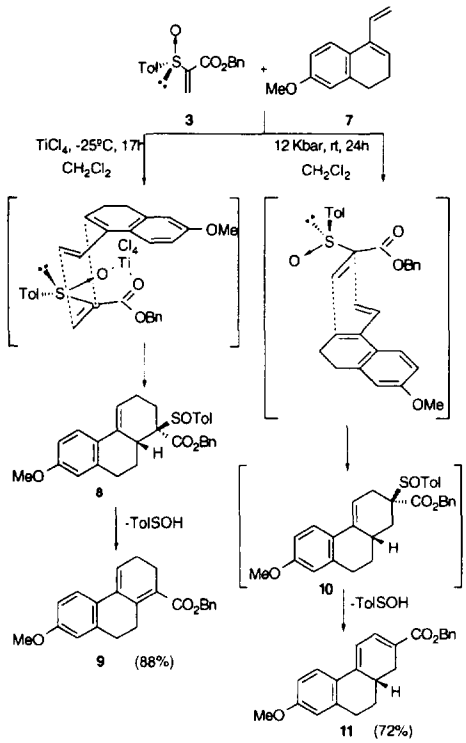
Figure 2.

absence of catalyst, Koizumi postulates that conformational equilibrium around the C–S bond must be completely shifted towards the rotamer with the sulfinyl oxygen in an *s-cis* arrangement (the most stable from an electrostatic point of view), making favored the approach of diene from the less hindered upper face supporting the lone electron pair (Figure 1). The chelation of the sulfinyl and carbonyl oxygens with metals shifts the conformational equilibria towards the *s-trans* rotamer, determining the inversion of the π-facial selectivity.

Results indicated in entry 7 suggest: i) $TiCl_4$ must become chelated to acrylate **3** in a similar way to ZnX_2 (entries 4 and 5) as indicated in Figure 1. ii) The different structure of the chelates with Zn (tetrahedral) and titanium (octahedral) is not able to invert the π-facial selectivity and only promotes slight changes in the π-facial selectivity (higher with ZnX_2). This makes invalid the explanation previously suggested by us to rationalize the different behavior of the maleates under $ZnBr_2$ and $TiCl_4$ catalysis.[1i,j] Taking into account that the results obtained from maleates and acrylates are identical under thermal and ZnX_2 catalyzed conditions, but the opposite under $TiCl_4$ catalysis, we propose that the second ester group must be responsible of the observed differences in the last case. The formation of a chelate involving the two ester groups (instead only one of them and the sulfinyl group) could explain the observed results (Figure 2) but the reasons because only $TiCl_4$ prefers this chelation is not clear.

Although dienophile **3** reacted with acyclic dienes like isoprene and piperylene[12] under $ZnCl_2$ or $TiCl_4$ catalysis, the most interesting results were obtained in the reaction of **3** with Dane's diene **7** (Scheme 4). The reaction catalyzed by $TiCl_4$ required 17 h at −25°C to be completed. The ^{1}H-NMR spectrum of the crude mixture indicated the formation of only one *endo*-adduct **8**, which suffers spontaneous desulfinylation at room temperature (it is completed in 36 h), affording the achiral compound **9** in 88% yield, whose structure was assigned by NOESY and DEPT experiments. When the reaction was carried out under high pressure (12 kbar, CH_2Cl_2) we could isolate compound **11** in 72% yield. Despite the reaction was conducted at room temperature, the presumed intermediate adduct **10** could not be detected in the reaction mixture.

The structural differences between **9** and **11** indicate that the regioselectivity of the cycloaddition has been the opposite in both cases. Under high pressures and absence of catalysts, the regioselectivity



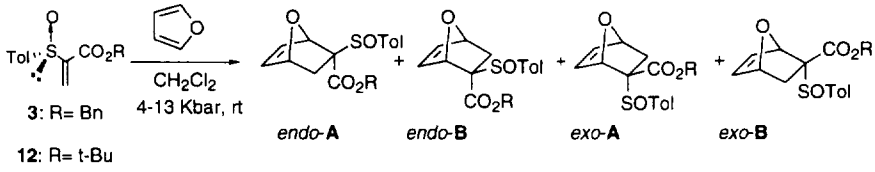
Scheme 4.

seems to be controlled by the aromatic residue at C-2 on the diene (*para* adduct is exclusively formed), whereas in the presence of $TiCl_4$ the regioselectivity is governed by the alkyl substituent at C-1 on the diene (*ortho* adduct is formed).[13] By assuming a presumably low influence of the high pressures on the regioselectivity, the observed differences could be attributed to the catalyst. Thus, despite the usual higher influence of the substituents at C-1 on the regioselectivity, the strongly donor electron character of the *p*-methoxyphenyl substituent at C-2 is dominant in reactions conducted in the absence of catalyst, overcoming the low donating effect of the methylene group at C-1. The coordination of the OMe group with $TiCl_4$ must decrease the electronic density of the aromatic ring and thus its ability as donating group. Under these conditions the alkyl group at C-1 become the main controller of the regioselectivity.

Finally, the high enantiomeric purity of compound **11** (ee>97% by ^{1}H-NMR) indicates that both the π-facial selectivity and the *endo/exo* selectivity have been completely controlled by the sulfinyl group. These results agree with other previously reported from maleates,[1i,j] and indicate that the reactions of acrylates with acyclic dienes are much more stereoselective than with cyclic ones. As the absolute configuration of **11** could not be unequivocally determined, we have tentatively assigned it as indicated in Scheme 4 by assuming the *endo* approach of diene to the less hindered face of dienophile on its presumably most stable *s-cis* conformation (Scheme 4).

In order to shed some more light on the stereochemical behavior of this kind of dienophiles we analyzed the results obtained in reactions of dienophiles **3** and **12** with furan (Table 2).[7] The low reactivity of furan determined that the formation of cycloadducts was not observed under thermal conditions even in the case when furan was used as solvent. In the presence of Lewis acids, like ZnI_2,[14] or $TiCl_4$, complex reaction mixtures were obtained under different conditions.[15] The reactions were then performed under high pressure conditions. Significant amounts of the four possible adducts **13** were formed in the reaction of **3** with furan at 13 kbar (entry 1), indicating that both the *endo/exo*

Table 2. Diels–Alder reactions of furan with compounds **3** and **12**[7]



3: R= Bn
12: R= t-Bu

Entry	Dienophile	Adduct	P (Kbar)[b]	t (h)	Conversion (%)[c]	product ratio[a] *endo*-**A**/*endo*-**B**/*exo*-**A**/*exo*-**B**
1	**3**	**13**	13	24	95	24/44/11/21
2	**3**	**13**	4	72	68	34/66/--/--[d]
3	**12**	**14**	13	24	95	24/44/--/--[e]
4	**12**	**14**	8	6	90	22/45/15/18
5	**12**	**14**	4	17	60	29/44/12/15
6	**12**	**14**	4	120	65	29/59/4/8

[a] Estimated by ^{1}H NMR from the reaction mixture. The configurational assigmment of both *endo* adducts was established by chemical correlations with enantiopure shikimic acid derivatives (see ref. 7). [b] CH_2Cl_2 as solvent except for entries 4 and 6 (furan as solvent). [c] Determined by ^{1}H NMR. [d] The *exo* adduct ratio could not be evaluated. [e] Formation of *bis*-adducts was detected.

and the π-facial selectivity was rather low. When the reaction was carried out at 4 kbar (entry 2), the *endo*-**13A**/*endo*-**13B** ratio obtained after 3 days was similar to that observed at 13 kbar, suggesting little or no influence of the pressure on the π-facial selectivity (at least for the *endo* approach). The obtained mixture of adducts **13** reverted spontaneously to the starting products at room temperature, which can be easily followed by NMR. It demonstrated that retro-Diels–Alder reaction is very fast, which makes difficult to evaluate the proportion of the adducts in some cases.[16]

In order to increase the stereoselectivity of the reaction we studied the bulkier t-butyl ester **12**. As we can see, our original aim was not achieved, because the stereoselectivity is barely affected by the alkyl residue of the ester, but the obtained adducts **14** are more stable than **13** allowing us a better study of the composition of the mixtures.

The lower conversion level obtained at 4 kbar (entries 2, 5 and 6) suggests that the retro Diels–Alder reaction could take place at this pressure. On the other hand, the fact that the *endo*-**A**/*endo*-**B** ratio remained almost unaltered from 4–13 kbar, whereas the *endo*/*exo* ratio was higher when the pressure decreses suggests that the retro Diels–Alder process must be much more easy for the *exo* adducts, which in turn must be more unstable than the corresponding *endo* ones. This would explain the increase of the *endo*/*exo* ratio when the reaction time become longer (compare entries 5 and 6).

In order to demonstrate the stability of the *endo* adducts under high pressures, towards the retro Diels–Alder reaction, we have treated independently purified samples of *endo*-**14A** and *endo*-**14B** with furan (excess) at 9 kbar during 24 h. In both cases, the adducts could be recovered unaltered and no other adducts were detected.[17] These results suggests that the fact that the *endo*-**A**/*endo*-**B** ratios collected in Table 2 remain almost constant in the different trials made, is not a consequence of the equilibration between them, but these ratios correspond to kinetic control.

Having clarified this point, we must remark that the π-facial selectivity of the reaction of **3** with furan is the opposite to that observed with cyclopentadiene. Thus *endo*-**B** adducts are the major obtained from furan (Table 2), whereas *endo*-**A** ones were predominant in reactions with cyclopentadiene (Table 1). In order to rationalize the inversion of the stereoselectivity, it is necessary to assume that both dienes

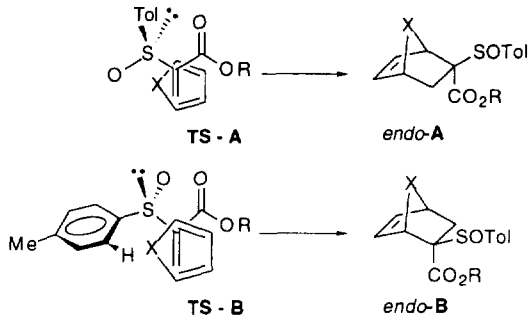


Figure 3.

have a different influence on the stability of the TS leading the adducts *endo*-**A** and *endo*-**B**, which are depicted in Figure 3.

According to Koizumi, the π-facial selectivity depends only on the conformational preferences of the dienophile. Thus, the results obtained from the acrylate **1** in the absence of Lewis acids are explained by assuming a steric approach control of diene on the rotamer with the sulfinyl group in *s-cis* arrangement, the most populated from electrostatic point of view.[4] As the structure of the diene is not able to modify the conformational behavior of dienophile, the inversion of the π-facial selectivity observed in reactions of **3** with cyclopentadiene and furan cannot be explained according to the Koizumi proposal. From the results obtained in reactions of sulfinylquinones with cyclopentadiene[1a,18] we have suggested that, taking into account the Curtin–Hammet principle, π-facial selectivity must be also related to the relative reactivity of the possible conformations around the C–S bond. In the case of the reactions of sulfinylacrylates with cyclopentadiene (X=CH_2 in Figure 3), both proposals lead to the same predictions, because the most populated conformation according to Koizumi is also the most reactive one during the *endo* approach (the steric interactions of the methylene at cyclopentadiene with the tolyl group are clearly higher than those with the sulfinyl oxygen). This situation changes in reactions with furan (X=O, in Figure 3), because of the lower magnitude of the steric interactions favoring the TS **A**, and the emerging repulsive electrostatic interactions which unstabilize it. This balance must favour TS-**B** leading the inversion of the π-facial selectivity.

Conclusions

The results of the present work clearly indicate that: i) π-facial selectivity of the Diels–Alder reactions of vinylsulfoxides must be explained by assuming a steric approach control of the diene on the less hindered face of dienophile (that supporting the lone electron pair at sulfur), taking into account the relative reactivity of the rotamers around the C–S bond, in addition to their populations (only factor so far considered); ii) Both *endo* and the π-facial selectivities of the cycloadditions of vinylsulfoxides with acyclic dienes are substantially higher than with cyclic ones. iii) $TiCl_4$ is the most efficient catalyst for the Diels–Alder reactions of sulfinyl acrylates, but ZnI_2 gives better stereochemical results; iv) The influence of the sulfinyl group on the dienophilic reactivity of double bonds seems to be variable (ranging from withdrawing to donating electron character) and dependent on the electronic effect of other groups attached to it.

Experimental section

^{1}H-NMR (200, 300 MHz) spectra and ^{13}C-NMR (50 MHz) spectra were recorded in $CDCl_3$. Both chemical shifts (ppm downfield from internal tetramethylsilane) and coupling constants (Hz) were obtained by first order analysis of spin patterns. Mass spectra (MS) were recorded with electron impact (EI, 70 eV). Mass data are reported in mass units (*m/z*), and the values in brackets report the relative intensity from the base peak (as 100%). High-resolution mass spectra were determined at an ionizing

voltage of 70 eV. High pressure reactions were performed in a UNIPRESSEQUIPMENT 101 LV 30/16 in polyethylene vials. Optical rotations were measured with a Perkin–Elmer 241 polarimeter.

Analytical thin-layer chromatography was performed on DC-Alufolien 0.2 mm silica gel 60-F plates (MERCK). Visualization was accomplished with UV light and ethanolic phosphomolybdic acid solution followed by heating. Flash chromatography was performed by using silica gel (MN-Kieselgel 60, 230–400 mesh).

All solvents were dried before use. THF and Et_2O were distilled from sodium–benzophenone under argon. CH_2Cl_2 and $CHCl_3$ were distilled from P_2O_5. Cyclopentadiene was freshly distilled. $ZnBr_2$ and ZnI_2 were dried at 160°C for 12 h with P_2O_5 under vacuo. $Eu(fod)_3$ and $TiCl_4$ were purchased from Aldrich and used without further purification. The synthesis of dienophiles **3** and **12** as well as the Diels–Alder reactions of **12** with furan were previously described in reference 7. Dane's diene was prepared according to described procedures.[19]

General procedure for the Diels–Alder reactions of ***3*** *catalyzed by* $ZnBr_2$ *or* ZnI_2

A solution of dienophile **3** (35 mg, 0.12 mmol, 1.0 equiv) in 0.6 ml of CH_2Cl_2 (the temperature is indicated in Table 1) was added, under an argon atmosphere, to a solution of ZnX_2 (0.14 mmol, 1.2 equiv) in 0.5 ml of CH_2Cl_2. The mixture was stirred for 10 min, and then cyclopentadiene (6–8 equiv) was added. Stirring was continued until the dienophile disappeared (the reaction times are indicated in Table 1). Then, 10% $NaHCO_3$ (2 ml) was added. The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (2×10 ml). The combined organic layers was dried ($MgSO_4$) and concentrated in vacuo. The mixture of adducts was analyzed by ^{1}H-NMR and purified by flash chromatography (hexane–ethyl acetate 6:1) to give 37 mg (85% overall yield) of adducts *endo*-**6B**+*exo*-**6B**.

General procedure for the Diels–Alder reaction of ***3*** *catalyzed by* $TiCl_4$

The Lewis acid (0.18 mmol, 1.2 equiv from a solution 1.0 M in CH_2Cl_2) was added dropwise, under argon atmosphere, to a solution of dienophile **3** (45 mg, 0.15 mmol, 1.0 equiv) in 0.7 ml of CH_2Cl_2 at −78°C. The mixture was stirred for 10 min, and then the corresponding diene was added. Stirring was continued until dienophile disappeared by TLC (the reaction times are indicated in Table 1 and in the text). Then, 10% $NaHCO_3$ (2 ml) was added. The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (2×10 ml). The combined organic layers was dried ($MgSO_4$) and concentrated in vacuo. The mixture of adducts was analyzed by ^{1}H-NMR.

The adducts obtained from cyclopentadiene were purified by flash chromatography (hexane–ethyl acetate 7:1) to give 51.6 mg as a mixture of adducts **6** (*endo*-**6A**:*endo*-**6B**:*exo*-**6A**:*exo*:**6B**=4:58:9:29) (94% overall yield). In the case of the Dane's diene 45.7 mg of cycloadduct **9** were obtained (88% yield) after flash chromatography (hexane:CH_2Cl_2 2:1).

Diels–Alder reaction of ***3*** *catalyzed by* $Eu(fod)_3$

A solution of dienophile **3** (25 mg, 0.08 mmol, 1.0 equiv) in 0.5 ml of CH_2Cl_2 was added, under an argon atmosphere, to a solution of $Eu(fod)_3$ (105 mg, 0.10 mmol, 1.2 equiv) in 0.3 ml of CH_2Cl_2 at 0°C. The mixture was stirred for 10 min, and then cyclopentadiene (6–8 equiv) was added. Stirring was continued for 1.5 h. Then, 5% HCl (2 ml) was added. The organic layer was separated, and the aqueous layer was extracted with CH_2Cl_2 (2×10 ml). The combined organic layers was dried ($MgSO_4$) and concentrated in vacuo. The mixture of adducts was analyzed by ^{1}H-NMR and purified by flash chromatography (hexane–ethyl acetate 6:1) to give 28.5 mg of adducts **6** (*endo*-**6A**:*endo*-**6B**:*exo*-**6A**:*exo*:**6B**=32:20:38:10) (93% overall yield).

(R_1,S_2,R_4,S_5)-*Benzyl 2-(*p*-tolylsulfinyl)-bicyclo[2.2.1]hept-5-ene-2-carboxylate* endo-***6A***

$[\alpha]_D^{20}$=+92.5 (c=1.0, $CHCl_3$). IR ($CHCl_3$): 2980, 2910, 1695, 1420, 1340, 1310, 1230, 1095 and 1025 cm^{-1}. ^{1}H-NMR ($CDCl_3$) δ: 1.44 (dt, 1H, J=1.4 and 8.8 Hz), 1.76 (dd, 1H, J=2.9 and 12.8 Hz), 2.11 (s, 3H), 2.47 (dd, 1H, J=3.6 and 12.8 Hz), 2.99 (bs, 1H), 3.44 (m, 1H), 4.76 and 4.87 (AB system,

2H, J=12.4 Hz), 5.88 (dd, 1H, J=3.0 and 5.6 Hz), 6.32 (dd, 1H, J=3.0 and 5.6 Hz), 7.16–7.39 (m, 9H). ^{13}C-NMR ($CDCl_3$) δ: 21.4, 31.0, 42.1, 49.3, 49.7, 67.1, 78.5, 125.0, 125.3, 128.0, 128.2, 128.4, 129.5, 132.1, 135.2, 138.5, 140.3, 142.1 and 169.1. MS (EI): 366 (1.4, M^+), 350 (0.2), 227 (4.1), 197 (5.3), 139 (6.5), 91 (100.0) and 77 (6.1).

*(S_1,R_2,S_4,S_s)-Benzyl 2-(*p*-tolylsulfinyl)-bicyclo[2.2.1]hept-5-ene-2-carboxylate* endo-***6B***

$[\alpha]_D^{20}$=−33.43 (c=2.8, $CHCl_3$). IR ($CHCl_3$): 3020, 2980, 1710, 1600, 1495, 1330, 1280, 1250 and 1150 cm^{-1}. ^{1}H-NMR ($CDCl_3$) δ: 1.59 (m, 1H), 1.82 (dd, 1H, J=2.8 and 12.8 Hz), 2.01 (dd, 1H, J=3.5 and 12.8 Hz), 2.03 (bd, 1H, J=9.3 Hz), 2.35 (s, 3H), 3.06 (bs, 1H), 3.78 (m, 1H), 4.81 and 4.88 (AB system, 2H, J=12.5 Hz), 5.92 (dd, 1H, J=3.0 and 5.6 Hz), 6.43 (dd, 1H, J=3.0 and 5.6 Hz) and 7.18–7.45 (m, 9H). ^{13}C-NMR ($CDCl_3$) δ: 21.4, 32.9, 43.3, 46.3, 47.5, 66.7 and 76.7, 124.8, 128.1, 128.3, 129.6, 133.9, 135.4, 137.7, 141.1, 141.9 and 167.9. MS (EI): 366 (2.3, M^+), 350 (0.7), 227 (5.7), 197 (8.0), 169 (5.2), 139 (8.2), 91 (100.0) and 77 (8.9). Anal. Calcd for $C_{22}H_{22}O_3S$: C, 72.10; H, 6.05; S, 8.75. Found: C, 72.06; H, 5.71; S, 8.55.

*(S_1,S_2,S_4,S_s)-Benzyl 2-(*p*-tolylsulfinyl)-bicyclo[2.2.1]hept-5-ene-2-carboxylate* exo-***6A***

$[\alpha]_D^{20}$=+12.67 (c=0.9, $CHCl_3$). IR ($CHCl_3$): 3025, 2975, 1710, 1485, 1330, 1260, 1235 and 1140. ^{1}H-NMR ($CDCl_3$) δ: 1.30 (bd, 1H, J=9.0 Hz), 1.60 (m, 1H), 2.16 (dd, 1H, J=2.8 and 13.5 Hz), 2.36 (s, 3H), 2.47 (dd, 1H, J=3.6 and 13.5 Hz), 3.04 (bs, 1H), 3.38 (bs 1H), 4.70 and 4.88 (AB system, 2H, J=12.5 Hz), 6.26 (dd, 1H, J=2.9 and 5.6 Hz), 6.46 (dd, 1H, J=3.0 and 5.6 Hz) and 7.12–7.45 (m, 9H). ^{13}C-NMR ($CDCl_3$) δ: 21.5, 28.2, 42.2, 46.6, 51.2, 66.9, 78.0, 125.4, 128.3, 128.4, 128.5, 129.5, 133.9, 135.4, 137.7, 142.1 and 168.6. MS (EI): 366 (1.7, M^+), 227 (2.4), 197 (4.6), 139 (5.6), 91 (100.0) and (6.3).

Benzyl 7-methoxy-2,3,9,10-tetrahydrophenanthrene-1-carboxylate ***9***

Eluent: hexane–CH_2Cl_2 (2:1). By using $TiCl_4$, yield: 88% (yellow oil). $[\alpha]_D^{20}\approx 0$ (c=2.4, $CHCl_3$). IR ($CHCl_3$): 2920, 1670, 1590, 1520, 1490, 1260, 1160 and 1030 cm^{-1}. ^{1}H-NMR ($CDCl_3$) δ: 2.41 (m, 2H), 2.63 (bs, 4H), 2.79 (m, 2H, H_3), 3.82 (s, 3H, OMe), 5.24 (s, 2H), 6.73 (bs, 1H), 6.77 (d, 1H, J=2.7 Hz), 7.10 (bs, 1H), 7.25 (d, 1H, J=8.2 Hz) and 7.39 (m, 5H). ^{13}C-NMR ($CDCl_3$) δ: 21.9, 23.9, 26.8, 28.7, 55.3, 66.1, 111.3, 113.8, 124.2, 124.9, 127.7, 128.1, 128.5, 134.4, 136.5, 138.1, 138.6, 159.2 and 167.2. MS (EI): 348 (5.6, M^++2), 347 (33.3, M^++1), 346 (100.0, M^+), 255 (7.1), 237 (19.3), 212 (45.3), 211 (48.4), 196 (13.3), 179 (16.6), 165 (22.5), 91 (61.2), 77 (8.4) and 65 (9.8). HRMS: exact mass calcd for $C_{23}H_{22}O_3$ (M^+): 346.1569, found: 346.1569.

(S)-Benzyl 7-methoxy-1,9,10,10a-tetrahydrophenanthrene-2-carboxylate ***11***

In a polyethylene high pressure tube was placed dienophile **3** (50 mg, 0.17 mmol, 1.0 equiv) in CH_2Cl_2 (1 ml). Then, Dane's diene 1.0 M in benzene was added (333 μl, 2.0 equiv) and the mixture reaction was pressured at 12 Kbar for 24 h at rt. Then, the mixture was carefully concentrated and the residue was purified by flash chromatography (hexane–dicloromethane 1:1) to give 42 mg of **11** as a yellow oil (Yield: 72%). $[\alpha]_D^{20}$=−241.8 (c=1.3, $CHCl_3$). e.e.≥97% [by using $Pr(hfc)_3$ as chiral shift reagent]. IR ($CHCl_3$): 2920, 1670, 1590, 1520, 1490, 1260, 1160 and 1030 cm^{-1}. ^{1}H-NMR ($CDCl_3$) δ: 1.45–1.65 (m, 1H), 2.01–2.28 (m, 1H), 2.56–2.74 (m, 2H), 2.78–2.91 (m, 3H), 3.82 (s, 3H), 5.23 (s, 2H), 6.59 (dd, 1H, J=2.7 and 6.1 Hz), 6.64 (d, 1H, J=2.7), 6.77 (dd, 1H, J=2.8 and 8.8 Hz), 7.24 (dd, 1H, J=3.1 and 6.1 Hz) and 7.38 (m, 5H), 7.71 (d, 1H, J=8.8 Hz). ^{13}C-NMR ($CDCl_3$) δ: 29.6, 29.9, 30.7, 36.4, 55.2, 65.0, 113.3, 114.0, 125.2, 125.6, 128.0, 128.4, 135.3, 136.5, 140.8, 143.0, 159.7 and 167.0 (CO). MS (EI): 348 (5.1, M^++2), 347 (31.4, M^++1), 346 (100.0, M^+),255 (13.8), 237 (30.1), 211 (73.0), 196 (18.2), 179 (24.9), 165 (33.6), 91 (92.9), 77 (33.4) and 65 (18.0). HRMS: exact mass calcd for $C_{23}H_{22}O_3$ (M^+): 346.1569, found: 346.1577.

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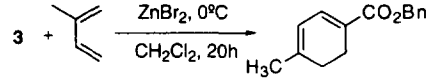
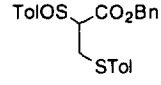
8. Other catalysts, like BF_3 and Et_2AlCl, have been used in reactions of dienophile **3** with cyclopentadiene but they do not improve the results depicted in Table 1 and therefore they have not been collected.
9. We have observed that the chemical shifts differences of the olefin protons (H_5 and H_6) and head protons (H_1 and H_4) in adducts **5** and **6** is very different and constitutes a diagnostic criteria of their *endo* or *exo* character. In all cases, $(\Delta\delta_{5,6})$*endo*=0.6–0.4 whereas $(\Delta\delta_{5,6})$*exo*=0.2–0.1 and $(\Delta\delta_{1,4})$*endo*=0.7–0.5 whereas $(\Delta\delta_{1,4})$*exo*=0.4–0.3.
10. The variation of the efficiency of zinc halides as catalyst ($ZnCl_2$<$ZnBr_2$<ZnI_2) in reactions involving chelation processes with sulfinyl derivatives has been observed in many other cases, Diels–Alder reaction of sulfinyl dienes (see for instance: Yang, T-K.; Chu, H-Y.; Lee, D-S.; Jiang, Y-Z.; Chou, T-S. *Tetrahedron Lett.* **1996**, *37*, 4537) and reduction of sulfinyl ketones (see Barros, D.; Carreño, M. C; García Ruano, J. L.; Maestro, M. C. *Tetrahedron Lett.* **1992**, *33*, 2733) and imines (García Ruano, J. L.; Lorente, A.; Rodriguez, J. H. *Tetrahedron Lett.* **1992**, *33*, 5637). Although a different ability of the zinc halides from chelates maybe invoked some cases, we suspect that their solubility differences ($ZnCl_2$<$ZnBr_2$<ZnI_2), determining that dispersion but no solubilization was observed in some cases at low temperatures, could be also responsible of this behavior.
11. Recently, from the study of the behavior of *bis-p*-tolylsulfinyl ethylene derivatives (Carretero, J.C.; García Ruano, J.L.; Martín Cabrejas, L.M. *Tetrahedron: Asymmetry* **1997**, *8*, 409–416), we have point out about the fact that the usual low effect of the sulfinyl group on the dienophilic reactivity

of vinylsulfoxides is strongly increases when the sulfinyl moiety takes part in a cyclic structure able to preclude the conjugation between the lone electron pair at sulfur and the double bond.

12. For instance, dienophile **3** reacted with isoprene (1.2 equiv $TiCl_4$, −30°C, 20 h) to give the achiral desulfinylated adduct shown below as the major product.



13. Changes of regioselectivity with the use of high pressures has been previously reported but no satisfactory explanation has been formulated (Arseniyadis S., Rodriguez R., Yashunsky D.V., Camara J., Ourisson, G. *Tetrahedron Lett.* **1994**, *35*, 4843).
14. This catalyst is specially useful to induce Diels–Alder reactions on furan (see Brion F., *Tetrahedron Lett.* **1982**, *23*, 5299).
15. Compound **16** was the only identified from these mixtures. It presumably derives from addition of sulfenic acid (generated by decomposition of dienophiles by the Lewis acids).



16

16. Taking into account that retro Diels–Alder processes are easier when the temperature became higher or Lewis acids are added, the fact that these reactions do not progress under thermal or catalytic conditions could be the result of the equilibration between starting products and final adducts, being the first the most stable ones, instead of the lack of reactivity of the furan.
17. A similar trial starting from the *exo* adduct could not be made because of their unstability which preclude to obtain pure sample of them.
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