CHEMISTRY
A EUROPEAN JOURNAL

DOI: 10.1002/chem.201001436

Sulfur Ylide Promoted Synthesis of N-Protected Aziridines: A Combined Experimental and Computational Approach

Irena Dokli,[a] Ivana Matanović,[b] and Zdenko Hameršak*[a]

Abstract: A range of N-protected aziridines [*N*-Tosyl (*N*-Ts), *N*-2-trimethylsilylethanesulfonamide (*N*-SES), *N*-*tert*-butoxycarbonylamido (*N*-Boc), and *N*-*o*-nitrobenzenesulfonamide (*o*Ns)] were prepared in moderate to good yield and with high enantiomeric excess of both isomers starting from N-protected imines, using a sulfonium salt derived from Eliel's oxathiane. The diastereoselectivities of the reactions are influenced by the imine N-protecting group, the imine substituent, and the sulfide structure. An unusual *cis* selectivity was observed in the formation of *N*-tosyl-2-phenyl-3-*tert*-butylaziridine and *N*-*o*-trimethylsilylethanesulfonamide-2-phenyl-3-*tert*-butylaziridine, which was explained by using computational models. The analysis suggests that betaine formation in the case of *N*-tosyl-*tert*-butylaldimine aziridination using oxathiane benzyl sulfonium ylide **1′** is reversible and that the selectivity is determined at the rotation step, which is unusual for semistabilized ylide aziridination. We have shown herein that the steric bulk of an imine substituent, in combination with a sterically demanding sulfonium ylide, can also affect the reversibility of the reaction. This is the first example of this sort involving aziridinations using semistabilized ylides.

Keywords: asymmetric synthesis · azomethine ylides · density functional calculations · diastereoselectivity · ylides

Introduction

Chiral aziridines are highly useful synthetic intermediates. The strained three-membered ring can undergo a range of transformations, especially, ring opening to afford versatile, optically active compounds. During the past two decades, many different methods for asymmetric aziridination have been developed.[1] Amongst them, a significant number involve imine aziridinations using a carbene,[2] or a carbene equivalent, such as sulfur ylides. The reactions of chiral sulfur ylides with imines have proven to be a very powerful method for asymmetric aziridinations.[3]

Eliel's oxathiane[4] was first used by Solladié-Cavallo's group as a precursor of diastereo- and enantiopure ylides for asymmetric epoxidation and cyclopropanation.[5] This oxathiane also proved to be a very efficient chiral auxiliary for the synthesis of aziridines. Solladié-Cavallo et al. reported a two-step asymmetric synthesis of disubstituted *N*-tosyl (*N*-Ts) aziridines using (*R*,*R*,*R*,*S*)-(−)-benzylsulfonium salt **1** derived from Eliel's oxathiane.[6] Phosphazene base (EtP_2) was used to generate the ylide. Even though *cis*/*trans* mixtures were obtained, both isomers had high enantiomeric purity (98.7–99.9%) and the method was applicable for gram-quantity synthesis. Furthermore, the chiral auxiliary could be recovered and reused. However, the practicality of this procedure is limited by the use of expensive phosphazene base.

Recently, we reported an application of the above method for the asymmetric synthesis of the *N*-Ts, *N*-2-trimethylsilylethanesulfonamide (*N*-SES), and *N*-*tert*-butoxycarbonylamido (*N*-Boc) disubstituted aziridines, also in high enantiomeric excess (*ee*).[7] Sodium hydride was successfully used as a substitute for the sensitive phosphazene base EtP_2 without any loss of yield, enantio- or diastereoselectivity. Herein, we present a further investigation into the influence of the imine substituent on diastereoselectivity in a combined experimental and computational approach.

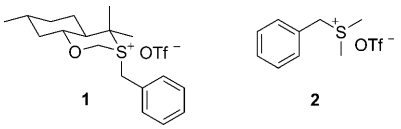
[a] I. Dokli, Dr. Z. Hameršak
Department of Organic Chemistry and Biochemistry
Rudjer Bošković Institute
P. O. Box 180, 10002 Zagreb (Croatia)
Fax: (+385) 14680108
E-mail: hamer@irb.hr

[b] Dr. I. Matanović
Department of Physical Chemistry, Rudjer Bošković Institute
P. O. Box 180, 10002 Zagreb (Croatia)

Supporting information for this article is available on the WWW under http://dx.doi.org/10.1002/chem.201001436.

Results and Discussion

Two sulfonium salts were used as ylide precursors in imine aziridinations: (R,R,R,S_s)-hexahydro-4,4,7-trimethyl-3-benzyl-1,3-benzoxathiane trifluoromethanesulfonate (**1**), which is a chiral benzyl sulfonium salt derived from 1,3-oxathiane for the synthesis of chiral aziridines, and benzyldimethylsulfonium triflate (**2**) for achiral aziridinations.

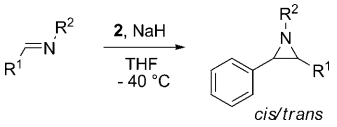


1 **2**

The sulfonium salt **1** was prepared from (R,R,R)-(+)-oxathiane[4] **3** and benzyl alcohol by using the triflate method reported by Vedejs et al.,[8] and was isolated as a single diastereomer with (R,R,R,S_s)-(−) configuration.[9] *N*-SES, *N*-Boc, and *N*-Ts imines were prepared according to literature procedures[10] and are all known compounds, except for *N*-(9-phenanthrylmethylidene)-2-trimethylsilylethanesulfonamide (**18**) and *N*-(9-anthrylmethylidene)-2-trimethylsilylethanesulfonamide (**21**). *N*-*o*-Nitrobenzenesulfonamide (*N*-*o*Ns) imines were prepared according to a slightly modified literature procedure[11] to that used for the preparation of *N*-*p*Ns imines, and are new compounds except for phenyl- (**7**) and 4-methoxyphenyl-substituted (**11**) imines.[11b] Chiral aziridines **24**–**42** were prepared from the corresponding N-protected imines **4**–**22** and oxathiane benzyl sulfonium salt **1** by using sodium hydride to generate the ylide (Table 1). Reactions were carried out in THF overnight at −40 °C. Aziridines **24**–**42** were also prepared in racemic form from imines **4**–**22** and benzyl sulfonium salt **2** under the same reaction conditions used for the preparation of chiral aziridines (Table 2).

We have successfully prepared *N*-(9-anthrylmethylidene)-2-nitrobenzenesulfonamide (**23**) but, although we observed conversion of the imine into the aziridine, we were not able to isolate pure aziridine because of its instability during purification. Lower yields were observed for 4-methoxyphenyl-substituted aziridines (Tables 1 and 2, entries 5–8), due to the presence of the electron-donat-

Table 2. Synthesis of aziridines using ylide derived from salt **2**.

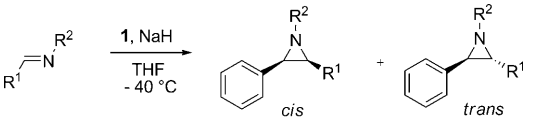


4-23 **24-42**

Entry	R^1	R^2	Imine	Product	Yield [%][a]	*cis*/*trans*[b]
1	phenyl	Boc	4	24	68	5:95
2	phenyl	SES	5	25	86	9:91
3	phenyl	Ts	6	26	70	19:81
4	phenyl	*o*Ns	7	27	58	29:71
5	PMP	Boc	8	28	54	2:98
6	PMP	SES	9	29	67	12:88
7	PMP	Ts	10	30	76	14:86
8	PMP	*o*Ns	11	31	35	21:78
9	1-naphthyl	Boc	12	32	78	0:100
10	1-naphthyl	SES	13	33	84	26:74
11	1-naphthyl	Ts	14	34	86	33:67
12	1-naphthyl	*o*Ns	15	35	53	38:62
13	*tert*-butyl	SES	16	36	66	67:33
14	*tert*-butyl	Ts	17	37	64	69:31
15	9-phenanthryl	SES	18	38	67	30:70
16	9-phenanthryl	Ts	19	39	76	39:61
17	9-phenanthryl	*o*Ns	20	40	39	41:59
18	9-anthryl	SES	21	41	81	77:23
19	9-anthryl	Ts	22	42	53	57:43
20	9-anthryl	*o*Ns	23	43	n.i.[c]	–

[a] Isolated yield after column chromatography. [b] The *cis*/*trans* ratios were determined by ^{1}H NMR spectroscopy of the crude product. [c] Not isolated due to decomposition.

Table 1. Asymmetric synthesis of chiral aziridines.



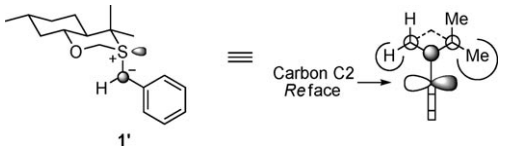
4-23 **24-42**

Entry	R^1	R^2	Imine	Product	Yield [%][a]	*cis*/*trans*[b]	*cis ee* [%][c]	*trans ee* [%][c]
1	phenyl	Boc	4	24	60	10:90	*meso*	97
2	phenyl	SES	5	25	70	44:56	*meso*	>99
3	phenyl	Ts	6	26	60	60:40	*meso*	97
4	phenyl	*o*Ns	7	27	67	53:47	*meso*	98
5	PMP	Boc	8	28	31	9:91	–	96
6	PMP	SES	9	29	47	63:37	>99	98
7	PMP	Ts	10	30	57	58:42	98	n.d.[d]
8	PMP	*o*Ns	11	31	55	61:39	99	n.d.[d]
9	1-naphthyl	Boc	12	32	75	2:98	–	96
10	1-naphthyl	SES	13	33	63	24:76	97	98
11	1-naphthyl	Ts	14	34	60	31:69	96	96
12	1-naphthyl	*o*Ns	15	35	65	58:42	97	98
13	*tert*-butyl	SES	16	36	61	100:0	98	–
14	*tert*-butyl	Ts	17	37	68	100:0	97	–
15	9-phenanthryl	SES	18	38	80	44:56	97	97
16	9-phenanthryl	Ts	19	39	76	45:55	98	99
17	9-phenanthryl	*o*Ns	20	40	76	70:30	98	98
18	9-anthryl	SES	21	41	53	9:91	–	98
19	9-anthryl	Ts	22	42	88	24:76	99	99
20	9-anthryl	*o*Ns	23	43	n.i.[e]	–	–	–

[a] Isolated yield after column chromatography. [b] The *cis*/*trans* ratios were determined by ^{1}H NMR spectroscopy of the crude product. [c] Determined by chiral HPLC on the *cis*/*trans* mixture. [d] Enantiomers could not be separated on the following columns: Chiralcel OJ, OD, OB, Chiralpak AS, or AD. [e] Product not isolated due to decomposition.

ing aromatic substituent, which led to partial ring opening during the purification step.

Enantiomeric purities of all the prepared chiral aziridines were very high (Table 1). We previously showed that the choice of base, solvent, and imine reagent had no effect on the enantioselectivity in the case of the aziridination reaction using ylide **1′** derived from oxathiane benzyl sulfonium salt **1**.[7] The excellent enantioselectivities of both isomers observed in all cases is in accordance with Solladie-Cavallo's model, which states that the approach of the aldimine occurs highly selectively at the *Re* face of the C2 carbon of the ylide **1′** (Scheme 1).[6] The absolute configurations were



Scheme 1. Solladie-Cavallo's model for enantioselectivity.[6]

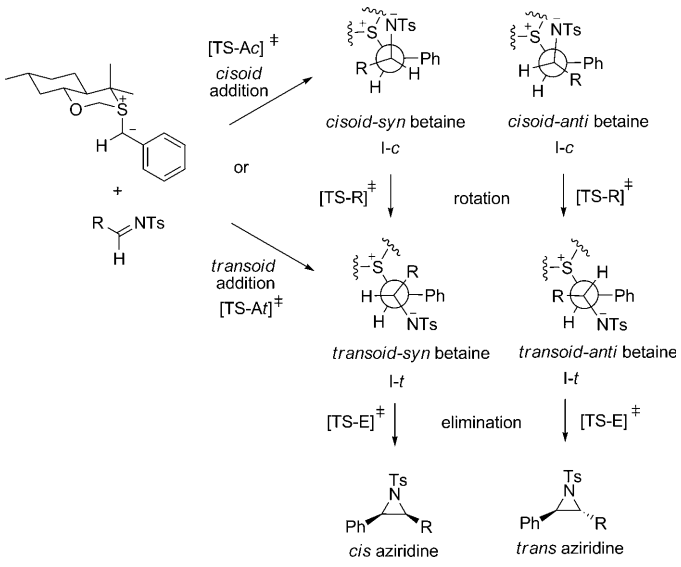
previously determined by X-ray analysis using the Bijvoet method to be (2*R*,3*S*) for *cis*-*N*-Ts-2-phenyl-3-*tert*-butylaziridine and (2*R*,3*R*) for *trans*-*N*-Ts-2-phenyl-3-naphthylaziridine. The *R*-configuration found at C-2 is consistent with the proposed model. Therefore, all of the *trans* aziridines were assigned (2*R*,3*R*) configuration, and all the *cis* aziridines, (2*R*,3*S*) configuration.[6] To further confirm this postulation, we deprotected *cis*-*N*-SES-2-phenyl-3-*tert*-butylaziridine (**36**) using tetrabutylammonium fluoride, and converted the unprotected *cis*-2-phenyl-3-*tert*-butylaziridine into *cis*-*N*-Ts-2-phenyl-3-*tert*-butylaziridine using tosyl chloride and diisopropylethylamine. The measured optical rotation of the product was in accordance with the literature data for the (2*R*,3*S*)-*N*-Ts-2-phenyl-3-*tert*-butylaziridine.[6]

The influence of the N-protecting group, imine substituent, and the sulfonium salt structure on the diastereoselectivity of the reaction was studied and found to be highly substrate dependent. The *cis*/*trans* ratios were determined by ^{1}H NMR spectroscopic analysis of the crude product. As expected,[3c] the best *trans* selectivity was obtained in the reactions with imines bearing the *N*-Boc substituent (*trans* diastereomeric excess (*de*) 80–100%, Tables 1 and 2). A combination of the *N*-Boc group and a smaller sulfonium salt **2** resulted in 90–100% *trans de* for the synthesis of aziridines **24**, **28**, and **32**. By using the larger, chiral salt **1**, somewhat lower *trans de* values of 80–96% were obtained. Unfortunately, we were unable to fully explore the effect of the imine substituent on the diastereoselectivity in the case of *N*-Boc imines because, so far, we could not prepare *N*-Boc imines with anthryl and phenanthryl substituents. We successfully prepared *N*-Boc-*tert*-butylaldimine, however, the reaction with both sulfonium salts failed. *N*-SES imines gave mostly *cis*/*trans* mixtures of aziridines with low *trans* selectivity. *N*-Ts and *N*-*o*Ns imines behaved in a similar manner, but with somewhat reduced *trans* selectivity than *N*-SES imines (Tables 1 and 2). By comparing the diastereoselectivity, the protecting groups can be arranged in the following order of decreasing *trans* selectivity: Boc > SES > Ts > *o*Ns.

The structure of the sulfonium salt affected the diastereoselectivity in almost all cases. The larger oxathiane benzyl sulfonium salt **1** induced the formation of more *cis* isomer, compared with the smaller sulfonium salt **2**. There is no general explanation for the influence of the imine substituent. The most interesting case appeared to be reactions of sulfonium salt **1** with *tert*-butylaldimines **16** and **17**, which gave the aziridine product with 100% *cis de* (Table 1, entries 13 and 14). In these cases, the N-protecting group had no effect on selectivity. In contrast, the sulfide structure had significant influence; the reaction with the smaller benzyl sulfonium salt **2** gave aziridines with a *cis de* of 24–38% (Table 2, entries 13 and 14).

To explain this selectivity, we conducted a computational investigation into the reaction profiles of the two aziridination reactions that resulted in the formation of aziridines with opposite diastereoselectivity. Until now, only a few DFT studies on aziridination reaction mechanisms and the stereoselectivity processes involved have been reported.[12] These include a theoretical study on the stability of different structures of the ylide carbanions and imines and their role in the aziridination reaction.[12d] The generally accepted mechanism for sulfonium ylide promoted aziridine formation involves the addition of the ylide to the imine to form a betaine, rotation around the formed C–C bond, and elimination of the sulfide, which is accompanied by ring closure to the aziridine (Scheme 2).[3d,13]

The reactions of benzyl sulfonium ylide **1′** with *N*-Ts-naphthaldimine (**14**) and *N*-Ts-*tert*-butylaldimine (**17**) repre-



Scheme 2. Generally accepted aziridination mechanism. TS-A*c* and TS-A*t* refer to the *cisoid* and *transoid* addition transition states in the C–C bond-forming step, I-*t* and I-*c* refer to the intermediate betaines with the *transoid* and *cisoid* orientation, TS-R denotes the transition state for *cisoid* to *transoid* rotation, and TS-E denotes the transition state for the elimination step.

sent two aziridination reactions in which the change of an imine substituent induces a large difference in the diastereoselectivity of the reaction: *N*-Ts-2-phenyl-3-(1-naphthyl)aziridine (**34**) *cis*/*trans* = 31:69 and *N*-Ts-2-phenyl-3-*tert*-butylaziridine (**37**) *cis*/*trans* = 100:0. To gain a better insight into the reaction mechanisms of the experimentally studied reactions, we calculated the energy profiles for the two representative reactions using DFT including solvent effects. The B3LYP/6-31G(d)[18] level of calculation was chosen to obtain optimal trade-off between the computational cost and the accuracy of the results; for this reason, the obtained energy profiles provide only a qualitative picture of the studied mechanisms. A reliable explanation or the ability to predict the extent of diastereoselectivity requires knowledge of the activation barriers for all of the elementary steps involved in the reaction.[12] The calculated energy profiles for the two aziridination reactions are shown in Figure 1.

In the first step in the mechanism of aziridine formation, addition of the ylide to the imine leads to the formation of intermediate betaines, which are designated *syn* or *anti* depending on the relative position of the ylidic phenyl group and the imine substituent (R) around the newly formed C–C bond. The approach of the ylide and the imine can be *cisoid* or *transoid* according to the arrangement of the aza and sulfonium groups around the formed C–C bond (*cisoid*: S^+ and N^- on the same side; *transoid*: S^+ and N^- on opposite sides). In this way, four betaine structures can be formed: *cisoid-syn*, *cisoid-anti*, *transoid-syn*, and *transoid-anti* betaine (Scheme 2). In the case of the *anti* pathway, in both aziridination reactions, only a *cisoid* transition state (TS-A*c*) was located. Every attempt to obtain a *transoid* structure (TS-A*t*) of an *anti* orientation revealed the higher energy of such a geometry and led to a *cisoid* transition state.[14] The tendency to adopt the *cisoid* orientation in an *anti* pathway was previously observed in the addition of an ylide to an aldehyde, and was attributed to the favorable Coulombic interactions between the charged aza and sulfonium groups.[12,15] However, besides the electrostatic effects, an important role in the stability of these structures can be attributed to the steric effects. The close proximity of the ylidic substituent (phenyl) and the imine substituent (1-naphthyl or *tert*-butyl) is destabilizing and leads to a lower barrier for the *cisoid* orientation in an *anti* approach. In the *syn* approach, the same steric effect favors the *transoid* orientation. The calculated barriers for betaine formation are shown in Figure 2. Consequently, it is reasonable to assume that, in the addition step, only two betaine intermediates are formed: the *cisoid-anti* betaine (I-*c*) and the *transoid-syn* betaine (I-*t*).

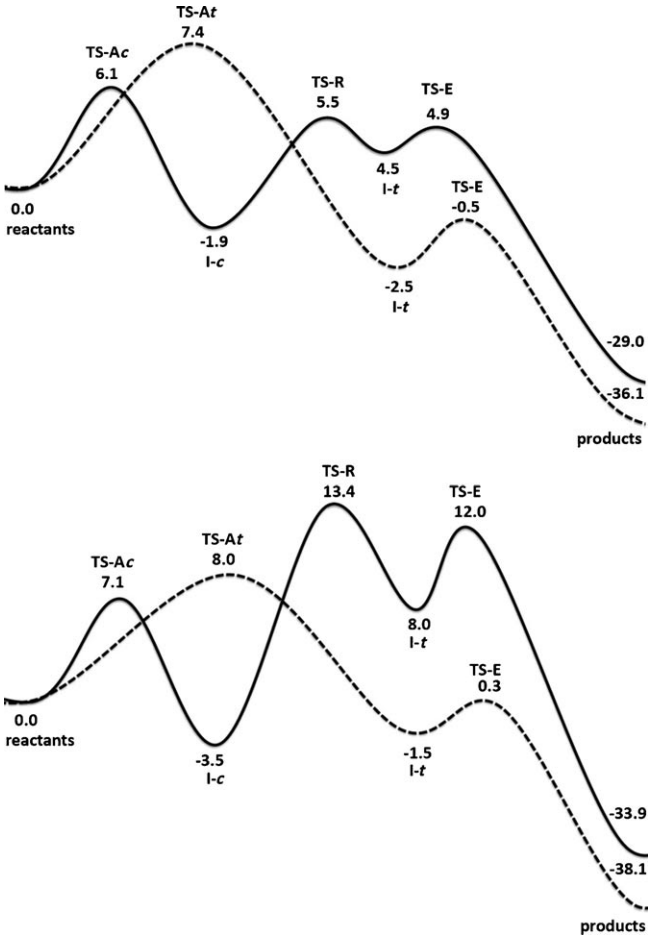


Figure 1. A schematic representation of the reaction profiles for the aziridination reaction of **14** (top) and **17** (bottom). ΔE [kcal mol^{-1}] values were calculated at the PCM(THF)/B3LYP/6-31G(d)//B3LYP/6-31G(d) level of theory and are given relative to separate reactants. ——: *anti* approach, -----: *syn* approach.

A careful analysis of the *transoid-syn* (I-*t*) and *cisoid-anti* (I-*c*) betaine structures, revealed that, in addition to the favorable Coulombic interactions between the charged S^+ and N^- groups and the favorable steric arrangement of the substituents, the presence of a C–H···O hydrogen bond between the oxygen of the *N*-Ts group and an ylidic hydrogen atom contributes to the greater stability of these structures. Short H···O distances and C–H···O angles in the range of 120–155° in the structures of *transoid-syn* and *cisoid-anti* betaines indicate the formation of stabilizing C–H···O hydrogen bonds.[16] For instance, in the case of the reaction with **14**, the H···O distance is 2.06 Å for the *transoid-syn* and 2.16 Å for the *cisoid-anti* betaine, while the C–H···O angles have values of 129 and 154°.

Transoid-syn betaine (I-*t*) directly eliminates an oxathiane group to yield the *cis* aziridine as a product. In the case of the *anti* approach, the elimination reaction also occurs from the *transoid* betaine, in which the S–C–C–N dihedral angle is close to 180°, and thus the *cisoid* intermediate must first undergo rotation around the newly formed C–C bond to form a *transoid* intermediate. The elimination reaction in *transoid-anti* betaine will then lead to the formation of a *trans* aziridine (Figure 1, top). The calculated energy profiles (Figure 1) reveal that the *transoid-anti* betaine formed in the rotation is much higher in energy than the *cisoid-anti* betaine. In the case of the reaction of **14**, the *transoid-anti* betaine is higher in energy than the *cisoid-anti* betaine by 6.4 kcal mol^{-1} and, in the reaction of **17**, by more than 11.5 kcal mol^{-1}.

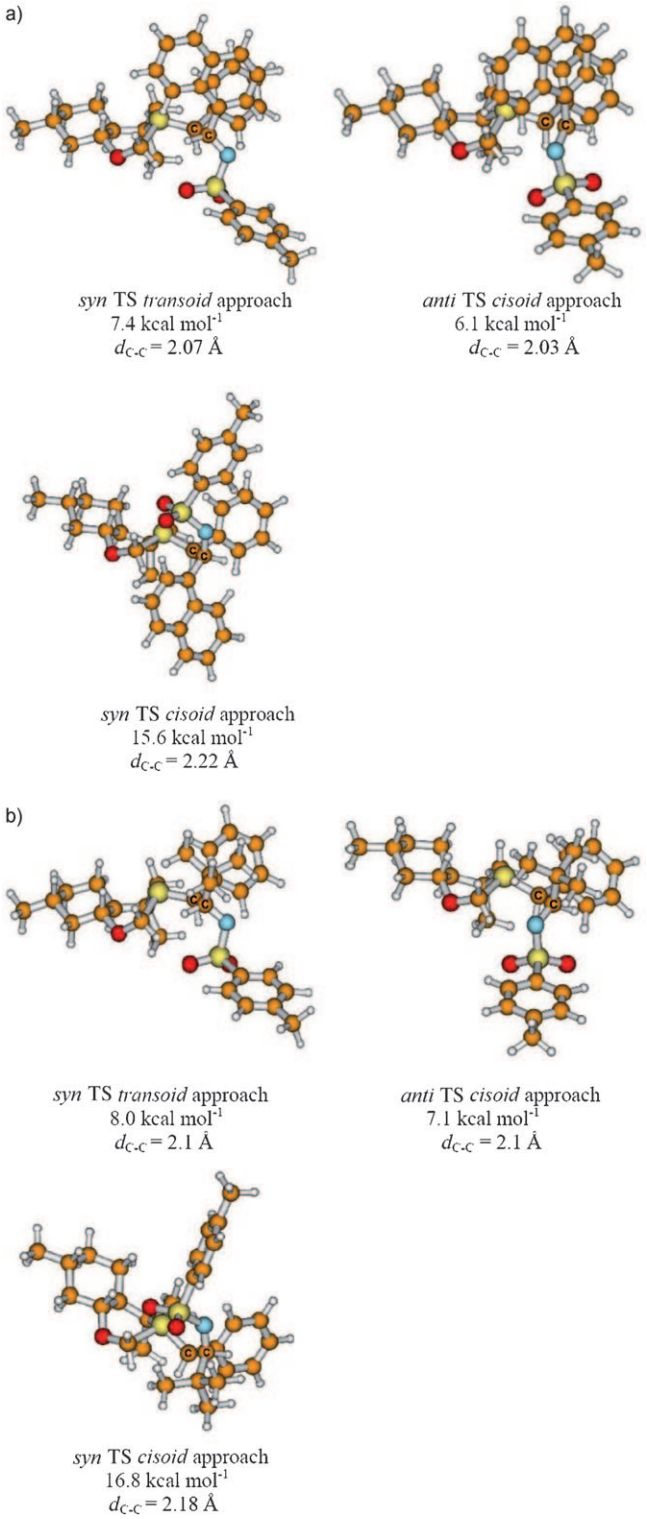


Figure 2. Transition-state structures for the addition of ylide **1′** to **14** (a) and **17** (b) obtained at the B3LYP/6-31G(d) level of theory. The energies were obtained at the PCM(THF)/B3LYP/6-31G(d)//B3LYP/6-31G(d) level and are given relative to separate reactants.

The calculated energy profiles (Figure 1) can easily explain the difference in the diastereoselectivity of the two aziridination reactions. In the reaction of benzyl sulfonium ylide **1′** with **14**, the highest points on the energy profile are the addition transition states, which lead to the formation of the *cisoid-anti* and *transoid-syn* betaine intermediates (Figure 1). This indicates that the overall *cis*/*trans* selectivity is determined by the relative energies of *syn* and *anti* addition transition states. This case is similar to the previously reported aziridine reactions in which the difference in energy between the transition states for the addition step can correctly predict the observed *trans*/*cis* ratio.[12d] Since the barrier for the formation of an *anti* betaine (6.1 kcal mol^{-1}; Figure 1, top) is slightly lower than for the formation of the *syn* betaine (7.4 kcal mol^{-1}), our calculations predict a low *trans* selectivity in the reaction of ylide **1′** with **14**. This is in good agreement with the experimental observations, which gives a *cis*/*trans* ratio of 31:69 of the aziridine product (Table 1, entry 11). In the reaction of ylide **1′** with **17**, the energy profile indicates that both intermediates can form in the course of the reaction (Figure 1, bottom); the *transoid-syn* betaine, which can directly undergo elimination of sulfide and yield the *cis* product, and the *cisoid-anti* betaine, which can ultimately lead to the formation of the *trans* product. However, for a *trans* product to form in the elimination reaction, the *cisoid-anti* betaine must transform into a *transoid-anti* betaine by rotating around the newly formed C–C bond. As the barrier for the *cisoid* to *transoid* rotation is too high (16.9 kcal mol^{-1}), the rotation is slow and reversion to reactants occurs instead. This leads to the domination of the *syn* pathway and to the high selectivity for the *cis* product. We can thus conclude that the aziridination reaction of **17** is similar to epoxidation[15] and cyclopropanation[17] reactions in which the *cisoid–transoid* interconversion of betaines through a torsional motion was determined to be the rate-limiting step. In the case of the aziridination reaction of **14**, the barrier for the *cisoid* to *transoid-anti* betaine rotation is much lower than in the aziridination reaction of **17** (7.4 vs. 16.9 kcal mol^{-1}). The large difference in rotation barriers for the two cases can be attributed to a large difference in the size of the imine substituents. Clearly, rotation of a bulky *tert*-butyl group around a C–C bond induces much more steric strain than rotation of a flat naphthyl group.

Conclusion

We have successfully prepared a range of *N*-Ts, *N*-SES, *N*-Boc, and *N*-*o*Ns aziridines in moderate to good yield and high enantiomeric excess of both isomers. The diastereoselectivities of the reactions are variable and are influenced by the imine N-protecting group, the imine substituent, and the sulfide structure. By comparing the diastereoselectivities, we can arrange the protecting groups in the following order of decreasing *trans* selectivity: Boc > SES > Ts > *o*Ns. The unusual 100% *cis* selectivity in the formation of *N*-SES-2-phenyl-3-(*tert*-butyl)aziridine (**36**) and *N*-Ts-2-phenyl-3-*tert*-butylaziridine (**37**) was explained through the use of computational models. The analysis suggests that betaine formation in the case of aziridination of *N*-Ts-*tert*-butylaldimine (**17**)

using benzyl sulfonium ylide **1′** is reversible and that the selectivity is determined at the rotation step. Previous investigations suggested that the degree of reversibility might be affected by the steric bulk and the electron-withdrawing ability of the N substituent.[1g,3g] We have shown here that the steric bulk of the imine substituent, in combination with a sterically demanding sulfonium ylide, can also affect the reversibility of the reaction. This is the first example of this sort of aziridination using a semistabilized ylide.

Experimental Section

Computational details: The gas-phase geometries of the intermediates, transition states, reactants, and products in the aziridine formation mechanism were obtained by using DFT with the B3LYP[18] exchange-correlation functional and the 6-31G(d) basis set. The energies in THF (total free energies in solution) were obtained by using the self-consistent reaction field approach with the polarizable continuum model (SCRF-PCM) as implemented in the Gaussian 03 quantum chemical software package.[19] Because of the large size of the studied molecules, the solvation effect in all of the calculated energy profiles was included only by means of single-point energy evaluation using the gas-phase geometries [PCM-(THF)/B3LYP/6-31G(d)//B3LYP/6-31G(d) level of theory]. To validate the quality of our computations, the first step in aziridine formation, that is, the C–C bond-forming step, was studied by performing the optimizations in the solvent. The changes in energy between the gas-phase geometries and fully optimized solvent-phase geometries were very small (less than 2 kcal mol^{-1}), which confirmed previous findings that gas-phase geometry optimization followed by single-point energy evaluation can give satisfactory estimates of the mechanism and stereoselectivity in sulfur ylide promoted aziridination reactions.[12b] Because of the low symmetry of the molecules and the high flexibility of the studied systems, transition states were located by calculating the relaxed energy scans along an appropriate internal coordinate (C–C bond length or S-C-C-N dihedral angle). The geometry with a highest energy along the calculated energy profile was used as a starting point for the transition state optimization using the Berny algorithm, as implemented in Gaussian 03. Frequency calculations otherwise used to confirm the nature of the obtained stationary points were not performed in this case due to the fact that it is extremely unlikely that the obtained geometries would correspond to anything other than transition states.

General methods: All reactions were conducted under an argon atmosphere unless otherwise noted. THF was distilled from sodium/benzophenone ketyl and CH_2Cl_2 was distilled from CaH_2. All other reagents and solvents were purchased from commercial sources and used without purification. TLC was performed on aluminum-backed silica plates (60 F_{254}, Merck) or aluminum-backed alox plates (neutral 60 F_{254}, Merck). UV light (254 nm) or phosphomolybdic acid were used for visualizing. Column chromatography was performed on silica gel (Silica gel 60, 70–230 mesh, Fluka) or aluminum oxide (Merck Aluminum oxide 90 active, neutral, activity I). ^{1}H and ^{13}C NMR spectra were recorded with Bruker AV 300 and AV 600 spectrometers. Chemical shifts (δ) are quoted in parts per million (ppm), referenced to TMS. Optical rotations were measured with an Optical Activity AA-10 automatic polarimeter. Melting points were determined with an Electrothermal 9100 apparatus in open capillaries. IR spectra were recorded with a Bruker ABB Bowen instrument.

***N*-(4-Methoxyphenylmethylidene)-2-nitrobenzenesulfonamide (11)**:[11b] A mixture of 4-methoxybenzaldehyde (300 mg, 2.2 mmol, 1 equiv), 2-nitrobenzenesulfonamide (295 mg, 2.3 mmol, 1.04 equiv), and tetraethyl orthosilicate (0.9 mL, 4.0 mmol, 1.8 equiv) was heated under argon at 170 °C for 3 h. After cooling, warm ethyl acetate (10 mL) was added and the mixture was stirred for 10 min and then filtered. The filtrate was concentrated under vacuum and the residue was washed with hexane (3× 10 mL) and then recrystallized from EtOAc/hexane. The crystals were collected by filtration and dried under vacuum. Product **11** was isolated as an olive-green powder (552 mg, 78 %). M.p. 152.9–153.4 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 3.90 (s, 3H), 6.98–7.02 (m, 2H), 7.75–7.80 (m, 3H), 7.94–7.97 (m, 2H), 8.36–8.38 (m, 1H), 8.97 ppm (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 55.8, 114.9, 124.6, 124.9, 131.8, 132.3, 132.5, 134.3, 134.4, 166.0, 172.6 ppm; IR (KBr): $\tilde{\nu}$ = 1683, 1604, 1540, 1513, 1364, 1273, 1162, 1123, 808 cm^{-1}.

***N*-(1-Naphthylmethylidene)-2-nitrobenzenesulfonamide (15)**: Compound **15** was prepared as described above, starting from 1-naphthaldehyde (300 mg, 1.92 mmol, 1 equiv), 2-nitrobenzenesulfonamide (390 mg, 1.95 mmol, 1.01 equiv), and tetraethyl orthosilicate (0.79 mL, 3.5 mmol, 1.8 equiv), and was isolated as a brown powder after recrystallization from EtOAc/hexane (470 mg, 72 %). M.p. 148.5–149.1 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.60–7.65 (m, 2H), 7.70–7.75 (m, 1H), 7.78–7.85 (m, 3H), 7.96 (d, 1H, J = 8.4 Hz), 8.18 (d, 1H, J = 8.2 Hz), 8.27 (dd, J_1 = 1.0, J_2 = 7.2 Hz, 1H), 8.46–8.49 (m, 1H), 9.01 (d, J = 8.5 Hz, 1H), 9.69 ppm (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 124.2, 124.8, 125.2, 127.1, 127.4, 129.2, 129.3, 132.1, 132.6, 133.8, 134.6, 135.7, 137.0, 148.6, 173.4 ppm; IR (KBr): $\tilde{\nu}$ = 1563, 1533, 1358, 1317, 1159, 1121, 811 cm^{-1}.

***N*-(9-Phenanthrylmethylidene)-2-nitrobenzenesulfonamide (20)**: Compound **20** was prepared as described above, starting from 9-phenantraldehyde (300 mg, 1.45 mmol, 1 equiv), 2-nitrobenzenesulfonamide (303 mg, 1.5 mmol, 1.03 equiv), and tetraethyl orthosilicate (1 mL, 4.5 mmol, 3 equiv), and isolated as a brown powder after recrystallization from EtOAc/hexane (266 mg, 47 %). M.p. 170.8–171.5 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.63–7.84 (m, 7H), 7.98–8.01 (m, 1H), 8.47 (dt, J_1 = 1.3, J_2 = 6.9 Hz, 1H), 8.51 (s, 1H), 8.66 (d, J = 8.4 Hz, 1H), 8.69–8.72 (m, 1H), 9.10–9.13 (m, 1H), 9.63 ppm (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 122.4, 122.7, 124.3, 124.9, 125.0, 126.0, 127.0, 127.3, 127.8, 128.5, 129.6, 130.2, 130.4, 130.5, 131.6, 132.2, 133.1, 134.1, 140.1, 148.1, 173.6 ppm; IR (KBr): $\tilde{\nu}$ = 1570, 1550, 1330, 1162, 1126, 826 cm^{-1}.

***N*-(9-Anthrylmethylidene)-2-nitrobenzenesulfonamide (23)**: Compound **23** was prepared as described above starting from 9-anthraldehyde (300 mg, 1.45 mmol, 1 equiv), 2-nitrobenzenesulfonamide (295 mg, 1.47 mmol, 1.02 equiv), and tetraethyl orthosilicate (1 mL, 4.5 mmol, 3 equiv), and isolated as an orange powder after recrystallization from EtOAc/hexane (368 mg, 65 %). M.p. 181.9–182.8 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.55–7.60 (m, 2H), 7.71–7.82 (m, 5H), 8.07 (d, J = 8.4 Hz, 2H), 8.52 (d, J = 7.2 Hz, 1H), 8.76 (s, 1H), 9.12 (d, J = 9.0 Hz, 2H), 10.49 ppm (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 120.8, 124.3, 124.8, 126.1, 129.7, 130.1, 131.1, 132.2, 132.3, 132.7, 133.7, 134.5, 137.8, 171.4 ppm; IR (KBr): $\tilde{\nu}$ = 1552, 1523, 1343, 1325, 1164, 1122 cm^{-1}.

***N*-(9-Phenanthrylmethylidene)-2-trimethylsilylethanesulfonamide (18)**: A mixture of phenanthrene-9-carboxaldehyde (300 mg, 1.45 mmol, 1 equiv), 2-(trimethylsilyl)ethanesulfonamide (272 mg, 1.5 mmol, 1.1 equiv), and anhydrous triethylamine (0.82 mL, 5.8 mmol, 4 equiv) in anhydrous CH_2Cl_2 (15 mL), under argon, was cooled to 0 °C. A solution of $TiCl_4$ (1.45 mL, 1 M in CH_2Cl_2, 1 equiv) was added slowly with a syringe, and the reaction mixture was stirred at 0 °C for 1 h, and then at RT for 20 h. The reaction mixture was filtered through Celite, concentrated, and toluene (20 mL) was added to the solid residue. After 10 min of stirring, the mixture was filtered again, and the filtrate was concentrated under reduced pressure. Product **18** was found to decompose on silica gel and was therefore used in the next step without further purification (327 mg, 63 %). ^{1}H NMR (300 MHz, $CDCl_3$): δ = 0.07 (s, 9H), 1.13–1.16 (m, 2H), 3.23–3.26 (m, 2H), 7.67 (ddd, J_1 = 7.7, J_2 = 7.1, J_3 = 0.9 Hz, 1H), 7.72–7.77 (m, 2H), 7.81 (ddd, J_1 = 8.3, J_2 = 7.0, J_3 = 1.3 Hz, 1H), 7.99 (dd, J_1 = 7.8, J_2 = 0.7 Hz, 1H), 8.42 (s, 1H), 8.67 (d, J = 8.3 Hz, 1H), 8.72–8.73 (m, 1H), 9.16–9.17 (m, 1H), 9.55 ppm (s, 1H). ^{13}C NMR (75 MHz, $CDCl_3$): δ = −2.5, 9.1, 48.7, 122.4, 122.7, 125.1, 126.1, 127.0, 127.2, 127.7, 128.5, 129.6, 130.1, 130.2, 130.3, 132.8, 139.4, 172.2 ppm; IR (KBr): $\tilde{\nu}$ = 2953, 2889, 1579, 1314, 1246, 1141, 1132, 833, 815 cm^{-1}.

***N*-(9-Anthrylmethylidene)-2-trimethylsilylethanesulfonamide (21)**: A mixture of anthracene-9-carboxaldehyde (300 mg, 1.45 mmol, 1 equiv), 2-trimethylsilylethanesulfonamide (270 mg, 1.49 mmol, 1.1 equiv), and BF_3·Et_2O (20 μL, 0.22 mmol) in toluene (20 mL) was heated under argon in a flask equipped with a Dean–Stark separator, at 110 °C for 5 h. After cooling, a 10 % aqueous solution of NaOH (20 mL) was added and the

layers were separated and the organic layer was washed with brine (10 mL). The organic layer was dried over Na_2SO_4, filtered, and concentrated under vacuum. Compound **21** was isolated as an orange powder after chromatography (360 mg, 68%). R_f=0.2 (hexane/EtOAc 9:1); m.p. 119–120°C; ^{1}H NMR (300 MHz, $CDCl_3$): δ=0.11 (s, 9H), 1.19–1.25 (m, 2H), 3.28–3.34 (m, 2H), 7.59–7.60 (m, 2H), 7.72–7.77 (m, 2H), 8.11 (d, J=8.0 Hz, 2H), 8.76 (s, 1H), 9.04 (d, J=8.0 Hz, 2H), 10.45 ppm (s, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=−2.0, 9.8, 49.2, 121.1, 124.2, 125.9, 129.6, 129.7, 131.1, 133.1, 136.6, 170.3 ppm; IR (KBr): $\tilde{\nu}$=2950, 1581, 1314, 1248, 1137, 859, 795 cm^{-1}.

2-Phenyl-3-(9-phenanthryl)-1-(2-trimethylsilylethanesulfonyl)aziridine (38): NaH (36 mg, 60% dispersion in paraffin, 0.9 mmol, 2 equiv) was added to a stirred solution of benzyl sulfonium salt **1** (198 mg, 0.45 mmol, 1.1 equiv) under argon in anhydrous THF (8 mL), cooled to −40°C. After 1 h, a solution of **18** (150 mg, 0.40 mmol, 1 equiv) in THF (2 mL) was added dropwise. The reaction mixture was stirred for 20 h at −40°C, then cold H_2O (15 mL) was added, and the mixture was extracted with dichloromethane (3×10 mL). The combined organic extracts were dried over Na_2SO_4, filtered, and concentrated under vacuum. The crude product was analyzed by ^{1}H NMR spectroscopy to determine the diastereomeric ratio and then purified by column chromatography on silica gel eluting with hexane/EtOAc 8:1. The first fraction contained recovered (*R*,*R*,*R*)-oxathiane **3** (72 mg, 90%); R_f=0.8 (hexane/EtOAc 8:2). The title compound **38** was isolated as a yellow oil (145 mg, 80%); R_f=0.21 (hexane/EtOAc 8:1). Isomers of **38** were separated by chiral HPLC. ***Trans* isomer**: *ee*>97% (Chiralpak AD; hexane/ethanol 97:3; 254 nm; 1 mL min^{-1}; t_{major}=21.9 min, t_{minor}=25.3 min); $[\alpha]_D^{25}$=+54 (c=0.57 in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=−0.04 (s, 9H), 1.07–1.13 (m, 2H), 2.95–3.14 (m, 2H), 4.36 (d, J=4.8 Hz, 1H), 4.84 (d, J=4.8 Hz, 1H), 7.42–7.49 (m, 3H), 7.61–7.72 (m, 6H), 7.91 (dd, J_1=7.8, J_2=1.5 Hz, 1H), 7.94 (s, 1H), 8.29–8.33 (m, 1H), 8.69 (d, J=8.0 Hz, 1H), 8.74–8.77 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=−2.1, 9.7, 48.7, 49.7, 51.1, 122.6, 123.3, 124.4, 126.4, 127.0, 127.0, 127.0, 127.4, 128.4, 128.5, 128.8, 129.0, 129.1, 130.6, 130.6, 130.9, 131.1, 133.1 ppm; IR (KBr): $\tilde{\nu}$=3067, 2953, 1715, 1448, 1323, 1246, 1143, 844 cm^{-1}. ***Cis* isomer**: *ee* 97% (Chiralpak AD; hexane/ethanol 97:3; 254 nm; 1 mL min^{-1}; t_{major}=13.4 min, t_{minor}=16.5 min); $[\alpha]_D^{25}$=+29 (c=0.61 in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=0.07 (s, 9H), 1.29–1.32 (m, 2H), 3.33–3.36 (m, 2H), 4.44 (d, J=7.3 Hz, 1H), 4.68 (d, J=7.3 Hz, 1H), 6.99–7.01 (m, 3H), 7.19–7.21 (m, 2H), 7.56–7.62 (m, 4H), 7.86 (dd, J_1=7.9, J_2=1.1 Hz, 1H), 7.89 (s, 1H), 8.10–8.12 (m, 1H), 8.58 (d, J=8.0 Hz, 1H), 8.60–8.62 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=−2.5, 9.5, 45.8, 47.0, 48.8, 122.0, 122.6, 123.1, 125.8, 126.2, 126.3, 126.3, 126.4, 126.7, 126.8, 127.4, 128.2, 129.6, 129.7, 130.5, 131.5 ppm; IR (KBr): $\tilde{\nu}$=3067, 2958, 1690, 1450, 1328, 1252, 1145, 833 cm^{-1}; elemental analysis calcd (%) for *cis*/*trans* mixture of $C_{27}H_{29}NO_2SSi$ (459): C 70.55, H 6.36, N 3.05; found: C 70.64, H 6.64, N 3.11.

2-Phenyl-3-(9-anthryl)-1-(2-trimethylsilylethanesulfonyl)aziridine (41): Compound **41** was prepared as described above starting from **21** (150 mg, 0.42 mmol), and isolated as a yellow oil after workup and silica gel chromatography (100 mg, 53%); R_f=0.15 (hexane/CH_2Cl_2/methyl *tert*-butyl ether 8:1:1). Product **41** was obtained as a *cis*/*trans* mixture (9:91). Isomers of **41** were separated by chiral HPLC and the assignments below are for the major *trans* isomer. ***Trans* isomer**: *ee* 98% (Chiralpak AD; hexane/ethanol 95:5; 370 nm; 1 mL min^{-1}; t_{major}=13.7 min, t_{minor}=18.3 min); $[\alpha]_D^{25}$=+39 (c=0.69 in CH_2Cl_2); ^{1}H NMR (300 MHz, $CDCl_3$): δ=−0.09 (s, 9H), 0.93–1.06 (m, 2H), 2.87–2.99 (m, 2H), 4.41 (d, J=5.0 Hz, 1H), 5.20 (d, J=5.0 Hz, 1H), 7.46–7.51 (m, 3H), 7.52–7.55 (m, 4H), 7.73–7.75 (m, 2H), 8.02 (dd, J_1=8.0, J_2=0.4 Hz, 2H), 8.48–8.50 ppm (m, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=−2.7, 8.9, 47.6, 50.2, 50.4, 124.3, 124.6, 124.6, 125.8, 128.2, 128.5, 128.6, 128.7, 128.8, 130.4, 130.8, 132.6 ppm; IR (KBr): $\tilde{\nu}$=3065, 2952, 1679, 1331, 1285, 1251, 1143, 859, 843 cm^{-1}; elemental analysis calcd (%) for *cis*/*trans* mixture of $C_{27}H_{29}NO_2SSi$ (459): C 70.55, H 6.36, N 3.05; found: C 70.85, H 6.56, N 2.74.

2-Phenyl-3-(*tert*-butyl)-1-(2-trimethylsilylethanesulfonyl)aziridine (36): Compound **36** was prepared as described above starting from **16** (120 mg, 0.48 mmol), and isolated as a colorless viscous oil after workup and silica gel chromatography (88 mg, 61%); R_f=0.39 (hexane/EtOAc 8:1). Product **36** was a pure *cis* isomer: *ee* 98% (Chiralcel OJ; hexane/2-propanol 95:5; 210 nm; 1 mL min^{-1}; t_{minor}=7.2 min, t_{major}=10.1 min); $[\alpha]_D^{25}$=−133 (c=1.09 in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$): δ=0.08 (s, 9H), 0.80 (s, 9H), 1.22–1.29 (m, 2H), 2.82 (d, J=7.6 Hz, 1H), 3.15–3.21 (m, 2H), 3.91 (d, J=7.6 Hz, 1H), 7.27–7.38 ppm (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=−1.8, 10.1, 27.9, 32.3, 46.2, 49.0, 53.6, 127.8, 128.5, 134.0 ppm; IR (KBr): $\tilde{\nu}$=3062, 3033, 2956, 1328, 1250, 1141 cm^{-1}; elemental analysis calcd (%) for $C_{17}H_{29}NO_2SSi$ (339): C 60.13, H 8.61, N 4.12; found: C 60.52, H 8.54, N 3.89. Data are in the accordance with the literature.[3c]

2-Phenyl-3-(4-methoxyphenyl)-1-(2-nitrobenzenesulfonyl)aziridine (31): Prepared as described above starting from **11** (100 mg, 0.31 mmol), and isolated as a light-yellow powder after workup and chromatography on neutral alumina, activity I (70 mg, 55%); R_f=0.35 (hexane/EtOAc 7:3). Although the crude product **31** was a *cis*/*trans* (61:39) mixture, after chromatography, only the *cis* isomer was isolated. ***Cis* isomer**: *ee* 99% (Chiralcel OD; hexane/2-propanol 80:20; 229 nm; 1 mL min^{-1}; t_{minor}=28.0 min, t_{major}=31.2 min); m.p. 128.2–128.8°C; ^{1}H NMR (300 MHz, $CDCl_3$): δ=3.69 (s, 3H), 4.40 (d, J=7.3 Hz, 1H), 4.43 (d, J=7.3 Hz, 1H), 6.66–6.69 (m, 2H), 7.02–7.03 (m, 2H), 7.12–7.14 (m, 2H), 7.15–7.17 (m, 3H), 7.75–7.77 (m, 3H), 8.29–8.31 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=49.1, 49.3, 55.1, 113.5, 123.7, 124.6, 127.9, 127.9, 128.1, 129.1, 131.4, 131.8, 131.8, 132.2, 134.6, 159.3 ppm; IR (KBr): $\tilde{\nu}$=3093, 2935, 1544, 1515, 1364, 1341, 1252, 1169, 1127, 1028 cm^{-1}; elemental analysis calcd (%) for $C_{21}H_{18}N_2O_5S$ (410): C 61.45, H 4.42, N 6.83; found: C 61.15, H 4.68, N 6.55.

2-Phenyl-3-(1-naphthyl)-1-(2-nitrobenzenesulfonyl)aziridine (35): Prepared as described above starting from **15** (120 mg, 0.35 mmol), and isolated as a light-brown viscous oil after workup and chromatography (102 mg, 65%); R_f=0.27 (hexane/EtOAc 7:3). Product **35** was obtained as a *cis*/*trans* mixture. Isomers of **35** were separated by chiral HPLC. ***Trans* isomer**: *ee* 98% (Chiralcel OD; hexane/ethanol 80:20; 254 nm; 1 mL min^{-1}; t_{major}=17.3 min, t_{minor}=20.6 min); $[\alpha]_D^{25}$=+258 (c=0.55 in CH_2Cl_2); ^{1}H NMR (300 MHz, $CDCl_3$): δ=4.52 (d, J=5.0 Hz, 1H), 4.97 (d, J=5.0 Hz, 1H), 7.38–7.43 (m, 4H), 7.48–7.54 (m, 4H), 7.60–7.65 (m, 4H), 7.80 (d, J=8.3 Hz, 1H), 7.87–7.84 (m, 2H), 8.14–8.15 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=50.9, 51.4, 123.5, 124.2, 125.2, 125.3, 126.1, 126.7, 128.3, 128.7, 128.7, 129.0, 129.1, 129.5, 130.8, 131.8, 132.5, 132.9, 133.2, 133.4, 134.0 ppm; IR (KBr): $\tilde{\nu}$=3065, 1541, 1367, 1341, 1166, 781 cm^{-1}. ***Cis* isomer**: *ee* 97% (Chiralcel OD; hexane/ethanol 90:10; 254 nm; 1 mL min^{-1}; t_{minor}=21.3 min, t_{major}=27.9 min); $[\alpha]_D^{25}$=+203 (c=0.36 in CH_2Cl_2); ^{1}H NMR (300 MHz, $CDCl_3$): δ=4.69 (d, J=7.3 Hz, 1H), 4.96 (d, J=7.3 Hz, 1H), 6.99–7.01 (m, 3H), 7.11–7.15 (m, 2H), 7.30–7.35 (m, 1H), 7.41–7.56 (m, 4H), 7.67–7.70 (m, 1H), 7.75–7.78 (m, 1H), 7.81–7.82 (m, 2H), 8.02–8.04 (m, 1H), 8.36–8.39 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=48.5, 46.6, 122.8, 124.7, 125.0, 125.8, 126.4, 127.3, 127.3, 127.8, 127.9, 128.5, 128.6, 131.1, 131.5, 131.6, 131.7, 132.3, 133.1, 134.8 ppm; IR (KBr): $\tilde{\nu}$=3062, 1544, 1367, 1341, 1169, 1127, 906 cm^{-1}; elemental analysis calcd (%) for *cis*/*trans* mixture of $C_{24}H_{18}N_2O_4S$ (430): C 66.96, H 4.21, N 6.51; found: C 66.78, H 4.56, N 6.82.

2-Phenyl-3-(9-phenanthryl)-1-(2-nitrobenzenesulfonyl)aziridine (40): Prepared as described above starting from **20** (100 mg, 0.25 mmol), and isolated as a light-brown viscous oil after workup and chromatography (93 mg, 76%); R_f=0.26 (hexane/EtOAc 7:3). Product **40** was a *cis*/*trans* mixture. Isomers of **40** were separated by HPLC. ***Trans* isomer**: *ee* 98% (Chiralcel OD; hexane/2-propanol/diethylamine 50:50:0.2; 254 nm; 1 mL min^{-1}; t_{major}=45.4 min, t_{minor}=72.4 min); ^{1}H NMR (600 MHz, $CDCl_3$): δ=4.59 (d, J=5.0 Hz, 1H), 4.98 (d, J_1=5.0 Hz, 1H), 7.40–7.50 (m, 4H), 7.53–7.69 (m, 8H), 7.79 (br s, 1H), 7.81–7.84 (m, 2H), 8.21 (d, J=7.6 Hz, 1H), 8.67 (d, J=8.1 Hz, 1H), 8.72 ppm (d, J=8.1 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ=50.6, 51.0, 122.1, 122.7, 123.7, 123.9, 126.2, 126.4, 126.4, 126.5, 126.8, 127.0, 127.2, 127.9, 128.3, 128.6, 128.6, 129.9, 130.2, 130.4, 130.4, 130.5, 131.3, 132.3, 132.6, 133.6 ppm; IR (KBr): $\tilde{\nu}$=3064, 2925, 1543, 1364, 1341, 1164, 1127 cm^{-1}. ***Cis* isomer**: *ee* 98% (Chiralcel OD; hexane/2-propanol/diethylamine 50:50:0.2; 254 nm; 1 mL min^{-1}; t_{major}=24.2 min, t_{minor}=31.2 min); $[\alpha]_D^{25}$=+16.7 (c=0.54 in CH_2Cl_2); ^{1}H NMR (300 MHz, $CDCl_3$): δ=4.72 (d, J=7.3 Hz, 1H), 4.92

(dd, $J_1=1.0$, $J_2=7.3$ Hz, 1H), 6.95–6.96 (m, 3H), 7.16–7.18 (m, 2H), 7.53–7.55 (m, 1H), 7.57–7.61 (m, 3H), 7.78–7.83 (m, 5H), 8.05–8.08 (m, 1H), 8.38–8.40 (m, 1H), 8.55 (d, $J=8$ Hz, 1H), 8.59–8.60 ppm (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=48.6$, 49.8, 122.4, 123.2, 123.5, 124.7, 125.7, 126.6, 126.7, 126.8, 126.9, 127.3, 127.7, 127.9, 128.0, 129.0, 129.9, 130.1, 130.2, 131.0, 131.5, 131.5, 131.6, 132.3, 134.9 ppm; IR (KBr): $\tilde{\nu}=$ 3067, 2924, 1541, 1364, 1340, 1168, 1125, 911 cm^{-1}; elemental analysis calcd (%) for *cis*/*trans* mixture of $C_{28}H_{20}N_2O_4S$ (480): C 69.98, H 4.20, N 5.83; found: C 69.65, H 4.31, N 5.50.

(2*R*,3*S*)-2-Phenyl-3-*tert*-butyl-1-tosylaziridine (37): Tetrabutylammonium fluoride (0.42 mL, 1 M in THF, 0.42 mmol, 2 equiv) was added to a solution of **36** (70 mg, 0.21 mmol, 1 equiv) in anhydrous THF (5 mL) and the reaction mixture was stirred for 48 h at 60 °C. After cooling, H_2O (20 mL) was added and the mixture was extracted with dichloromethane (3×10 mL). The combined organic extracts were dried with Na_2SO_4, filtered, and concentrated under vacuum. Crude 2-phenyl-3-*tert*-butylaziridine (40 mg) was obtained and used in the next step without further purification. 2-Phenyl-3-*tert*-butylaziridine (40 mg) was dissolved in CH_2Cl_2 (2 mL) and tosyl chloride (48 mg, 0.25 mmol) and diisopropylethylamine (0.39 mL, 2.3 mmol) were added. The reaction mixture was stirred for 20 h at RT. Water acidified with phosphoric acid (pH 3, 10 mL) was added, and the mixture was extracted with CH_2Cl_2 (3×5 mL). The combined organic extracts were dried with Na_2SO_4, filtered, and concentrated under vacuum. The crude product was purified by silica gel column chromatography (CH_2Cl_2/hexane 8:2) and the title compound **37** was isolated as a white powder (37 mg, 54 %). $R_f=0.36$ (CH_2Cl_2/hexane 8:2); $[\alpha]_D^{25}=-129$ ($c=1.6$ in $CHCl_3$) {in an accordance with the original data[20] for the (2*R*,3*S*)-2-phenyl-3-*tert*-butyl-1-tosylaziridine}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=0.67$ (s, 9H), 2.45 (s, 3H), 2.77 (d, $J=7.5$ Hz, 1H), 3.92 (d, $J=7.5$ Hz, 1H), 7.16–7.25 (m, 5H), 7.33–7.36 (m, 2H), 7.90–7.93 ppm (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=21.7$, 27.5, 31.9, 46.0, 54.3, 127.4, 127.7, 128.1, 128.3, 129.7, 133.8, 135.0, 144.5 ppm.

Acknowledgements

We thank the Ministry of Science, Education and Sports of the Republic of Croatia for financing (grant nos. 098-0982933-2908 and 098-0352851-2921).

[1] For reviews on asymmetric aziridinations and ring transformations, see: a) T. Tanner, *Angew. Chem.* **1994**, *106*, 625–646; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 599–619; b) W. McCoull, F. A. Davis, *Synthesis* **2000**, 1347–1365; c) B. Zwanenburg, P. T. Holte, *Top. Curr. Chem.* **2001**, *216*, 93–124; d) J. B. Sweeney, *Chem. Soc. Rev.* **2002**, *31*, 247–258; e) P. Müller, C. Fruit, *Chem. Rev.* **2003**, *103*, 2905–2919; f) *Aziridines and Epoxides in Organic Synthesis* (Ed.: A. K. Yudin), Wiley-VCH, Weinheim, **2006**; g) E. M. McGarrigle, E. L. Myers, O. Illa, M. A. Shaw, S. L. Riches, V. K. Aggarwal, *Chem. Rev.* **2007**, *107*, 5841–5883; h) E. M. McGarrigle, V. K. Aggarwal in *Enantioselective Organocatalysis: Reactions and Experimental Procedures* (Ed.: P. I. Dalko), Wiley-VCH, Weinheim, **2007**, Chapter 10; i) G. K. Friestad, A. K. Mathies, *Tetrahedron* **2007**, *63*, 2541–2569; j) A. Padwa in *Comprehensive Heterocyclic Chemistry III, Vol. 1* (Eds.: K. A. Katrizky, C. A. Ramsden, E. F. V. Scriven, R. J. K. Taylor), Elsevier, Oxford, **2008**, Chapter 1, p. 1; k) H. Pellissier, *Tetrahedron* **2010**, *66*, 1509–1555.

[2] a) K. B. Hansen, N. S. Finney, E. N. Jacobsen, *Angew. Chem.* **1995**, *107*, 750–752; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 676–678; b) K. G. Rasmussen, K. A. Jorgensen, *J. Chem. Soc. Perkin Trans. 1* **1997**, 1287–1292; c) K. Juhl, R. G. Hazell, K. A. Jorgensen, *J. Chem. Soc. Perkin Trans. 1* **1999**, 2293–2297; d) J. C. Antilla, W. D. Wulff, *J. Am. Chem. Soc.* **1999**, *121*, 5099–5100; e) J. C. Antilla, W. D. Wulff, *Angew. Chem.* **2000**, *112*, 4692; *Angew. Chem. Int. Ed.* **2000**, *39*, 4518.

[3] a) V. K. Aggarwal, A. Thompson, R. V. H. Jones, M. C. H. Standen, *J. Org. Chem.* **1996**, *61*, 8368–8369; b) V. K. Aggarwal, E. Alonso, G. Fang, M. Ferrara, G. Hynd, M. Porcelloni, *Angew. Chem.* **2001**, *113*, 1482–1485; *Angew. Chem. Int. Ed.* **2001**, *40*, 1433–1436; c) V. K. Aggarwal, M. Ferrara, C. J. O'Brien, A. Thompson, R. V. H. Jones, R. Fieldhouse, *J. Chem. Soc. Perkin Trans. 1* **2001**, 1635–1643; d) V. K. Aggarwal, J. P. H. Charment, C. Ciampi, J. M. Hornby, C. J. O'Brien, G. Hynd, R. Parsons, *J. Chem. Soc. Perkin Trans. 1* **2001**, 3159–3166; e) V. K. Aggarwal, G. Hynd, W. Picoul, J.-L. Vasse, *J. Am. Chem. Soc.* **2002**, *124*, 9964–9965; f) A. H. Li, Y. G. Zhou, L. X. Dai, X. L. Hou, L. J. Xia, J. Lin, *J. Org. Chem.* **1998**, *63*, 4338–4348; g) X. L. Hou, J. Wu, R. H. Fan, C. H. Ding, Z. B. Luo, L. W. Dai, *Synlett* **2006**, 181–193; h) T. Saito, M. Sakairi, D. Akiba, *Tetrahedron Lett.* **2001**, *42*, 5451–5454; i) D. Morton, D. Pearson, R. A. Field, R. A. Stockman, *Org. Lett.* **2004**, *6*, 2377–2380.

[4] E. L. Eliel, J. E. Lynch, F. Kume, S. V. Frye, *Org. Synth.* **1987**, *65*, 214–223.

[5] a) A. Solladié-Cavallo, A. Adib, *Tetrahedron* **1992**, *48*, 2453–2464; b) A. Solladié-Cavallo, A. Diep-Vohuule, *J. Org. Chem.* **1995**, *60*, 3494–3498; c) A. Solladié-Cavallo, A. Diep-Vohuule, V. Šunjić, V. Vinković, *Tetrahedron: Asymmetry* **1996**, *7*, 1783–1788; d) A. Solladié-Cavallo, A. Diep-Vohuule, T. Isarno, *Angew. Chem.* **1998**, *110*, 1824–1827; *Angew. Chem. Int. Ed.* **1998**, *37*, 1689–1691; e) A. Solladié-Cavallo, M. Roje, T. Isarno, V. Šunjić, V. Vinković, *Eur. J. Org. Chem.* **2000**, 1077–1080.

[6] A. Solladié-Cavallo, M. Roje, R. Welter, V. Šunjić, *J. Org. Chem.* **2004**, *69*, 1409–1412.

[7] I. Stipetić, M. Roje, Z. Hameršak, *Synlett* **2008**, 3149–3152.

[8] E. Vedejs, D. A. Engler, M. J. Mullins, *J. Org. Chem.* **1977**, *42*, 3109–3113.

[9] A. Solladié-Cavallo, A. Adib, M. Schmitt, J. Fischer, A. DeCian, *Tetrahedron: Asymmetry* **1992**, *3*, 1597–1602.

[10] *N*-SES imines and *N*-Ts imines were prepared according to: a) W. R. McKay, G. R. Proctor, *J. Chem. Soc. Perkin Trans. 1* **1981**, 2435–2442; b) W. B. Jennings, C. J. Lovely, *Tetrahedron* **1991**, *47*, 5561–5568. *N*-Boc imines were prepared according to: c) A. M. Kanazawa, J. Denis, A. E. Greene, *J. Org. Chem.* **1994**, *59*, 1238–1240; d) B. M. Trost, J. Jaratjaroonphong, V. Reutrakul, *J. Am. Chem. Soc.* **2006**, *128*, 2778–2779.

[11] a) T. Hayashi, M. Ishigedani, *J. Am. Chem. Soc.* **2000**, *122*, 976–977; b) Y. Xu, G. Lu, S. Matsunaga, M. Shibasaki, *Angew. Chem.* **2009**, *121*, 3403–3406; *Angew. Chem. Int. Ed.* **2009**, *48*, 3353–3356.

[12] a) R. Robiette, *J. Org. Chem.* **2006**, *71*, 2726–2734; b) D. Janardanan, R. B. Sunoj, *Chem. Eur. J.* **2007**, *13*, 4805–4815; c) D. Janardanan, R. B. Sunoj, *J. Org. Chem.* **2008**, *73*, 8163–8174; d) Y. Arroyo, Á. Meana, J. F. Rodríguez, M. A. Sanz-Tejedor, I. Alonso, J. L. García Ruano, *J. Org. Chem.* **2009**, *74*, 4217–4224.

[13] D. K. Wang, L. X. Dai, X. L. Hou, *J. Chem. Soc. Chem. Commun.* **1997**, 1231–1232.

[14] In fact there are two possible *cisoid* approaches, corresponding to S–C–C–N dihedral angle of approximately +60° or −60°. The geometries in Figure 2. correspond to the more stable conformation.

[15] V. K. Aggarwal, J. N. Harvey, J. Richardson, *J. Am. Chem. Soc.* **2002**, *124*, 5747–5756.

[16] G. R. Desiraju, *Acc. Chem. Res.* **1996**, *29*, 441–449.

[17] D. Janardanan, R. B. Sunoj, *J. Org. Chem.* **2007**, *72*, 331–341.

[18] a) A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5684–5684; b) A. D. Becke, *Phys. Rev. A* **1988**, *38*, 3098–3100; c) C. Lee, W. Yang, R. G. Parr, *Phys. Rev. B* **1988**, *37*, 785–789; d) S. H. Vosko, L. Wilk, M. Nusair, *Can. J. Phys.* **1980**, *58*, 1200–1211; e) P. J. Stephens, F. J. Devlin, C. F. Chabalowski, M. J. Frisch, *J. Phys. Chem.* **1994**, *98*, 11623–11627.

[19] Gaussian 03, Revision B.05, M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery, Jr., T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian,

J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez, J. A. Pople, Gaussian, Inc., Pittsburgh, **2003**.

[20] An original sample of (2*R*,3*S*)-2-phenyl-3-*tert*-butyl-1-tosylaziridine was obtained from the author, and we measured the optical rotation to be $[\alpha]_D^{25} = -132$ ($c = 1.0$ in $CHCl_3$).

Received: May 24, 2010
Published online: September 8, 2010

