Stereoselectivity in the Cycloaddition of Cyclopentadiene to *N*-Fumaroyl-[2*R*,*S*(*R*)]-Bornane-10,2-sulfinamide Monomethyl Ester

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The cyclic [2*R*,*S*(*R*)]-bornane-10,2-sulfinamide (−)-**2b**, an analogue of *Oppolzer*'s camphor-derived sultam (−)-**2a**, was synthesized by reduction of the known *N*-alkylidenesulfinamide (+)-**1b** with $NaBH_4$. The uncatalyzed [4 + 2] cycloaddition of cyclopentadiene to the methyl ester (−)-**3b** of the *N*-fumaroylsulfinamide, obtained from (−)-**2b**, proceeds with lower *endo* and π-facial selectivity as compared to dienophiles (−)-**3a**,**c**. In contrast to these latter, the diastereoselectivity is reversed either in apolar CCl_4 or in the presence of $TiCl_4$. This inversion is explained by a competitive C(α)-*si* addition on the reactive *anti*-s-*trans* conformer.

Introduction. – We recently presented the complete π-facial selectivity observed in the $TiCl_4$-catalyzed [4 + 2] cycloaddition of cyclopenta-1,3-diene to *N*-fumaroylmono- and *N*,*N*′-fumaroylbis[(2*R*)-bornane-10,2 sultam] derived from (−)-**1a** [1][2]. Besides the influence of various *Lewis* acids, as well as applications to various dienes [3], we also reported in detail the influence of the solvent polarity, the latter ranging from the apolar CO_2 supercritical fluid to ionic liquid salts [4][2]). For this type of auxiliary, with respect to the disguised C_2-symmetrical 2,5-disubstituted pyrrolidine concept developed by *Kim* and *Curran* [8], we have been, for several years, interested in determining the steric and electronic role [9] of each S=O substituent of the sultam moiety[3]). Recently, the preparation of *N*-alkylidenesulfinamide (+)-**1b** [10] by one of us opened the way to a more detailed study on the preparation and influence of the new chiral auxiliary (−)-**2b** on its derived dienophile (−)-**3b**.

Results and Discussion. – Reduction of *N*-alkylidenesulfinamide (+)-**1b** with $NaBH_4$ (MeOH, 5.8 mol-equiv., 20°; yield 89%) cleanly afforded the new crystalline *N*-alkylsulfinamide (−)-**2b**. Interestingly, the known diastereoisomeric *N*-alkylidenesulfinamide (−)-**1c** [10] also gave, under similar reductive conditions, exclusively the same cyclic sulfinamide (−)-**2b**. This suggests competitive epimerization at the S-atom either after or before the reduction, as observed earlier [10]. The ^{1}H-NMR spectrum of (−)-**2b** shows a very broad signal for the NH group, probably due to exchange with traces of humidity. Indeed, a solution of (−)-**2b** in rigorously dried $CDCl_3$ reveals a long-range coupling (^4J) of NH with one H−C(10) and a vicinal coupling with its neighboring H−C(2) ($^3J = 2.0$ Hz).

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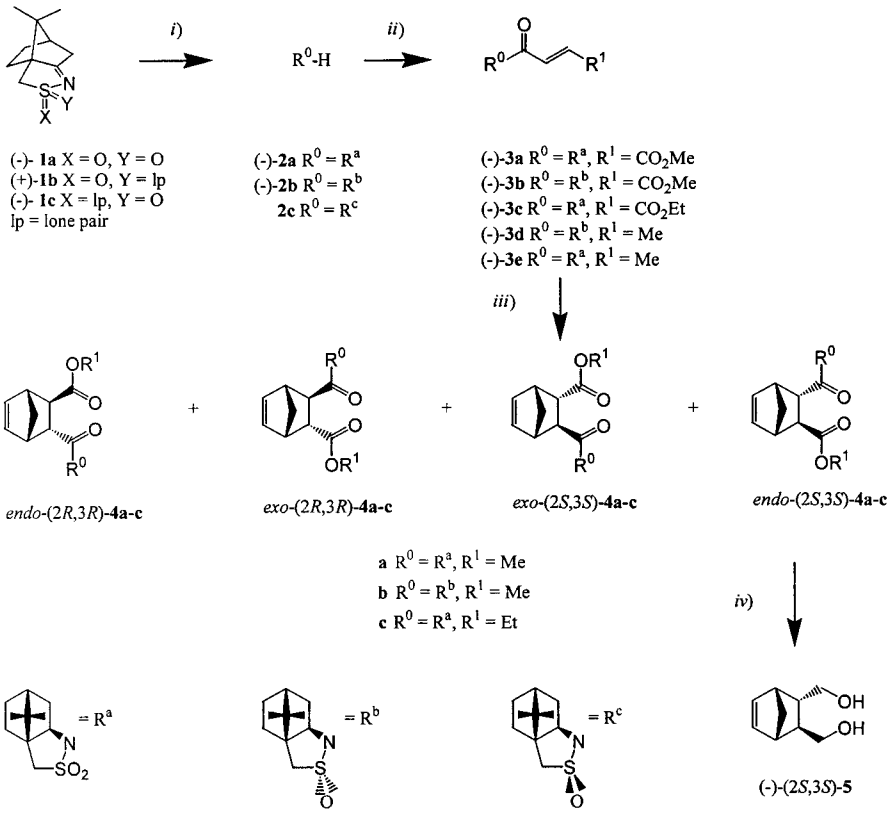
[2]) For previous asymmetric [4 + 2] cycloadditions of fumarates, see ref. cit. in [1–4]. For recent examples involving chiral dienes, chiral dienophiles, and chiral catalysts, see [5], [6], and [7], respectively.

[3]) Questions and proposals of *C. C.* to Prof. *D. P. Curran* at the occasion of the '34th Euchem Conference on Stereochemistry', 24–30 April, 1993, Bürgenstock (president Prof. *W. Oppolzer*), as well as to *R. K.* at the occasion of the 'IX European Symposium of Organic Chemistry', 18–23 June, 1995, Warsaw (see Abstracts, p. 128).

Scheme 1



Conditions for $R^0 = R^b$: *i*) $NaBH_4$, MeOH. *ii*) $AlMe_3$, toluene 110°, dimethyl fumarate or methyl crotonate. *iii*) Cyclopentadiene, solvent, without (20°) or with (−78°) 1.0 mol-equiv. of $TiCl_4$. *iv*) $LiAlH_4$, THF.

An X-ray analysis of (−)-**2b**[4]), allowed the confirmation of the [*S*(*R*)]-configuration at the S-atom (see *Fig. 1*). PM3 Calculations [13] suggest that the more stable conformer of (−)-**2a**, directing its H−N bond *anti*-periplanar to the H−C(2) bond as expressed by its X-ray analysis[5]), is 1.66 kcal/mol lower in energy than the conformer possessing a H−N bond bisecting the O=S=O angle. The barrier of the pyramidal inversion was calculated to be 3.17 kcal/mol. In contrast, conformer (−)-**2b**, projecting the N lone pair *anti*-periplanar to the S=O bond, as depicted in *Fig. 1*, is 2.31 kcal/mol lower in energy than the conformer orientating the H−N bond *anti*-periplanar to the S=O moiety[6]). The barrier of pyramidal inversion was estimated to be 5.92 kcal/mol.

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[4]) For the X-ray analysis of a [*S*(*S*)]-bornane-10,2-sulfinamide derivative with a calculated rather than a measured H−N position, see [12].

[5]) See Footnote 9 in [11].

[6]) This conformation benefits from the anomeric stabilization of the N lone pair, *anti*-periplanar to the pseudoaxial S=O group as well as to the reduced steric interaction of the H−N substituent with respect to the S lone pair.

Experiments from -80 to $+50°$ in CD_2Cl_2 and $CDCl_3$ respectively, were performed without noticeable dynamic conformational changes in both ^{1}H- and ^{13}C-NMR analyses. With the more sophisticated density-function DN** method [13], (−)-**2b** was found to be 2.41 kcal/mol lower in energy than the corresponding diastereoisomer **2c**, suggesting a possible thermodynamic epimerization at the S-atom after the reductive process. The steric interaction of the Me(8) with the S=O group may partially account for this destabilization.

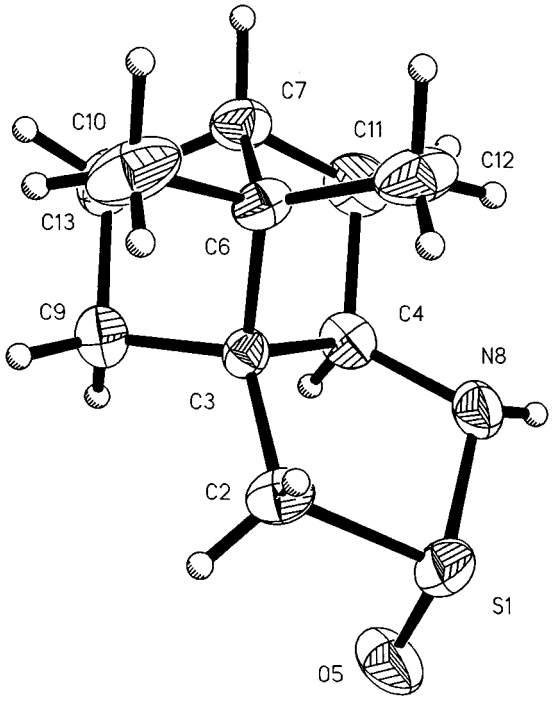

Fig. 1. *X-Ray crystal structure of (−)-***2b**

As a reactive dienophile, whose *endo* and π-facial selectivity may easily be determined by ^{1}H-NMR analysis, we selected the methyl ester derivative (−)-**3b** of the *N*-fumaroylsulfinamide, readily obtained from (−)-**2b** under neutral conditions (Me_3Al, toluene 60°, dimethyl fumarate (1.0 mol-equiv.); yield 59% [14]). It is noteworthy to mention that, under the usual basic conditions (*viz.* NaH or Et_3N, toluene, 20°; acid chloride of methyl hydrogen fumarate (1.0 mol-equiv.) [15], the reaction failed[7]).

For the comparison of the two dienophiles (−)-**3a**,**b**, we decided to perform their uncatalyzed cycloadditions to cyclopenta-1,3-diene (10 mol-equiv., 20°, 20 h) in solvents of different polarity, since strong inverted-directing effects were already observed for similar chiral auxiliaries [18]. As before, the extent of diastereoselectivity

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[7]) Under these basic conditions, the preparation of the *N,N′*-fumaroylbis[(2*R*)-bornane-10,2-sulfinamide] also failed. For alternative neutral acylation conditions, see [16][17].

was determined by integration of the signals of the olefinic H-atoms in the 500-MHz ^{1}H-NMR spectra of the crude cycloadducts **4a**,**c** [1][8]). Purification by chromatography (SiO_2, cyclohexane/AcOEt 95:5 → 8:2) allowed the isolation of a faster-eluting pair of diastereoisomers *endo*/*exo*-(2*S*,3*S*)-**4b** as well as a more polar pair of diastereoisomers *endo*/*exo*-(2*R*,3*R*)-**4b**, similarly to their **4a**,**c** counterparts [1]. Reduction of each pair of diastereoisomers (THF, $LiAlH_4$ 2.0 mol-equiv., 20°, 95%) afforded optically pure known diols (−)-(2*S*,3*S*)-**5** and (+)-(2*R*,3*R*)-**5**, respectively, as confirmed by chiral GC analysis and attribution of the absolute configuration by comparison with authentic material [19][9]).

The results summarized in *Table 1* show several aspects of interest. For example the global diastereoselectivity of (−)-**3a** (*Entries 1–4*) decreases from 66 to 20% de from $MeNO_2$ to CCl_4[10]). Although slightly more selective, the analogous monoethyl ester (−)-**3c** (*Entries 11–14*) exhibits the same trend, the diastereoselectivity decreasing from 68 to 50% de. With 46% de in $MeNO_2$, the diastereoselectivity of (−)-**3b** is in all cases lower than that of (−)-**3a** (*Entries 6–9*), but in addition, the sense of induction is even reversed from the C(α)-*re* to the C(α)-*si* face in CCl_4. The same trends are also observed for the *endo*-π-facial selectivity, although, for the uncatalyzed cycloadditions, the *endo*/*exo* ratio remains almost constant for (−)-**3a**,**b** despite the polarity changes

Table 1. *Uncatalyzed Cyclopentadiene [4+2] Cycloaddition* (20 h at 20°) *to (−)*-**3a**–**c**

Entry	Dieno-phile	Solvent	Yield [%]	**4a**–**c**					de		
				endo-(2*R*,3*R*)	*exo*-(2*R*,3*R*)	*exo*-(2*S*,3*S*)	*endo*-(2*S*,3*S*)	*endo*/*exo*	global	*endo*	exo
1	(−)-**3a**	$MeNO_2$	98	54	29	9	8	62:38	66	74	53
2	(−)-**3a**	MeCN	97	53	29	10	8	61:39	64	74	49
3 [1]	(−)-**3a**	CH_2Cl_2	98	51	29	12	8	59:41	60	73	41
4	(−)-**3a**	CCl_4	96	41	19	18	22	63:37	20	30	3
5[a]) [1]	(−)-**3a**	CH_2Cl_2	95	88	5	3	4	92: 8	86	91	25
6	(−)-**3b**	$MeNO_2$	97	46	27	13	14	60:40	46	53	35
7	(−)-**3b**	MeCN	97	44	26	13	17	61:39	40	44	33
8	(−)-**3b**	CH_2Cl_2	96	34	24	20	22	56:44	16	21	9
9	(−)-**3b**	CCl_4	95	16	9	34	41	57:43	−50	−44	−58
10[a])	(−)-**3b**	CH_2Cl_2	95	1	2	19	78	79:21	−94	−97	−81
11	(−)-**3c**	$MeNO_2$	96	60	24	9	7	67:33	68	79	45
12	(−)-**3c**	MeCN	96	56	26	10	8	64:36	64	70	56
13 [1]	(−)-**3c**	CH_2Cl_2	95	54	23	12	11	65:35	54	66	31
14	(−)-**3c**	CCl_4	94	40	25	16	19	59:41	50	36	22
15[a])	(−)-**3c**	CH_2Cl_2	94	90	3	3	4	94: 6	86	91	0

[a]) Reaction performed with 1.0 mol-equiv. of $TiCl_4$ at −78°.

[8]) Due to partially overlapping signals of the olefinic H-atoms (see *Exper. Part*), the MeO signals of **4b** were integrated, since they exhibit the same displacement pattern as for **4a** [1]. The *endo*-(2*R*,3*R*)-, *endo*-(2*S*,3*S*)-, *exo*-(2*R*,3*R*)-, and *exo*-(2*S*,3*S*)-diastereoisomers **4b** resonate at 3.70, 3.69, 3.63, and 3.62 ppm, respectively.

[9]) By means of a commercially available chiral *Brechbuehler BGB-174* capillary column (30 m, 0.25 mm, 0.25 μm, 120°, 94 KPa He), the enantiomers could be separated: t_R 145.6 min for (+)-(2*R*,3*R*)-**5** and 148.2 min for (−)-(2*S*,3*S*)-**5**.

[10]) As earlier reported for analogous dienophiles and shown in *Fig. 2*, a linear relationship is observed between the logarithm of the diastereoisomer ratio and the solvent polarity according to the *Reichardt* scale [4][18].

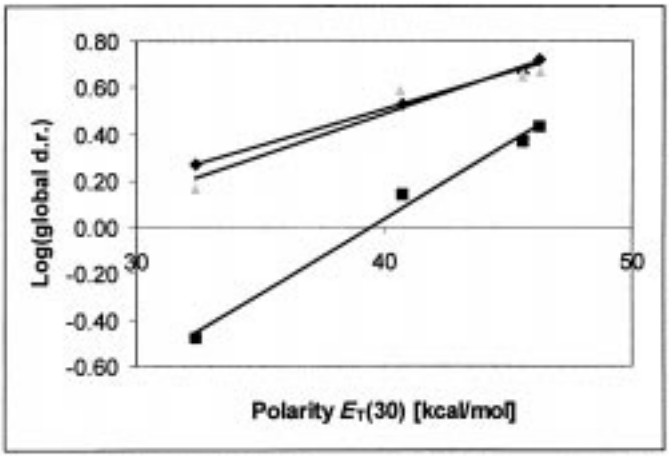

Fig. 2. *Dependence of the global π-facial selectivity of (−)-***3a** (▲), (−)-**3b** (■) and (−)-**3c** (◆) *with respect to the solvent polarity for the uncatalyzed [4 + 2] cycloaddition to cyclopenta-1,3-diene*

((−)-**3a**,**b** *ca.* 60:40). The variation of the *endo*/*exo* ratio is more pronounced for dienophile (−)-**3c**, 67 to 59:33 to 41, due to a decrease, in apolar solvents, of the enhanced *endo* selectivity resulting from the presence of a more bulky alkyl substituent. Except for (−)-**3b** in apolar CCl_4, the π-facial selectivity for *exo*-attack is usually lower when compared to the *endo*-approach. This results from the weaker steric interaction of the cyclopentadiene methylene group with the chiral auxiliary; this interaction predominates when involving the S=O moiety of the *anti*-s-*trans* conformation.

In the case of the sultam derivative (−)-**3e** [15], X-ray analysis of the 1:1 $TiCl_4$ complex has shown chelation of the metal with both the C=O and the pseudoequatorial S=O moieties [20]. It was also reported that addition of 1.0 mol-equiv. of $TiCl_4$ to (−)-**3a** at −78° (*Entry 5*) drastically increases the *endo* (92%) as well as global π-facial (86%) selectivities [1]. We confirmed similar topological discrimination with dienophile (−)-**3c** (*Entry 15*, 94% *endo*), but we were especially interested in comparing the influence of this *Lewis* acid on (−)-**3b**, with respect to the absence of the pseudoequatorial S=O group. In this specific case, despite a relatively disappointing *endo*/*exo* ratio (*Entry 10*, *ca.* 80:20), both *endo*- and *exo*-π-facial selectivities strongly favored the opposite C(α)-*si* approach, with 97 and 81% de, respectively.

To rationalize these results, we compared, by PM3 semi-empirical methods [13][11]), the energies of the possible coplanar s-*cis* and s-*trans* conformations of the simplified dienophiles (−)-**3d**,**e**[12]). A systematic rotation around the N−C(O) bond (*Fig. 3*) shows, as expected, similar energy profiles for both auxiliaries, despite a wider well of energy for s-*cis* (−)-**3d**, resulting from weaker steric interactions in the 120–140° and 300–340° regions. Nevertheless, in the *syn*- (340–360°) and *anti*- (160–180°)

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[11]) An identical constraint of 0.2 mdyn/Å^2 for the O=C−C=C torsion angle was used for comparison with an earlier report [9d].

[12]) The *N*-but-2-enoylsulfinamide (−)-**3d** was obtained in 70% yield from (−)-**2b** (Me_3Al (1.1 mol-equiv.), methyl crotonate (1.6 mol-equiv.), toluene, 60°, 20 h).

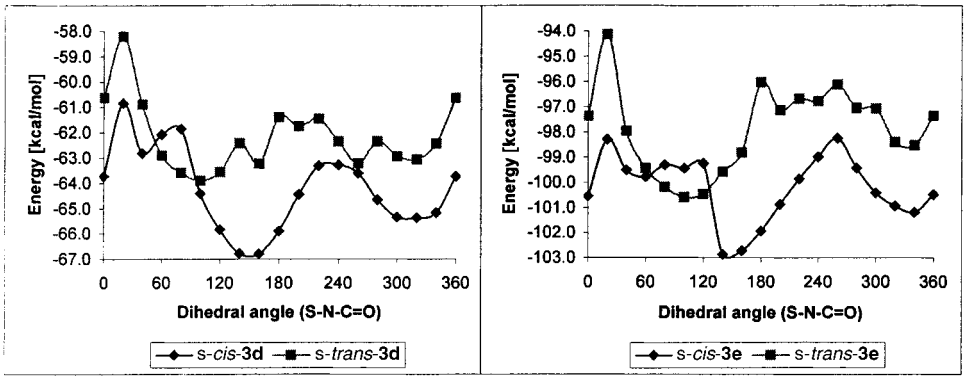

Fig. 3. *Rotomer energies for coplanar dienophiles (–)-***3d,e**

Scheme 2

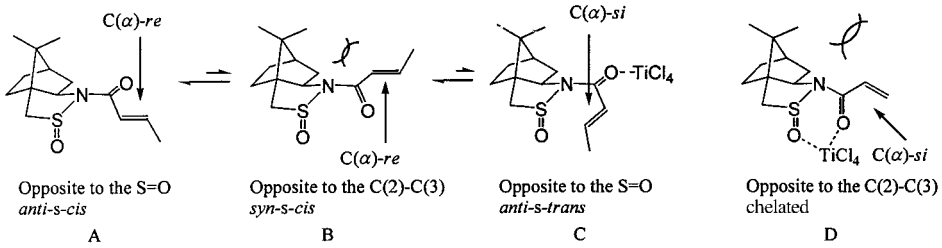

Table 2. *Energy, LUMO, and Dipole Moment of Selected Coplanar Conformations of (–)-***3d,e**

S–N–C=O [°]	Conformation	(–)-**3d**			(–)-**3e**		
		Energy [kcal/mol]	LUMO [eV]	Dipole [D]	Energy [kcal/mol]	LUMO [eV]	Dipole [D]
340	*syn*-s-*cis*	– 65.2	– 0.337	5.8	– 101.2	– 0.411	7.2
0	*syn*-s-*cis*	– 63.7	– 0.322	6.4	– 100.5	– 0.394	7.3
160	*anti*-s-*cis*	– 66.8	– 0.424	3.6	– 102.7	– 0.557	2.8
180	*anti*-s-*cis*	– 65.9	– 0.431	3.2	– 101.9	– 0.565	2.7
340	*syn*-s-*trans*	– 62.4	– 0.421	6.2	– 98.5	– 0.467	7.7
0	*syn*-s-*trans*	– 60.6	– 0.351	6.8	– 97.4	– 0.443	7.8
160	*anti*-s-*trans*	– 63.3	– 0.505	4.4	– 98.8	– 0.652	3.1
180	*anti*-s-*trans*	– 61.4	– 0.529	3.9	– 96.0	– 0.677	3.0

conformations, allowing the optimum stereoelectronic interaction between the sulfinamide/sulfonamide N and the dienophilic π-system, subtle differences appear. Indeed, in the case of the sultam derivative (–)-**3e**, in contrast to the *anti*-s-*trans* and *syn*-s-*trans* conformers, higher in energy by 3.9 and 4.2 kcal/mol, respectively, only the *anti*-s-*cis* and *syn*-s-*cis* conformers, separated by *ca.* 1.5 kcal/mol (see *Table 2*), were earlier considered [9d]. The situation might well change with (–)-**3d**, since the *anti*-s-*trans* conformer is closer in energy to the C(α)-*re* directing *anti*-s-*cis* and *syn*-s-*cis* conformers **A** (3.5 kcal/mol) and **B** (1.9 kcal/mol), respectively (*Scheme 2*). Due to the

opposite direction of their S=O and C=O partial dipole moments, the global dipoles of the *anti*-s-*cis*/*anti*-s-*trans* conformers are smaller than their *syn* conformers (*Table 2*). By analogy with the sultam analogues (−)-**3a**,**e**, their transition states should also possess smaller dipole moments [4] and thus, as a consequence of their stabilization and participation in apolar solvents, the reverse C(α)-*si* attack on the *anti*-s-*trans* conformer should induce a decrease or inversion of the π-facial selectivity. To explain this kind of reverse selectivity, *Oppolzer* earlier proposed chelation with the pseudoaxial S=O group [21], and this rationalization can not be fully excluded in our case, since the sulfinyl O-atom is even more basic than the sulfonyl one. Nevertheless, we argue that this chelating mode (*Scheme 2*, **D**) precludes the optimum electronic activating interaction of the O=C−C=C moiety with the sulfinamide/sulfonamide N-π-system[13]). Thus, since the sense of induction can not be rationalized by $TiCl_4$ chelation of both C=O and S lone pairs, we prefer to invoke an argument used in the case of the uncatalyzed cycloaddition in apolar solvents, namely complexation of the more accessible C=O lone pair, forcing the C=C bond into a more reactive s-*trans* conformation as shown in *Scheme 2* (**C**) and by the lower LUMO level or larger atomic coefficient (*Table 2*, *Footnote 13*). This hypothesis is in accord with both the bathochromic and hypsochromic shifts of the C=O and S=O bond frequencies, respectively, observed in the IR spectrum of the $TiCl_4$/(−)-**3d** 1:1 complex[14]), in contrast to (−)-**3e**, which shows bathochromic shifts of both moieties when chelated by $TiCl_4$ [15].

Conclusion. – According to *Kim* and *Curran*, the masked C_2 symmetry of the (2*R*)-bornane-10,2-sultam chiral auxiliary (−)-**2a** is based on the C(α)-*re* directing effect of both the C(2)−C(3) substituent and the pseudoaxial S=O in the *syn*-s-*cis* and *anti*-s-*cis* conformations, respectively. Although we could not study the comparative steric or electronic influence of this missing pseudoaxial S=O group in **2c**, due to epimerization at the S-center, we nevertheless showed that the pseudoequatorial S=O substituent in (−)-**2a** is essential in controlling the s-*cis*/s-*trans* conformation, hence the inductive sense of the auxiliary on the derived dienophiles (−)-**3a**,**b**. Indeed, as compared to (−)-**3b**, higher diastereoselectivity was observed under similar uncatalyzed conditions when the conformationally restricted dienophile (−)-**3a** was allowed to react with cyclopenta-1,3-diene. The participation of the *anti*-s-*trans* conformer in the stereochemical course of the cycloaddition of (−)-**3b** allows inversion of the sense of induction and the attainment of up to 97% de for *endo* attack, when the cycloaddition is carried out in an apolar solvent or in the presence of a *Lewis* acid.

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[13]) In addition, this chelate suffers from a potential steric interaction between the H−C(2) and the apical Cl-Ti atoms. This same halogen atom sterically interacts with one of the H−C(10) atoms, when the chelating S=O moiety is forced into a pseudoequatorial orientation. These interactions may be avoided at the price of *syn*-periplanarity of both the N and S lone pair. Finally, N-inversion of this latter conformer would lead to the opposite π-facial selectivity. PM3 Calculations suggest that, despite a lower LUMO level, the chelated form **D** (LUMO = −2.88 eV, C(α) = 0.00, C(β) = −0.06) could be less reactive than the complex **C** (LUMO = −2.35 eV, C(α) = 0.07, C(β) = −0.20), since the chemical reactivity is a function of the square of the atomic coefficients [9d].

[14]) In the presence of $TiCl_4$ (1.0 mol-equiv. in CH_2Cl_2), the C=O (1672 cm^{-1}) and S=O (1093 cm^{-1}) bands of (−)-**3d** were shifted to 1605 and 1097 cm^{-1}, respectively. For chelation of both C=O groups of a *N*-glyoxyloyl-(2*R*)-bornane-10,2-sultam, see [9b].

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Experimental Part

General. See [22].

X-Ray Crystal-Structure Determination of (−)-**2b**. A crystal grown from a hexane/CH_2Cl_2 soln., of $0.35 \times 0.28 \times 0.35$ mm size, covered by epoxy glue, was used for data collection by means of the *Nonius-MACH3* diffractometer. Unit-cell dimensions calculated for 15 reflections (θ range 18.62–23.79°) are: $a = b = 7.0640(4)$, $c = 43.620(3)$ Å, $V = 2176.9(9)$ Å^3; $Z = 8$, $d_{calc} = 1.216$ g·cm^{-3}, $\mu(CuK_\alpha) = 2.336$ cm^{-1}. Experimental intensities were corrected for *Lorentz*, polarization, and ψ-scan base absorption ($T_{min} = 93.13$, $T_{max} = 99.68$). A total of 1604 independent reflections with $I > 3\sigma(I)$ were obtained ($R_{int} = 0.02$). The structure was solved in the tetragonal $P4_12_12$ space group. During the final stage of refinement, the enantiomer was reversed, and subsequently the space group was transferred to $P4_32_12$, yielding a much better *R* factor and reasonable absolute structure parameter (−0.03(6)) [23]. Final R_1 and wR_2 are 0.0553 and 0.1312, resp. H-Atoms attached to C-atoms were included at their geometrical positions and refined with B_{iso} set at 1.2 of that of the parent atom; the NH group H-atom was found from difference map and refined isotropically. The structure was solved by the SHELXS86 [24] and refined with the SHELXL93 [25] programs. Crystallographic data for (−)-**2b** have been deposited with the *Cambridge Crystallographic Data Centre* as supplementary publication No. CCDC 153961. Copies of the data can be obtained, free of charge, on application to the CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44(1223)336033; e-mail: deposit@ccdc.cam.ac.uk).

*(1*S*,*S*(*R*),5*R*,7*R*)-10,10-Dimethyl-4-aza-3-thiatricyclo[5.2.1.0^{1,5}]decane 3-Oxide* (=*(2*R*,3a*S*,6*R*,7a*R*)-Hexahydro-8,8-dimethyl-3*H*-3a,6-methano-2,1-benzisothiazole 2-Oxide* (−)-**2b**). $NaBH_4$ (0.65 g, 17.1 mmol) was added in small portions at 20° (cooling with cold water) to a soln. of *N*-alkylidenesulfinamide (+)-**1b** (0.58 g, 2.94 mmol) in MeOH (20 ml). The mixture was stirred at 20° for 40 min and then evaporated. The solid residue was dissolved in H_2O (10 ml), and 10% aq. HCl soln. was added to pH 8. The mixture was extracted with CH_2Cl_2 and the org. phase dried ($MgSO_4$) and evaporated: 0.52 g (89%) of (−)-**2b**. Colorless solid. An anal. sample was obtained by crystallization from CH_2Cl_2/hexane. R_f (cyclohexane/AcOEt 6:4) 0.1. M.p. 158–162° (CH_2Cl_2/hexane). $[\alpha]_D^{20} = -84.9$ ($c = 2.25$, $CHCl_3$). IR (KBr): 3429, 3151, 1058. ^{1}H-NMR: 0.82 (*s*, 3 H); 0.92 (*s*, 3 H); 1.2–1.38 (*m*, 1 H); 1.5–2.05 (*m*, 6 H); 2.47 (*d*, *J* = 14.0, 1 H); 3.28 (*d*, *J* = 14.0, 1 H); 4.02 (br. *s*, 1 H); 4.28 (*dd*, *J* = 4.6, 8.1, 1 H). ^{13}C-NMR: 20.3 (C(8)); 20.8 (C(9)); 27.1 (C(5)); 31.6 (C(6)); 36.3 (C(3)); 46.5 (C(7)); 46.6 (C(4)); 56.9 (C(1)); 58.0 (C(10)); 70.5 (C(2)). Anal. calc. for $C_{10}H_{17}NOS$: C 60.26, H 8.60, N 7.03, S 16.09; found: C 59.98, H 8.60, N 7.12, S 16.22.

*(−)-[2*R*,*S*(*R*)]-*N*-[(*E*)-3-(Methoxycarbonyl)prop-2-enoyl]bornane-10,2-sulfinamide* (=*(−)-4-[(2*R*,3a*S*,6*R*,7a*R*)-Hexahydro-8,8-dimethyl-2-oxido-3*H*-3a,6-methano-2,1-benzisothiazol-1-yl]-4-oxobut-2-enoic Acid Methyl Ester (−)*-**3b**). A 1.0M soln. of Me_3Al in hexane (0.5 ml, 0.5 mmol) was added to a soln. of (−)-**2b** (199 mg, 1.0 mmol) and methyl hydrogen fumarate (144 mg, 1.0 mmol) in toluene (5.0 ml). After 20 h at 60°, the cold soln. was diluted with toluene, washed with 10% aq. HCl soln., dried, and evaporated. The crude oil was chromatographed (SiO_2, cyclohexane/AcOEt 95:5 → 3:2): 56% of pure crystalline (−)-**3b**. R_f (cyclohexane/AcOEt 6:4) 0.32. M.p. 118° (CH_2Cl_2/cyclohexane). $[\alpha]_D^{20} = -272.4$ ($c = 1.0$, $CHCl_3$), IR: 2970, 2890, 1729, 1692, 1440, 1360, 1302, 1269, 1167, 1136. ^{1}H-NMR: 0.86 (*s*, 3 H); 0.93 (*s*, 3 H); 1.1–1.7 (*m*, 2 H); 1.8–2.0 (*m*, 3 H); 2.1–2.2 (*m*, 2 H); 2.88 (*d*, *J* = 14, 1 H); 3.77 (*d*, *J* = 14, 1 H); 3.81 (*s*, 3 H); 4.44 (*dd*, *J* = 6, 6.8, 1 H); 6.90 (*d*, *J* = 15, 1 H); 7.45 (br. *s*, 1 H). ^{13}C-NMR: 19.9 (C(9)); 20.5 (C(8)); 27.0 (C(5)); 31.2 (C(6)); 38.0 (C(3)); 44.4 (C(4)); 47.0 (C(7)); 52.3 (MeO); 57.5 (C(1)); 59.4 (C(10)); 70.2 (C(2)); 132.7 (C(3′)); 133.4 (C(2′)); 163.8 (C(1′)); 165.3 (C(4′)). MS: 311 (1, M^+), 280 (2), 199 (2), 182 (10), 135 (40), 113 (100), 94 (12), 85 (14), 59 (14), 41 (12), 28 (22).

*(−)-[2*R*,*S*(*R*)]-*N*-[(*E*)-But-2-enoyl]bornane-10,2-sulfinamide* (=*(−)-(2*R*,3a*S*,6*R*,7a*R*)-Hexahydro-8,8-dimethyl-1-(1-oxobut-2-enyl)-3*H*-3a,6-methano-2,1-benzisothiazole 2-Oxide;* (−)-**3d**). A 1.0M soln. of Me_3Al in hexane (0.14 ml, 0.14 mmol) was added to a soln. of (−)-**2b** (25 mg, 0.126 mmol) and methyl crotonate (= methyl (2*E*)-but-2-enoate; 20 mg, 0.2 mmol) in toluene (2.0 ml). After 20 h at 60°, the cold soln. was diluted with toluene and 10% aq. HCl soln. After extraction and evaporation, the crude oil was chromatographed (SiO_2, cyclohexane/AcOEt 95:5 → 3:2): 70% of pure crystalline (−)-**3d**. R_f (cyclohexane/AcOEt 6:4) 0.38. M.p. 142–144° (AcOEt/cyclohexane). $[\alpha]_D^{20} = -306.2$ ($c = 0.4$, CH_2Cl_2). IR: 2966, 2894, 1694, 1650, 1457, 1365, 1326, 1298, 1229, 1131, 1064, 981. ^{1}H-NMR: 0.86 (*s*, 3 H); 0.92 (*s*, 3 H); 1.26 (*m*, 1 H); 1.38 (*m*, 1 H); 1.59 (*t*, *J* = 2.3, 1 H); 1.88 (*m*, 2 H); 1.92 (*d*, *J* = 7, 3 H); 2.07 (*dd*, *J* = 7.9, 13.9, 1 H); 2.18 (*m*, 1 H); 2.84 (*d*, *J* = 14.0, 1 H);

3.70 (*d*, *J* = 14.0, 1 H); 4.42 (*dd*, *J* = 4.8, 12.8, 1 H); 6.44 (br. *d*, *J* = 13.5, 1 H); 7.06 (*sext.*, *J* = 6.9, 1 H). ^{13}C-NMR: 18.3 (C(4′)); 19.9 (C(9)); 20.4 (C(8)); 27.0 (C5)); 31.2 (C(6)); 38.3 (C(3)); 44.4 (C(4)); 46.9 (C(7)); 57.3 (C(1)); 59.0 (C(10)); 70.0 (C(2)); 122.7 (C(2′)); 144.8 (C(3′)); 165.5 (C(1′)). MS: 267 (3, M^+), 219 (2), 203 (3), 182 (9), 135 (13), 107 (4), 93 (6), 79 (6), 69 (100), 53 (3), 41 (21).

*(1*R*,2*S*,3*S*,4*S*)-3-{[(2*R*,3*a*S*,6*R*,7*a*R)-Hexahydro-8,8-dimethyl-2-oxido-3*H*-3a,6-methano-2,1-benzisothiazol-1-yl]carbonyl}bicyclo[2.2.1]hept-5-ene-2-carboxylic Acid Methyl Est*er (*exo*-(2*S*,3S)-**4b**). To a soln. of (−)-**3b** (31 mg, 0.1 mmol) in CH_2Cl_2 (2 ml), 0.1M $TiCl_4$ in CH_2Cl_2 (1 ml, 0.1 mmol) was added. The mixture was cooled to −78°, and precooled 1M cyclopenta-1,3-diene in CH_2Cl_2 (1 ml, 1 mmol) was added dropwise and slowly along the inner cold surface of the reaction flask. After 18 h, the reaction was quenched with NH_4F and equilibrated. After addition of H_2O, the mixture was extracted with CH_2Cl_2 and the extract dried ($MgSO_4$) and evaporated under medium then high vacuum. ^{1}H-NMR: full conversion to a 1:2:19:78 mixture of *endo*-(2*R*,3*R*)/*exo*-(2*R*,3*R*)/*exo*-(2*S*,3*S*)/*endo*-(2*S*,3*S*)-cycloadducts **4b**. Chromatography (SiO_2, cyclohexane/AcOEt 95:5 → 8:2) afforded a faster eluting pair of diastereoisomer (1:4 mixture; 95%) and a more polar pair of diastereoisomer (1:1 mixture; 1.8%) as white crystalline material. Minor *exo*-(2*S*,3*S*)-diastereoisomer **4b** isolated from the mixture: R_f (cyclohexane/AcOEt 6:4) 0.58. M.p. 130–136°; IR: 2966, 1749, 1692, 1302, 1264, 1167, 1135. ^{1}H-NMR: 0.83 (*s*, 3 H); 0.92 (*s*, 3 H); 1.20–1.75 (*m*, 5 H); 1.80–2.1 (*m*, 4 H); 2.85 (*d*, *J* = 20, 1 H); 3.03 (br. *s*, 1 H); 3.20 (br. *s*, 1 H); 3.28 (br. *s*, 1 H); 3.40 (*t*, *J* = 4.0, 1 H); 3.62 (*s*, 3 H); 3.72 (*m*, 3 H); 4.40 (*dd*, *J* = 4.8, 7.8, 1 H); 6.15 (*dd*, *J* = 2.8, 5.5, 1 H); 6.36 (*dd*, *J* = 2.8, 5.5, 1 H). ^{13}C-NMR: 20.0 (*q*); 20.3 (*q*); 27.0 (*t*); 31.3 (*t*); 38.0 (*t*); 45.2 (*d*); 46.1 (*t*); 47.0 (*s*); 47.1 (*d*); 47.6 (*d*); 48.3 (*d*); 49.7 (*d*); 51.7 (*q*); 57.3 (*s*); 59.4 (*t*); 70.7 (*d*); 135.6 (*d*); 138.3 (*d*); 173.7 (*s*); 174.7 (*s*). MS: 377 (0, M^+), 280 (4), 262 (1), 199 (4), 182 (7), 144 (6), 135 (40), 113 (100), 85 (14), 59 (13), 41 (11), 28 (6).

*(1*S*,2*S*,3*S*,4*R*)-3-{[(2*R*,3*a*S*,6*R*,7*a*R)-Hexahydro-8,8-dimethyl-2-oxido-3*H*-3a,6-methano-2,1-benzisothiazol-1-yl]carbonyl}bicyclo[2.2.1]hept-5-ene-2-carboxylic Acid Methyl Ester* (*endo*-(2*S*,3*S*)-**4b**). Major *endo*-(2*S*,3*S*) diastereoisomer **4b** isolated from the above mixture: R_f (cyclohexane/AcOEt 6:4) 0.55. M.p. 130–136°. IR: 2966, 1749, 1692, 1302, 1264, 1167, 1135. ^{1}H-NMR: 0.84 (*s*, 3 H); 0.91 (*s*, 3 H); 1.20–1.75 (*m*, 5 H); 1.80–2.1 (*m*, 4 H); 2.63 (*dd*, *J* = 4, 6, 1 H); 2.84 (*d*, *J* = 20, 1 H); 3.18 (br. *s*, 1 H); 3.45 (br. *s*, 1 H); 3.69 (*s*, 3 H); 3.72 (*m*, 3 H); 4.34 (*dd*, *J* = 4.9, 7.8, 1 H); 6.09 (*dd*, *J* = 2.9, 5.5, 1 H); 6.29 (*dd*, *J* = 2.9, 5.5, 1 H). ^{13}C-NMR: 20.0 (*q*); 20.2 (*q*); 26.9 (*t*); 31.3 (*t*); 38.0 (*t*); 44.4 (*d*); 47.0 (*s*); 47.1 (*d*); 47.6 (*d*); 48.4 (*t*); 48.5 (*d*); 49.8 (*d*); 52.0 (*q*); 57.3 (*s*); 59.4 (*t*); 70.7 (*d*); 134.8 (*d*); 136.5 (*d*); 173.4 (*s*); 174.7 (*s*). MS: 377 (0, M^+), 311 (3), 280 (4), 262 (1), 199 (4), 182 (7), 144 (6), 135 (40), 113 (100), 85 (14), 59 (13), 41 (11), 28 (6).

*(1*S*,2*R*,3*R*,4*R*)-3-{[(2*R*,3*a*S*,6*R*,7*a*R)-Hexahydro-8,8-dimethyl-2-oxido-3*H*-3a,6-methano-2,1-benzisothiazol-1-yl]carbonyl}bicyclo[2.2.1]hept-5-ene-2-carboxylic Acid Methyl Ester* (*exo*-(2*R*,3*R*)-**4b**). To a soln. of (−)-**3b** (31 mg, 0.1 mmol) in $MeNO_2$ (2 ml), 1M cyclopenta-1,3-diene in $MeNO_2$ (1 ml, 1 mmol) was added dropwise. After 4 h, the mixture was evaporated under medium then high vacuum. ^{1}H-NMR: full conversion to a 47:27:13:14 mixture of *endo*-(2*R*,3*R*)/*exo*-(2*R*,3*R*)/*exo*-(2*S*,3*S*)/*endo*-(2*S*,3*S*)-cycloadducts **4b**. Chromatography (SiO_2, cyclohexane/AcOEt 95:5 → 8:2) afforded a faster eluting pair of diastereoisomers (1:1 mixture, 25%) and a more polar pair of diastereoisomers (5:3 mixture; 70%) as white crystalline material. Minor *exo*-(2*R*,3*R*)-diastereoisomer **4b** isolated from the mixture: R_f (cyclohexane/AcOEt 6:4) 0.43. M.p. 139–145°. IR: 3003, 2965, 1749, 1695, 1440, 1360, 1302, 1263, 1167, 1133. ^{1}H-NMR: 0.90 (*s*, 3 H); 0.93 (*s*, 3 H); 1.30–1.70 (*m*, 5 H); 1.80–2.1 (*m*, 4 H); 2.84 (*d*, *J* = 20, 1 H); 2.96 (*dd*, *J* = 2, 5, 1 H); 3.02 (br. *s*, 1 H); 3.28 (br. *s*, 1 H); 3.63 (*s*, 3 H); 3.72 (*m*, 3 H); 4.51 (*dd*, *J* = 4, 7, 1 H); 6.15 (*dd*, *J* = 2.5, 5.3, 1 H); 6.29 (*dd*, *J* = 2.5, 5.3, 1 H). ^{13}C-NMR: 19.9 (*q*); 20.5 (*q*); 26.9 (*t*); 31.3 (*t*); 38.5 (*t*); 44.4 (*d*); 45.5 (*d*); 46.2 (*d*); 46.8 (*d*); 47.0 (*s*); 47.4 (*d*); 48.5 (*d*); 51.7 (*q*); 57.3 (*s*); 59.4 (*t*); 70.7 (*d*); 136.2 (*d*); 136.9 (*d*); 174.7 (*s*); 175.0 (*s*). MS: 377 (0, M^+), 355 (1), 311 (2), 280 (5), 262 (2), 221 (1), 199 (3), 182 (10), 150 (6), 135 (30), 113 (100), 85 (11), 59 (11), 41 (8), 28 (23).

*(1*R*,2*R*,3*R*,4*S*)-3-{[(2*R*,3*a*S*,6*R*,7*a*R)-Hexahydro-8,8-dimethyl-2-oxido-3*H*-3a,6-methano-2,1-benzisothiazol-1-yl]carbonyl}bicyclo[2.2.1]hept-5-ene-2-carboxylic Acid Methyl Ester* (*endo*-(2*R*,3*R*)-**4b**). Major *endo*-(2*R*,3*R*) diastereoisomer **4b** isolated from the above mixture: R_f (cyclohexane/AcOEt 6:4) 0.43. M.p. 139–145°. IR: 3077, 2968, 2938, 1743, 1463, 1386, 1271, 1120, 1068. ^{1}H-NMR: 0.91 (*s*, 3 H); 0.93 (*s*, 3 H); 1.30–1.70 (*m*, 5 H); 1.80–2.1 (*m*, 4 H); 2.87 (*d*, *J* = 20, 1 H); 2.96 (*dd*, *J* = 2, 5, 1 H); 3.19 (br. *s*, 1 H); 3.33 (br. *s*, 1 H); 3.70 (*s*, 3 H); 3.72 (*m*, 3 H); 4.39 (*dd*, *J* = 4, 7, 1 H); 5.92 (*dd*, *J* = 2.5, 5.3, 1 H); 6.36 (*dd*, *J* = 2.5, 5.3, 1 H). ^{13}C-NMR: 19.9 (*q*); 20.3 (*q*); 26.9 (*t*); 31.2 (*t*); 38.5 (*t*); 44.4 (*d*); 45.5 (*d*); 46.2 (*d*); 46.8 (*d*); 47.0 (*s*); 47.4 (*t*); 48.3 (*d*); 52.0 (*q*); 57.3 (*s*); 59.4 (*t*); 70.5 (*d*); 132.7 (*d*); 138.3 (*d*); 174.7 (*s*); 175.0 (*s*). MS: 377 (0, M^+), 355 (1), 311 (2), 280 (5), 262 (2), 221 (1), 199 (3), 182 (10), 150 (6), 135 (30), 113 (100), 85 (11), 59 (11), 41 (8), 28 (23).

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