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Rigid backbone 1,8-anthracene-linked bis-oxazolines (AnBOXes): design, synthesis, application and characteristics in catalytic asymmetric aziridination

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Abstract—A series of rigid backbone 1,8-anthracene-linked bis-oxazolines (AnBOXes) have been designed, synthesized, and evaluated in the catalytic asymmetric aziridination with [*N*-(*p*-toluenesulfonyl)imino]phenyliodinane (PhI=NTs) as a nitrene source. The results indicate that highly enantioselective aziridination of chalcones catalyzed by an AnBOX and CuOTf complex with up to >99% ee and the opposite enantioselectivity, compared with the ligands of Evans et al., can be achieved. The enantioselectivity is substituent dependent with respect to chalcones. Chalcones with electron-donating substituents show higher enantioselectivities due to the stronger Lewis basicity of the oxygen of their carbonyl groups than those with electron-withdrawing substituents. The results also indicate that the coordination between the oxygen of the carbonyl group in chalcones and the ether group in alkenes with the copper in the catalyst is essential for high enantioselectivity, while the π–π stacking interaction between two reactants plays an importantly additional role for high enantioselectivity in asymmetric aziridination. An excellent backbone-controlled stereoselectivity was observed for the AnBOX ligands in asymmetric aziridination, as this will provide very important information for designing novel ligands.

1. Introduction

The C_2-symmetric chiral bis-oxazolines have emerged as one class of important and efficient ligands in an increasing number of asymmetric transformations over the last decade.[1] The bis-oxazolines have been found to be excellent chiral ligands for numerous asymmetric reactions, including cyclopropanation of olefins, aziridination of olefins and imines, (hetero)-Dields–Alder reactions, Henry reactions, allylic substitution and oxidation, transfer hydrogenation, hydrosilylation and cyanosilylation of aldehydes and ketones, addition of dialkylzinc to aldehydes and ketones, addition of alkyllithiums to imines, addition of silylketene acetal to aldehyde, free radical initiated addition of allyltributylstannane, etc.[1]

Over the last decade, numerous chiral bis-oxazolines with different backbones, such as methylene,[2] dimethylmethylene,[3] ethylene,[2] benzene,[2,4] pyridine,[5] dibenzofuran,[6] dibenzothiophene,[7] dibenzopyrrole,[8] bicyclic compounds,[9] dibenzo[*a*,*c*]cycloheptadiene,[10] etc. have been reported. The effects of the structure and chelate size of bis-oxazoline ligands, the two oxazolines of which were linked with a single bond, methylene, ethylene, 1,2-phenylene, and 4,5-dioxolane, in the asymmetric copper-catalyzed cyclopropanation and aziridination of olefins,[2,11] and in the asymmetric Diels–Alder reaction[12] were investigated previously. The results indicated that fine tuning of the ligand structure could improve enantioselectivity. It is well known that a well-ordered chiral environment at the catalytic center will play an important role in controlling the enantioselectivity in an asymmetric catalytic reaction. The size of the chelate in the reactive metal complex of bis-oxazolines is another important feature of the catalyst since it will control the orientation of the substituents on the two oxazolines around the metal ion and the distance of the substituents to the metal ions. This implies that the chelate size of bis-oxazolines can tune the chiral environment at the catalytic center and then affect the enantioselectivity of asymmetric catalytic reactions. To keep the designed chiral environment at the

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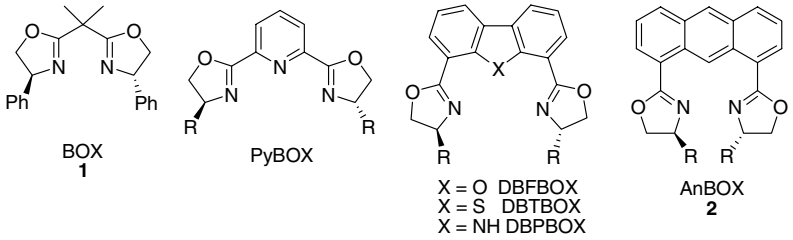


Scheme 1. Different rigid backbone bis-oxazoline ligands.

catalytic center, a series of rigid backbone-linked bis-oxazolines were designed and synthesized. Compared with some conformationally rigid backbone-containing bis-oxazoline ligands, in which the two oxazoline rings were linked by benzene,[2,4] pyridine,[5] dibenzofuran,[6] dibenzothiophene,[7] dibenzopyrrole,[8] etc. our design for these ligands focuses on the backbone possessing some different structural features from previously reported bis-oxazoline ligands.[2–11] Our ligand (AnBOX), the two oxazoline rings of which are attached on the 1,8-positions of a rigid anthracene ring, possesses only bidentate, instead of tridentate in the previously reported rigid bis-oxazoline ligands with pyridine,[5] dibenzofuran,[6] dibenzothiophene,[7] or dibenzopyrrole[8] as the backbones, and their two substituents on the oxazoline rings are closer than previously reported ones.[5–8] When they coordinate with a metal during the catalysis, their stereogenic centers (substituents) are close to the metal ion. Thus, they should have a different chiral environment near the reaction center (Scheme 1).

There have been three major approaches for catalytic asymmetric aziridinations developed during the past decade,[13] including nitrene transfer to olefins[3,14] and carbene transfer to imines[15] under the catalysis of chiral ligands and transition metals,[16] and carbene transfer to imines via chiral sulfonium ylides.[17] Among them, the nitrene transfer to olefins is a powerful strategy for the synthesis of enantiomerically enriched aziridines with a variety of functional groups.[3,14] In transition metal-chiral ligand catalyzed asymmetric aziridinations, the C_2-symmetric chiral bis-oxazolines have emerged as one class of the most efficient ligands. We have recently reported preliminary results on the asymmetric aziridination of chalcones catalyzed by our bis-oxazoline ligand (AnBOX)–copper complex.[18] Herein, we present full details on the preparation of anthracene-linked bis-oxazolines, along with their stereoselectivity and characteristics in asymmetric catalytic aziridinations of olefins.

2. Results and discussion

2.1. Synthesis of 1,8-bisoxazolinylanthracenes

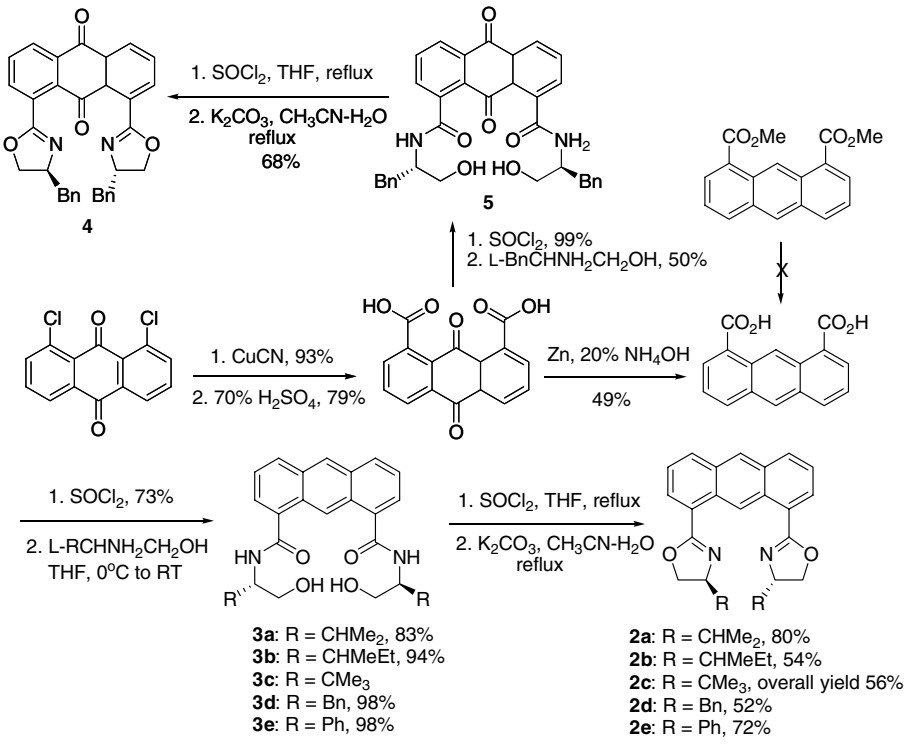
Although several synthetic methods are available for the preparation of bis-oxazolines, the most efficient one is using diacids as starting materials via dihydroxy diamides as intermediates. Dimethyl 1,8-anthracenedicarboxylate is commercially available and could be used to prepare the dihydroxy diamide directly by aminolysis of amino alcohols.[19] However, we discarded this method due to the very low yield. In order to synthesize our ligands (AnBOXes) **2**, we first had to prepare 1,8-anthracenedicarboxylic acid firstly. When we attempted to prepare 1,8-anthracenedicarboxylic diacid via saponification of its dimethyl ester, we found that the corresponding disodium salt is insoluble in a variety of solvents. Finally, we chose 1,8-dichloroanthraquinone as starting material to prepare 1,8-anthracenedicarboxylic diacid according to the method reported by Rogers and Averill.[20]

Commercially available 1,8-dichloroanthraquinone was converted to 1,8-anthraquinonedicarboxylic diacid via cuprous cyanide substitution and hydrolysis in high yields.[20] 1,8-Anthraquinonedicarboxylic diacid was reduced to 1,8-anthracenedicarboxylic acid by zinc, followed by the activation with $SOCl_2$ in PhCl to give 1,8-anthracenedicarbonyl dichloride,[21] which was treated with L-amino alcohols to afford the corresponding dihydroxy diamides **3** in high yields. The diamides **3** were activated with $SOCl_2$ in THF to yield dichlorodiamides, which were treated with K_2CO_3 in a mixture of CH_3CN–H_2O as a co-solvent to produce 1,8-bisoxazolinylanthracenes **2** (AnBOXes) in satisfactory yields.[22] In most cases, the intermediates **3** were used without further purification due to their poor solubility. The final ligands were conveniently purified by silica gel chromatography (Scheme 2).

Because 1,8-anthraquinonedicarboxylic diacid is a key intermediate in the preparation of 1,8-anthracenedicarboxylic diacid, a tridentate bis-oxazoline ligand, 1,8-bisoxazolinylanthraquinone **4**, with anthraquinone as a backbone was also synthesized from 1,8-anthracenedicarboxylic diacid and enantiomerically pure L-phenylalaninol using a similar method (Scheme 2).

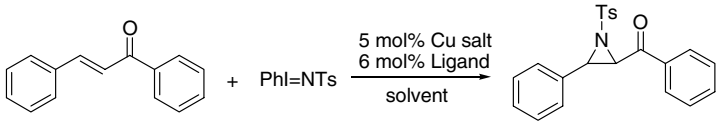
2.2. Optimizing reaction conditions for the asymmetric aziridination of chalcone

First, the copper-catalyzed asymmetric aziridination of chalcone with [*N*-(*p*-toluenesulfonyl)imino]phenyliodinane (PhI=NTs) as a nitrene source in the presence of AnBOXes was investigated in detail in order to determine the efficiency of the new ligand system and to optimize reaction conditions. Different temperatures, solvents, and copper salts were evaluated with chalcone and ligand **2a**. The results are summarized in Table 1. It was found that excellent enantioselectivity and good



Scheme 2. Synthesis of 1,8-bisoxazolinylanthracenes **2** and 1,8-bisoxazolinylanthraquinone **4**.

Table 1. Optimizing the reaction conditions by the aziridination of chalcone **6a**



6a **7a** or *ent*-**7a**

Entry	Ligand	Solvent	Copper	Temp (°C)	Yield[a] (%)	ee[b] (%)	Configuration[c]
1	**2a**	CH_2Cl_2	CuOTf	−17 warm to 23	46	55	**7a** (2*S*,3*R*)
2	**2a**	CH_2Cl_2	CuOTf	0 warm to 23	64	86	**7a** (2*S*,3*R*)
3	**2a**	**CH_2Cl_2**	**CuOTf**	**24**	**80**	**96**	**7a** (2*S*,3*R*)
4	**2a**	CH_2Cl_2	CuOTf	30	80	79	**7a** (2*S*,3*R*)
5	**2a**	CH_3CN	CuOTf	24	80	88	**7a** (2*S*,3*R*)
6	**2a**	C_6H_6	CuOTf	24	18	58	**7a** (2*S*,3*R*)
7	**2a**	CH_2Cl_2	$Cu(acac)_2$	24	33	28	**7a** (2*S*,3*R*)
8	**2a**	CH_2Cl_2	$Cu(CH_3CN)_4PF_6$	24	81	62	**7a** (2*S*,3*R*)
9	**2a**	CH_2Cl_2	$Cu(OTf)_2$	24	52	65	**7a** (2*S*,3*R*)
10	**2b**	CH_2Cl_2	CuOTf	24	79	26	**7a** (2*S*,3*R*)
11	**2c**	CH_2Cl_2	CuOTf	24	25	10	**7a** (2*S*,3*R*)
12	**2d**	CH_2Cl_2	CuOTf	24	76	61	**7a** (2*S*,3*R*)
13	**2e**	CH_2Cl_2	CuOTf	24	73	32	**7a** (2*S*,3*R*)
14	**4**	CH_2Cl_2	CuOTf	24	32	23	**7a** (2*S*,3*R*)
15	**1**	CH_2Cl_2	CuOTf	24	38	86	*ent*-**7a** (2*R*,3*S*)

[a] Isolated yield after flash silica gel chromatographic separation.
[b] Determined by HPLC analysis using chiralcel OD column.
[c] The absolute configuration was determined by comparing the determined specific rotations with that reported.[24]

yields were obtained in CH_2Cl_2 at 24 °C (room temperature) (Table 1, entry 3). Although Evans et al. reported the highest enantioselectivity was obtained in benzene,[3] we found that dichloromethane is the best solvent for our asymmetric reaction. We also conducted the asymmetric reaction at different temperatures and found that almost no desired reaction occurred at −78 to 0 °C possibly due to poor reactivity of chalcone with nitrene TsN:. The reaction proceeded efficiently at room temperature (around 24 °C). The highest enantioselectivity was achieved by portion wise addition of PhI=NTs. For copper salts, CuOTf is soluble in many organic

solvents and is often employed in asymmetric aziridination.[3] However, CuOTf is sensitive to air and moisture, and relatively expensive. It was reported that bis-oxazolines catalysts derived from Cu(I) and Cu(II) resulted in the same level of asymmetric induction.[23] We examined other copper sources, such as $Cu(acac)_2$, $Cu(CH_3CN)_4PF_6$, and $Cu(OTf)_2$ (Table 1 , entries 7–9) in the hope of finding a relatively inexpensive copper salt. The results indicated that CuOTf is indeed the best one and $Cu(CH_3CN)_4PF_6$ ranked second with a comparable yield to that of CuOTf but lower enantioselectivity.

After optimizing reaction conditions, the bidentate AnBOXes **2b–e** (Table 1, entries 10–13) and tridentate ligand **4** (Table 1, entry 14) were examined under the same conditions. They showed lower enantioselectivities than AnBOX **2a**. Particularly, ligand **2c**, with the more sterically bulky group *t*-Bu on AnBOX (Table 1, entry 11), led to a further decrease in reactivity (25% yield) and enantioselectivity (10% ee). It was suggested that sterically hindered ligand might not provide suitable chiral environment for our aziridination as reported by Andersson et al. because it does not leave sufficient space for the copper to simultaneously coordinate with both nitrogen atoms of the oxazoline rings.[2]

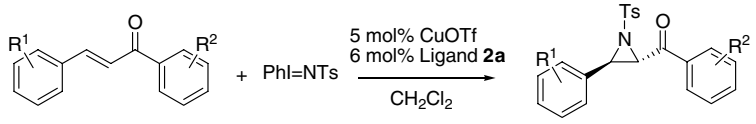
So far, it can be seen from Table 1 that the AnBOX **2a**–CuOTf is the most efficient catalyst for our model reaction, and the reaction performed at 24 °C in CH_2Cl_2 gives the best results in terms of the enantioselectivity and reactivity.

In comparison with the asymmetric aziridination catalyzed by bis-oxazoline (BOX) **1** of Evans et al. (Table 1, entry 15),[3] it is very interesting to note that our ligand AnBOXes **2** show a different stereoselectivity, whereby chalcone is aziridinated in an opposite configuration (2*S*,3*R*) despite AnBOXes being derived from the L-amino alcohols as used in the BOX ligands of Evans et al.[3]

2.3. Asymmetric aziridination of chalcones under the optimized conditions

Aziridination of chalcones with PhI=NTs as the nitrene precursor was conducted with the AnBOX **2a**–CuOTf as the catalyst under the optimal conditions. The results are summarized in Table 2. Obviously, the ee values are dependent on the substituents on both phenyl groups in the chalcones. The chalcones with electron-donating substituents, which do not contain heteroatoms with coordinated unshared electron pairs, for example, O, S, show higher enantioselectivities (87% to

Table 2. Aziridination of chalcones **6** catalyzed by ligand **2a** under the optimized conditions



6 **7**

Entry	Product	R^1	R^2	Yield[a] (%)	ee[b] (%)
1	**7a**	H	H	80	96
2	**7b**	*p*-Me	H	86	98
3	**7c**	*p*-Ph	H	35	87
4	**7d**	*p*-F	H	72	62
5	**7e**	*p*-Cl	H	70	76
6	**7f**	*p*-Br	H	58	52
7	**7g**	*p*-MeO	H	61	37
8	**7h**	*o*-MeO	H	21	27
9	**7i**	*p*-MeS	H	NR	—
10	**7j**	*p*-Me	*p*-Me	59	>99
11	**7k**	H	*p*-Me	92	>99
12	**7l**	H	*p*-F	72	54
13	**7m**	H	*p*-Cl	74	58
14	**7n**	H	*p*-Br	64	50
15	**7o**	H	*p*-NO_2	61	ND
16	**7p**	H	*p*-MeO	74	62
17	**7q**	*p*-Cl	*p*-Cl	68	43
18	**7r**	*p*-Cl	*p*-Me	66	39
19	**7s**	*p*-Me	*p*-Cl	51	68
20	**7t**	*o*-Cl	H	91	79
21	**7u**	*m*-Cl	H	76	84
22	**7v**	*m*-F	H	85	71
23	**7w**	*p*-CF_3	H	69	67

[a] Isolated yield after flash silica gel chromatographic separation.

[b] Ee value was determined by HPLC analysis using chiralpak AS column, chiralcel OD, OD-H columns. For **7a**, the absolute configuration was determined by comparing the determined specific rotation with that reported.[24] For **7b–w** except for **7i**, the absolute configurations were tentatively assigned according to the reaction mechanism and their relative retention times on chiral columns.

>99% ee values) (Table 2, entries 2, 3, 10, and 11) than those with electron-withdrawing substituents (Table 2, entries 4–6, 12–14, and 17–23) in the asymmetric aziridination. To the best of our knowledge, the AnBOX **2a**–CuOTf is the best catalyst with the highest enantioselectivity in the asymmetric aziridination of chalcones. It was noticeable that chalcones with *p*-MeO, an electron-donating substituent (Table 2, entries 7, 8, and 16), showed decreased enantioselectivities (37%, 27%, and 62% ee, respectively). There are two possible reasons that cause the decreased enantioselectivity. The first is that the oxygen in the MeO group reacts with TsN=IPh to form an O–N ylide, which aziridinates the C=C double bond to give rise to racemic aziridination product similar to halo substituted styrenes in asymmetric cyclopropanation, in which a halo-carbon ylide is formed and then reacts with the C=C double bond to yield the racemic cyclopropanation product.[25] The second is that the coordination of the oxygen in MeO to the copper ion in the catalyst. This is a competitive coordination with that between the copper and the carbonyl group of the chalcones. To determine the reason, 2-methoxychalcone was azirinated under same reaction conditions and 27% ee value was obtained (Table 2, entry 8). This indicates that no O–N ylide formed in the reaction. If it was formed, complete racemic aziridination product would be obtained due to an intramolecular aziridination via the O–N ylide. To verify the coordination, 4-methylthiochalcone with a strong coordinating sulfur atom was prepared and tested. No expected aziridine product was detected in the reaction mixture and the starting materials were recovered quantitatively (Table 2, entry 9). It is obvious that both MeO and MeS substituents, including coordinating heteroatoms oxygen and sulfur, are capable of coordinating with the copper ion. Therefore, coordination seems to be responsible for the decreased enantioselectivity and reactivity.

The oxygen of the MeO-group in the MeO-substituted chalcones competed for coordination with the copper in the catalyst, which decreased the amount of the carbonyl group-coordinated complex, so that their enantioselectivities decreased because the MeO-coordinated complex could not undergo an asymmetric catalytic aziridination due to unsuitable positioning of the C=C bond of the chalcones in the ether-coordinated complex. The MeS-substituted chalcone did not react with PhI=NTs and was recovered quantitatively since the coordination of the sulfur atom with the copper is so strong that the catalytic amount of copper was caught completely by the MeS-groups and removing the copper from the reaction system. Thus, the nitrene cannot be generated due to the absence of free non-coordinated copper, and the aziridination of the MeS-substituted chalcone did not occur.

2.4. Influence of the electronic effect on the enantioselectivity in the asymmetric aziridination of chalcones

An obvious influence of the electronic effect of substrates on the enantioselectivity was observed in our asymmetric aziridination. The substrates with electron-donating groups afforded higher enantioselectivities than those bearing electron-withdrawing groups. From Hammett plots of Log([2*S*,3*R*]/[2*R*,3*S*]) versus Hammett constants σ_p,[26] a straight line for 4-substituted chalcones (Table 2, entries 1–6) was obtained with $R^2 = 0.88$, slope $= -3.65$ (Fig. 1). The same tendency with more obvious influence, $R^2 = 0.94$, slope $= -5.41$ (Fig. 2), was also observed for 4′-substituted chalcones (Table 2, entries 1 and 11–14). 4′-Substituent showed more obvious influence than 4-substituent because 4′-substituent is closer to the carbonyl group than 4-substituent.

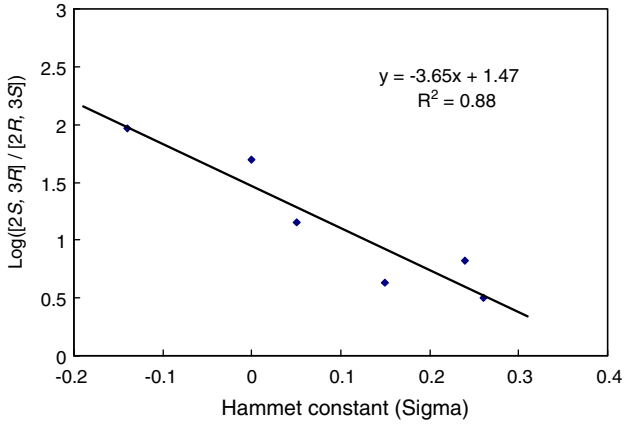


Figure 1. Hammett plot of the asymmetric aziridination of 4-substituted chalcones (Log([2*S*,3*R*]/[2*R*,3*S*]) of the aziridination products versus Hammett constant σ_p, Me, −0.14; H, 0; Ph, 0.05; F, 0.15; Cl, 0.24; Br, 0.26).

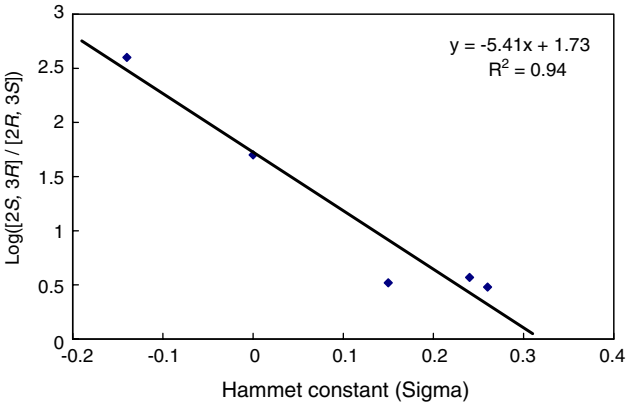
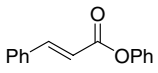
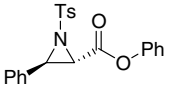
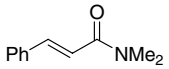
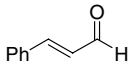
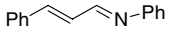
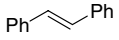
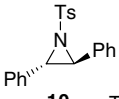
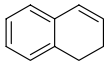
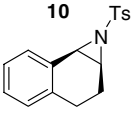


Figure 2. Hammett plot of the asymmetric aziridination of 4′-substituted chalcones (Log([2*S*,3*R*]/[2*R*,3*S*]) of the aziridination products versus Hammett constant σ_p, Me, −0.14; H, 0; F, 0.15; Cl, 0.24; Br, 0.26).

The electronic effect-dependent enantioselectivity was rationalized by the electron-donating groups in chalcones increasing the Lewis basicity of the oxygen of the carbonyl group in the chalcones with electron-donating groups so that they increase their coordination with the copper. The stronger coordination will preferentially allow the reaction to proceed via the asymmetric catalytic path catalyzed by the chiral catalyst. Thus, it produces higher enantioselectivity. A similar phenomenon was also observed in the asymmetric borane

Table 3. Scope and limitation of AnBOX ligand **2a** in the asymmetric aziridination

Entry	Substrate	Product	Yield (%)[a]	ee (%)	Configuration[e]
1		 **8**	61	44[b]	(2*S*,3*R*)[24]
2			NR		
3			NR		
4			NR		
5		 **9**	92	7[c]	(*R*)[14a]
6		 **10**	71	13[d]	(*S*,*S*)[28]
7		 **11**	63	5[d]	(1*R*,2*S*)[14a]

[a] Isolated yields after the column chromatography; NR, no reaction occurred.
[b] Determined by ^{1}H-NMR chiral shift reagent.
[c] Determined by HPLC analysis using a chiralcel OJ column.
[d] Determined by HPLC analysis using a chiralcel OD-H column.
[e] The absolute configurations were assigned according to the sign of the specific rotation as reported in Refs. 24,14a,28 and was further verified via detosylation by the treatment with sodium naphthalene[29] to afford (*S*,*S*)-2-benzyl-3-phenylaziridine according to the reported sign of the specific rotation.[30]

reduction of ketones catalyzed by chiral boroxazolidine.[27] The substituent electronic effect-dependent enantioselectivity also indicated that the coordination step is an enantioselectivity-determining step in the catalytic cycle.

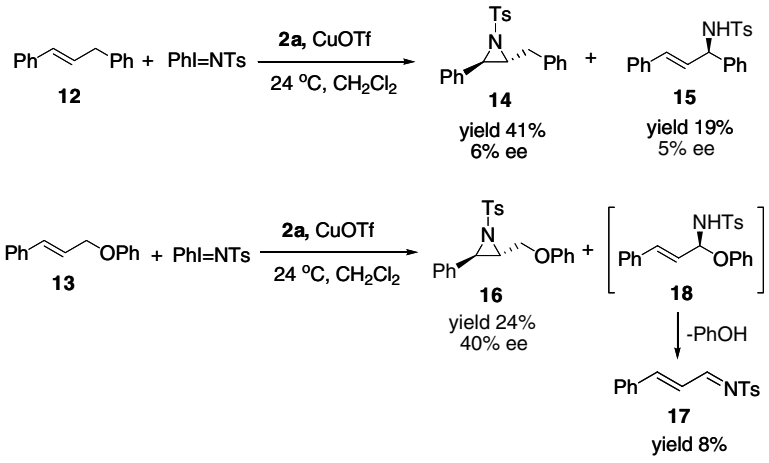
2.5. Scope and limitation of AnBOX ligand 2a in the asymmetric aziridination

After successful asymmetric aziridination of chalcones, we attempted to apply CuOTf–AnBOX **2a** complex to other substrates under the optimized conditions (Table 3). The reaction of phenyl *trans*-cinnamate (Table 3, entry 1), a similar structure to chalcone, afforded the corresponding aziridine with 44% ee and 61% yield. It was noteworthy that the aziridination of phenyl *trans*-cinnamate was also in (2*S*,3*R*) configuration, opposite to the one obtained by Evans et al.[3b] However, no aziridination occurred for *N*,*N*-dimethyl *trans*-cinnamamide, *trans*-cinnamaldehyde, and *trans*-*N*-cinnamylideneaniline (*trans*-PhCH=CHCH=NPh), even though they have similar structural features with chalcones. We also tested unfunctionalized olefins, such as styrene, *trans*-stilbene, and 1,2-dihyronaphthalene (Table 3, entries 5–7). For all of them, low enantioselectivities and moderate to good yields were obtained.

2.6. The coordination effect of oxyatoms in substrates with copper in the catalyst

It should be noted that the structural difference of chalcones and cinnamate from simple olefins is the presence of a carbonyl group in chalcones and cinnamate, which led to the increased enantioselectivities due to the presence of the coordination between the oxygen in oxygen-containing substrates and the copper in the catalyst. The coordination was also previously proposed via calculation.[31]

To verify the coordination, 1,3-diphenyl-1-propene **12** and cinnamyl phenyl ether **13**, carbonyl group-free structural analogues of chalcone and phenyl cinnamate were designed, synthesized, and asymmetrically aziridinated under the same reaction conditions (Scheme 3). The results indicated that the reaction of 1,3-diphenyl-1-propene **12** afforded aziridine product **14** with only 6% ee and 41% yield, along with allylic insertion product, (*E*,*R*)-*N*-(1,3-diphenyl-2-propenylidene)-(4-methyl)benzenesulfonamide **15** in 5% ee and 19% yield.[32] For cinnamyl phenyl ether **13**, the reaction proceeded in a very similar way. The corresponding aziridine **16** with an obviously higher enantioselectivity (40% ee) was obtained in 24% yield. Meanwhile, a byproduct (*E*)-*N*-(3-phenyl-2-propenylidene)-(4-methyl)benzenesulfonamide **17**[33] was also obtained in 8% yield. It was assumed that the imine was formed via an allylic insertion intermediate **18**, which is unstable and readily underwent a β-elimination to furnish **17**. Actually, phenol was also detected in the reaction mixture, which confirmed our assumption. Obviously, the enantioselectivities seriously decreased due to the absence of the carbonyl group in these two substrates. Herein, our results provide experimental evidence to

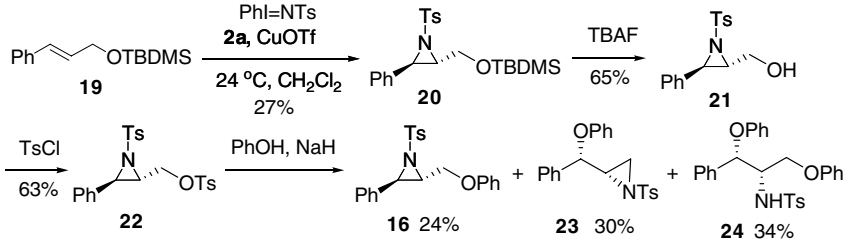


Scheme 3. Asymmetric aziridination of 1,3-diphenylpropene and cinnamyl phenyl ether, carbonyl group-free structural analogues of chalcone and phenyl cinnamate.

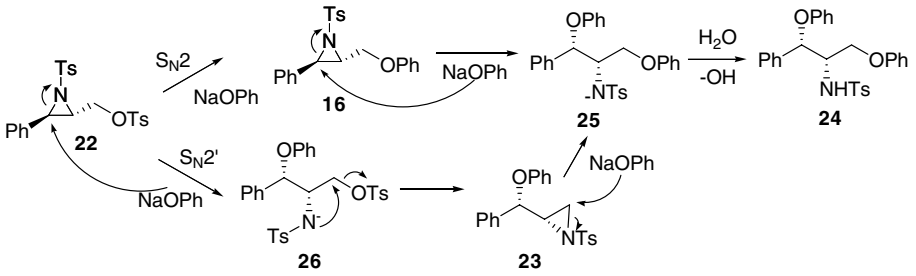
support the coordination of the carbonyl group of chalcones with the copper in the catalyst in the copper-catalyzed aziridination. This also suggests that the oxygen of the ether group seems to play a coordination role with the copper because olefin **13** shows higher enantioselectivity than olefin **12** due to the existence of an ether group in olefin **13**.

The difference in enantioselectivity between chalcone and phenyl cinnamate was rationalized to oxygen coordination of substrates with the copper in the catalyst. Because phenyl cinnamate could furnish two different coordinations due to the existence of the carbonyl and ether oxygens, which could result in two different orientations of C=C bond of phenyl cinnamate in the transition state and thus opposite configurational aziridines could be generated. Another possible reason is that because the oxygen of the carbonyl group in phenyl cinnamate is attached with a more electron-withdrawing group PhO, instead of Ph group in chalcone, it shows weaker Lewis bacisity than that in chalcone so that phenyl cinnamate shows lower enantioselectivity than chalcone in the asymmetric aziridination. On the basis of the configuration of aziridine **16** and the influence of the electronic effect on the enantioselectivity, we consider that the influence of the electronic effect is the major reason for the decreasing enantioselectivity because cinnamyl phenyl ether **13** shows the same enantiofacial selectivity with chalcones and 1,3-diphenylpropene **12**. If it adopts a different coordinating orientation, it would show an opposite enantiofacial selectivity between chalcones and 1,3-diphenylpropene **12**. Thus, it is very important to know the configuration of aziridine **16**.

In order to identify the configuration of aziridine **16** via chemical correlation, *tert*-butyldimethylsilyl cinnamyl ether **19** was prepared from cinnamyl alcohol with *tert*-butyldimethylsilyl chloride.[34,35] It was asymmetrically aziridinated with TsN=IPh under AnBOX **2a**–CuOTf complex catalysis to afford 2-*tert*-butyldimethylsiloxylmethyl-3-phenyl-1-tosyl-aziridine **20** with 27% ee, which was assigned the (2*S*,3*R*)-configuration with the negative specific rotation according to the reported sign of specific rotation.[33] Aziridine **20** was detrialkylsilylated with TABF to yield (2*S*,3*R*)-2-hydroxymethyl-3-phenyl-1-tosyl-aziridine **21**, which was tosylated with tosyl chloride to afford (2*S*,3*R*)-3-phenyl-1-tosyl-aziridin-2-ylmethyl tosylate **22**. Tosylate **22** was then substituted with sodium phenolate[36] to give rise to an aziridine with the configuration of 2*S*,3*R* and a negative specific rotation in low yield due to the existence of the aziridine ring-opening reaction. Both the sign of the specific rotation and HPLC retention time on a chiral column indicated that the obtained aziridine has the same configuration with aziridine **16**. Thus, the configuration of aziridine **16** is 2*S*,3*R*. Meanwhile, in the substitution reaction, another aziridine **23** and a toluenesulfonamide **24** were also obtained in yields of 30% and 34%, respectively (Scheme 4). Their proposed formation processes are shown in Scheme 5. Tosylate **22** could undergo an S_N2 substitution with sodium phenolate to afford aziridine **16**, which could



Scheme 4. Determination of the absolute configuration of asymmetric aziridination product of cinnamyl phenyl ether.



Scheme 5. Substitution reaction of (2*S*,3*R*)-3-phenyl-1-tosyl-aziridin-2-ylmethyl tosylate **22** with sodium phenolate.

be further attack at the benzylic position of the aziridine ring by sodium phenolate to yield intermediate **25**, followed by work-up to afford toluenesulfonamide **24**. Tosylate **22** could also undergo an S_N2' displacement via the attack at the benzylic position of the aziridine ring by sodium phenolate to yield an intermediate **26**, followed by an intramolecular S_N2 substitution to produce aziridine **23**. Aziridine **23** could be further attacked at the less sterically bulky carbon atom of the aziridine ring by sodium phenolate to yield the intermediate **25**, followed by work-up to afford toluenesulfonamide **24**. Both benzylic and less sterically bulky carbon atoms in an N-tosylated aziridine are active positions, which are preferentially attacked by a nucleophile as we summarized previously.[37]

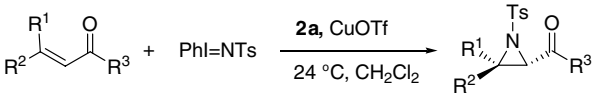
2.7. π–π Stacking interaction between aryl groups of nitrene and substrates

It is well known that the effects and benefits of the π–π stacking interaction between reactants or reactants and catalysts can improve the stereoselectivity in asymmetric synthesis, especially in the asymmetric induction achieved with chiral auxiliaries and asymmetric catalysis catalyzed by chiral catalysts.[38] The π–π stacking interaction can lock one conformation of a reactant in a given transition state assembly, which can preferentially yield one of the product enantiomers.

The π–π stacking interaction between the aryl groups of substrates and the tosyl group of a nitrene was also observed and presumed in our asymmetric catalytic system. In the aziridination of chalcones, an AnBOX ligand, chalcone, and CuOTf were allowed to stir for one hour to furnish a pre-transition state. The subsequent portionwise addition of the nitrene precursor PhI=NTs made the pre-transition state to transfer to a transition state, in which nitrene TsN: was generated via copper catalysis in the system and coordinated with the copper. It was assumed that the π–π stacking interaction between the aryl group attached to the C=C bond of chalcone and that of nitrene in the transition state made the transition state relatively more stable and favored to producing (2*S*,3*R*)-aziridination products of chalcones.

To confirm our assumption, four substrates, 4-phenyl-3-buten-2-one **27**, 1-phenyl-2-buten-1-one **28**, 4-methyl-3-penten-2-one **29**, and 5,5-dimethyl-3-hexen-2-one **30** were examined. The results are summarized in Table 4.

Table 4. Aziridination of α,β-unsaturated ketones **27**–**30** catalyzed by ligand **2a** under the optimized conditions



27-30 **31-34**

Entry	Product	R^1	R^2	R^3	Yield[a] (%)	ee[b] (%)
1	**31**	H	Ph	Me	65	50
2	**32**	H	Me	Ph	42	9
3	**33**	Me	Me	Me	20	6
4	**34**	H	*t*-Bu	Ph	Trace[c]	ND[d]

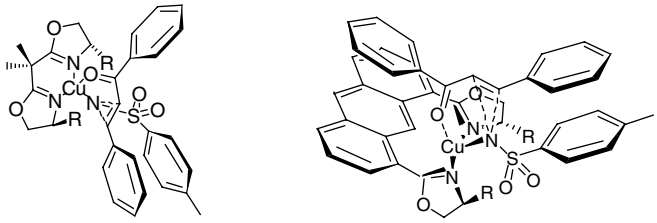
[a] Isolated yield after flash silica gel chromatographic separation.
[b] Ee value was determined by HPLC analysis using chiralcel OD and OD-H columns. For **31**, the absolute configuration was determined by comparing the determined rotation to that reported.[24] For **32** and **33**, the absolute configurations were tentatively assumed according to the reaction mechanism.
[c] 93% starting materials were recovered.
[d] Not determined.

Obviously, displacing a phenyl group with methyl group in different positions of chalcone diminished the enantioselectivities in comparison with chalcone (96% ee). The results indicate that the two phenyl groups in chalcone show unequal effects on the enantioselectivity. The phenyl group attached to the C=C double bond demonstrates more efficient π–π stacking interaction with the aryl group of the nitrene than that of the phenyl group attached to the carbonyl group with the anthracene ring in the ligand.

In order to further confirm the π–π stacking interaction, we also attempted to prepare alkanesulfonyl nitrene precursors $MeSO_2N{=}IPh$ and $BuSO_2N{=}IPh$ and hoped to test the asymmetric aziridination of chalcone with them. Unfortunately, we did not obtain pure $MeSO_2N{=}IPh$ and $BuSO_2N{=}IPh$ due to their instability although intramolecular aziridination of olefins with alkyl nitrene was achieved successfully.[39]

2.8. Explanation of the different stereoselectivities of AnBOX 2 and BOX 1 and the proposed transition states of aziridination of chalcones

In comparison with the asymmetric aziridination catalyzed by bis-oxazoline BOX **1** of Evans et al. (Table 1, entry 15), it is very interesting to note that our ligand AnBOX **2a** showed completely different stereoselectivity,



The nitrene attacks from the bottom (2*R*,3*S*)-aziridine produced

The nitrene attacks from the (2*S*,3*R*)-aziridine produced

Figure 3. Proposed transition states in the asymmetric aziridination of chalcone catalyzed by BOX **1** and AnBOX **2**.

whereby chalcones were aziridinated in an opposite configuration (2*S*,3*R*) with 96% ee although AnBOX **2a** was derived from the L-amino alcohol as used in the BOX **1** of Evans et al.[3b] To further confirm the difference, additional chalcones **6k** and **6l** were subjected to the asymmetric aziridination under the catalysis of BOX **1** to afford *ent*-**7k** and *ent*-**7l** in yields 24% and 10% with 85% and 86% ee, respectively. Both of their HPLC analysis and the sign of their specific rotations indicate that they were asymmetrically aziridinated in opposite enantiofacial selectivity in both cases compared with those under the catalysis of AnBOX **2a**. The different orientations for the different enantioselectivities could be due to the fact that AnBOX **2a** has a more crowded environment between two oxazoline rings than BOX **1** of Evans et al. Copper has to locate above or below the anthrancene ring after it coordinates with AnBOX. Actually, the two locations are the same case because of C_2-symmetry of the AnBOX ligand. The oxazoline rings rotate a certain angles and exist in a non-planar mode to the anthrancene ring, in which the nitrene attacks from the top of chalcone to produce (2*S*,3*R*)-product. However, in the BOX ligands of Evans et al., where the copper locates between two oxazoline rings, in which the nitrene attacks from the bottom of chalcone to generate (2*S*,3*R*)-product. Proposed transition states for the asymmetric aziridination of chalcones for the reactions catalyzed by BOX **1** and AnBOX **2a** are shown, respectively, in Figure 3.

3. Conclusion

In summary, a class of new bidentate bis-oxazolines (AnBOXes) **2** with anthracene as the backbone and a novel tridentate bis-oxazoline ligand **4** with anthraquinone as the backbone have been designed, synthesized, and applied in the asymmetric aziridination of olefins with PhI=NTs as a nitrene precursor. The results indicated that AnBOX **2a** with isopropyl substituent on the oxazoline ring is superior to the other enantiopure ligands **2** and **4** in the asymmetric aziridination, and the enantioselectivity is substituent dependent with respect to the chalcones. Generally, the chalcones with electron-donating substituents show higher enantioselectivities than those with electron-withdrawing substituents. In addition, the results also indicated that the coordination of the oxyatom of the carbonyl group in chalcones with copper in the catalyst and the π–π stacking interaction between the aryl group of the nitrene and aryl group attached to the C=C double bond in chalcones are indispensable for high enantioselectivity in the asymmetric aziridination. It is worth noting that our ligands **2** and **4** showed different enantiofacial selectivity in the asymmetric aziridination of chalcones and cinnamate, and better enantioselectivities in the asymmetric aziridination of chalcones, as compared with bis-oxazoline ligands of Evans et al.[3] On the basis of our results, the transition states of the aziridination reaction catalyzed by BOX and AnBOX–Cu complexes were proposed. It is very interesting that a backbone-controlled stereoselectivity was observed for the AnBOX ligands in the asymmetric aziridination. This provides very important information for designing novel ligands. This also indicated that the enantiofacial selectivity of a ligand could be changed via tuning its backbone, which linked the coordinating group(s). Although opposite enantiofacial selectivity could be achieved via displacing the stereogenic center(s) of the ligand by using enantiopure starting materials of opposite configuration in its synthesis, changing enantiofacial selectivity via the tuning backbone method is a very useful and alternative method in the case, in enantiopure starting materials of opposite configuration are not available.

4. Experimental

4.1. General

Melting points were measured on a Yanaco MP-500 melting point apparatus and are uncorrected. IR spectra were recorded on a Bruker Vector 22 FT-IR spectrophotometer. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Varian Mercury 200 (200 MHz), Varian Mercury Plus 300 (300 MHz), or Brucker 400 AMX (400 MHz) spectrometer in $CDCl_3$ or DMSO-d_6 solution with TMS as an internal standard and chemical shifts are reported in parts per million. Mass spectra were obtained on a VG-ZAB-HS spectrometer or a Bruker ESQUIRE∼LC™ ESI ion trap spectrometer. CH analyses were performed on an Elementar Vario EL analyzer. Optical rotations were measured on a Perkin–Elmer Model 341LC polarimeter with a thermally jacketed 10 cm cell (concentration c given as g/100 mL). HPLC analyses were performed on an HP1100 HPLC equipment with chiralcel chiral columns (4.6 × 250 mm) using a mixture

of hexane/isopropanol as an eluent. THF and benzene were heated under reflux over sodium benzophenone ketyl and distilled prior to use. Dichloromethane was heated under reflux over calcium hydride and distilled prior to use.

4.2. Synthesis of chiral ligand AnBOXes 2 and 4

Anthracene-1,8-dicarboxylic acid was prepared as previously reported[20] and anthracene-1,8-dicarbonyl dichloride and anthraquinone-1,8-dicarbonyl dichloride were synthesized according to the literature procedure.[21]

4.2.1. General procedure for the synthesis of (*S*,*S*)-*N*,*N*′-bis[1-(hydroxymethyl)alkyl]-anthracene-1,8-dicarboxamide 3. A 250 mL flask fitted with a magnetic stirring bar was charged with a solution of anthracene-1,8-dicarbonyl dichloride (0.87 g, 2.9 mmol) in 50 mL of dry THF. The solution was cooled in an ice bath, and a solution of L-amino alcohol (8.7 mmol) in 30 mL of dry THF was added dropwise. The resulting mixture was allowed to warm to room temperature and was stirred overnight. After filtration, the solution was concentrated to give a solid residue, which was recrystallized from ethanol to afford yellow crystals of the product.

4.2.1.1. (*S*,*S*)-*N*,*N*′-Bis[1-(hydroxymethyl)-2-methylpropyl]-anthracene-1,8-dicarboxamide 3a. After filtration, yellow solid crude product was obtained directly, which was recrystallized from ethanol to afford 1.04 g as yellow needle crystals in 83% yield, mp 252–254 °C; $R_f = 0.47$ (ethyl acetate, silica gel plate); $[\alpha]_D^{24} = -65.9$ (*c* 0.41, CH_3OH); IR (KBr) (cm^{-1}): 3314 (O–H), 1635 (C=O); ^1H NMR (400 MHz, DMSO-d_6): δ 0.95 (d, $J = 6.8$ Hz, 6H, $2CH_3$), 1.01 (d, $J = 6.8$ Hz, 6H, $2CH_3$), 2.00 (q, $J = 6.8$ Hz, 2CH), 3.55–3.58 (m, 4H, $2CH_2O$), 3.93–3.97 (m, 2H, 2CHN), 4.62 (t, $J = 5.6$ Hz, 2H, 2OH), 7.53–7.61 (m, 4H, 2NH and 2ArH), 8.15–8.19 (m, 2H, ArH), 8.66 (s, 1H, ArH), 9.18 (s, 1H, ArH); ^{13}C NMR (100 MHz, DMSO-d_6): δ 18.3, 19.8, 28.4, 56.2, 61.5, 123.1, 124.8, 125.0, 126.8, 128.2, 129.6, 131.0, 136.0, 168.5; MS (EI) *m*/*z* (rel. intensity, %): 436 (M^+, 9), 418 (M^+-H_2O, 6), 406 (38), 388 (17), 357 (4), 348 (5), 334 (33), 316 (27), 307 (23), 289 (35), 272 (35), 248 (61), 233 (13), 221 (16), 204 (36), 190 (5), 176 (33); Anal. Calcd for $C_{26}H_{32}N_2O_4$: C, 71.53; H, 7.39; N, 6.42. Found: C, 71.72; H, 7.28; N, 6.12.

4.2.1.2. (*S*,*S*)-*N*,*N*′-Bis[1-(hydroxymethyl)-2-methylbutyl]-anthracene-1,8-dicarboxamide 3b. Yellow powder, yield 94%, mp 209–210 °C; $R_f = 0.52$ (ethyl acetate, silica gel plate); $[\alpha]_D^{24} = -64.2$ (*c* 0.53, CH_3OH); IR (KBr) (cm^{-1}): 3291 (O–H), 1635 (C=O); ^1H NMR (200 MHz, DMSO-d_6): 0.82–0.98 (m, 12H, $4CH_3$), 1.14–1.29 (m, 2H in $2CH_2CH_3$), 1.56 (m, 2H in $2CH_2CH_3$), 1.76 (m, 2H, $2CHCH_3$), 3.58–3.61 (m, 4H, $2CH_2O$), 3.98 (m, 2H, 2CHN), 4.75 (s, br, 2H, 2OH), 7.50–7.63 (m, 4H, ArH), 8.16 (d, $J = 8.0$ Hz, 2H, ArH), 8.31 (d, $J = 9.0$ Hz, 2H, 2NH), 8.66 (s, 1H, ArH), 9.20 (s, 1H, ArH); ^{13}C NMR (75.5 MHz, DMSO-d_6): 22.2, 23.5, 24.5, 24.6, 49.4, 64.0, 123.1, 124.8, 125.2, 127.0, 128.2, 129.8, 131.1, 135.7, 168.3; MS (EI) *m*/*z* (rel. intensity, %): 464 (M^+, 1.1), 446 (M^+-H_2O, 7.0), 428 (20), 416 (17), 389 (6.0), 371 (20), 344 (100), 330 (33), 303 (22), 287 (7.9), 272 (67), 244 (31), 230 (14), 216 (21), 202 (21), 190 (6.7), 176 (16); Anal. Calcd for $C_{28}H_{36}N_2O_4$: C, 72.39; H, 7.81; N, 6.03. Found: C, 72.19; H, 8.02; N, 5.85.

4.2.1.3. (*S*,*S*)-*N*,*N*′-Bis[1-(hydroxymethyl)-2,2-dimethylpropyl]-anthracene-1,8-dicarboxamide 3c. Yellow powder was used directly in the following step without purification due to very poor solubility.

4.2.1.4. (*S*,*S*)-*N*,*N*′-Bis[1-(hydroxymethyl)-2-phenylethyl]-anthracene-1,8-dicarboxamide 3d. Yellow powder yield 98%, mp 242–243 °C; $R_f = 0.38$ (ethyl acetate, silica gel plate); $[\alpha]_D^{24} = -21.2$ (*c* 0.25, CH_3OH); IR (KBr) (cm^{-1}): 3306 (O–H), 1639 (C=O); ^1H NMR (200 MHz, DMSO-d_6): 2.85 (dd, $J = 8.2$, 14.0 Hz, 2H in $2CH_2Ph$), 3.03 (dd, $J = 6.1$, 14.0 Hz, 2H in $2CH_2Ph$), 3.43–3.65 (m, 4H, $2CH_2O$), 4.25–4.29 (m, 2H, 2CHN), 4.86 (t, $J = 5.6$ Hz, 2H, 2OH), 7.20–7.34 (m, 10H, ArH), 7.41–7.57 (m, 4H, ArH), 8.15 (d, $J = 8.4$ Hz, 2H, ArH), 8.42 (d, $J = 8.2$ Hz, 2H, 2NH), 8.66 (s, 1H, ArH), 9.27 (s, 1H, ArH); ^{13}C NMR (75.5 MHz, DMSO-d_6): 36.5, 53.1, 62.7, 123.0, 124.8, 125.1, 126.0, 126.9, 128.2, 129.3, 129.9, 131.0, 135.4, 139.4, 168.3; MS (EI) *m*/*z* (rel. intensity, %): 532 (M^+, 2.6), 502 (M^+-CH_2O, 9.1), 484 (12), 441 (M^+-PhCH_2, 21), 423 (21), 405 (23), 382 (35), 378 (26), 364 (22), 337 (10), 307 (8.8), 290 (14), 272 (100), 248 (50), 233 (12), 216 (16), 204 (20), 190 (5.4), 176 (32), 152 (3.0); Anal. Calcd for $C_{34}H_{32}N_2O_4$: C, 76.67; H, 6.06; N, 5.26. Found: C, 76.40; H, 6.02; N, 4.96.

4.2.1.5. (*S*,*S*)-*N*,*N*′-Bis[1-(hydroxymethyl)-phenylmethyl]-anthracene-1,8-dicarboxamide 3e. Yellow powder, yield 98%; mp 307–309 °C; $R_f = 0.59$ (ethyl acetate, silica gel plate); $[\alpha]_D^{22} = +31.8$ (*c* 0.42, DMF); IR (KBr) (cm^{-1}): 3306 (O–H), 1639 (C=O); ^1H NMR (200 MHz, DMSO-d_6): 3.68 (dd, $J = 7.0$, 11.4 Hz, 2H in $2CH_2O$), 3.80 (dd, $J = 7.0$, 11.4 Hz, 2H in $2CH_2O$), 4.95 (t, $J = 5.8$ Hz, 2H, 2OH), 5.20 (ddd, $J = 7.0$, 7.0, 8.2 Hz, 2H, 2CHN), 7.22–7.74 (m, 14H, ArH), 8.21 (d, $J = 8.6$ Hz, 2H, ArH), 8.70 (s, 1H, ArH), 8.92 (d, $J = 8.2$ Hz, 2H, 2NH), 9.41 (s, 1H, ArH); ^{13}C NMR (75.5 MHz, DMSO-d_6): 55.8, 64.7, 123.1, 124.9, 126.0, 126.9, 127.2, 128.2, 130.3, 131.1, 134.9, 137.2, 141.3, 168.2; MS (EI) *m*/*z* (rel. intensity, %): 504 (M^+, 2.6), 502 (9.1), 484 (12), 441 (M^+-PhCH_2, 21), 423 (21), 405 (23), 382 (35), 378 (26), 364 (22), 337 (10), 307 (8.8), 290 (14), 272 (100), 248 (50), 233 (12), 216 (16), 204 (20), 190 (5.4), 176 (32), 152 (3.0); MS (ESI) *m*/*z*: 505 (MH^+); Anal. Calcd for $C_{32}H_{28}N_2O_4$: C, 76.17; H, 5.59; N, 5.55. Found: C, 75.89; H, 5.61; N, 5.67.

4.2.2. General procedure for the synthesis of (*S*,*S*)-1,8-bis[4-alkyl/aryloxazolin-2-yl]anthracene (AnBOX) 2. A 250 mL flask fitted with a magnetic stirring bar was charged with a solution of above dihydroxy diamide **3** (2.39 mmol) in 80 mL of dry THF, 12.1 mL (166 mmol) of $SOCl_2$ was added and the resulting mixture was heated to reflux for 4 h to give clear yellow solution. After removal of solution and excess $SOCl_2$, in vacuo,

the residue was dissolved in 120 mL of ethyl acetate, then washed with 48 mL of 2 mol/L K_2CO_3, water, and brine, respectively. The organic layer was dried over Na_2SO_4, filtered, and concentrated in vacuo to yield yellow solid, which was used in further reaction without purification. The yellow solid was dissolved in 112 mL of acetonitrile, then 24.2 g (175 mmol) K_2CO_3 and 9.7 mL of water were added. After refluxing for 8 h, the resulting solution was cooled to room temperature and concentrated, then 640 mL of ethyl acetate and 160 mL of water were added. The organic extract was dried over Na_2SO_4, filtered, and concentrated to give crude product, which was purified by column chromatography (silica gel 50 g, ethyl acetate/petroleum 1:4, v/v) to afford yellow crystals of the product.

4.2.2.1. (*S*,*S*)-1,8-Bis[4-(1-methylethyl)oxazolin-2-yl]-anthracene 2a. Yellow crystals, yield 80%, mp 122–124 °C; $R_f = 0.35$ (ethyl acetate/petroleum ether 1:2, v/v, silica gel plate); $[\alpha]_D^{20} = +64.7$ (*c* 0.97, $CHCl_3$); IR (KBr) (cm^{-1}): 1645 (C=N); ^1H NMR (300 MHz, $CDCl_3$): 1.03 (d, $J = 6.9$ Hz, 6H, $2CH_3$), 1.15 (d, $J = 6.9$ Hz, 6H, $2CH_3$), 2.00–2.06 (m, 2H, $2CH(CH_3)_2$), 4.23–4.33 (m, 4H, $2CH_2O$), 4.51–4.56 (m, 2H, 2CHN), 7.48 (dd, $J = 8.4$, 6.9 Hz, 2H, ArH), 8.08–8.13 (m, 4H, ArH), 8.47 (s, 1H, ArH), 10.64 (s, 1H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 18.1, 19.4, 32.8, 69.5, 73.2, 124.5, 124.9, 125.9, 127.5, 129.4, 129.5, 131.5, 131.7, 163.8; MS (EI) *m*/*z* (rel. intensity, %): 400 (M^+, 22), 357 ($M^+-C_3H_7$, 19), 330 (100), 287 (7.9), 271 (72), 244 (24), 228 (6.0), 216 (12), 202 (12), 190 (4.1), 176 (4.3); Anal. Calcd for $C_{26}H_{28}N_2O_2$: C, 77.97; H, 7.05; N, 6.99. Found: C, 77.99; H, 7.26; N, 6.76.

4.2.2.2. (*S*,*S*)-1,8-Bis[4-(1-methylpropyl)oxazolin-2-yl]-anthracene 2b. Yellow crystals, yield 54%, mp 95–97 °C; $R_f = 0.29$ (ethyl acetate/petroleum ether 1:4, v/v, silica gel plate); $[\alpha]_D^{20} = +17.9$ (*c* 0.80, $CHCl_3$); IR (KBr) (cm^{-1}): 1642 (C=N); ^1H NMR (400 MHz, $CDCl_3$): 1.03–1.06 (m, 12H, $4CH_3$), 1.54–1.59 (m, 2H in $2CH_2CH_3$), 1.88–1.98 (m, 4H, $2CHCH_3$ and 2H in $2CH_2CH_3$), 4.14 (dd, $J = 7.8$, 8.0 Hz, 2H in $2CH_2O$), 4.53–4.60 (m, 2H in 2CHN), 4.65 (dd, $J = 8.0$, 9.2 Hz, 2H in $2CH_2O$), 7.49 (dd, $J = 7.2$, 8.4 Hz, 2H, ArH), 8.10–8.14 (m, 4H, ArH), 8.47 (s, 1H, ArH), 10.70 (s, 1H, ArH); ^{13}C NMR (100.6 MHz, $CDCl_3$): 22.6, 23.1, 25.6, 45.7, 65.7, 72.6, 124.5, 124.9, 125.6, 127.5, 129.4, 129.5, 131.4, 131.9, 163.8; MS (EI) *m*/*z* (rel. intensity, %): 428 (M^+, 14), 371 ($M^+-C_4H_9$, 6.6), 359 (5.5), 344 (100), 317 (3.7), 301 (6.6), 271 (21), 244 (31), 230 (9.6), 202 (9.8), 176 (4.1); Anal. Calcd for $C_{28}H_{32}N_2O_2$: C, 78.47; H, 7.53; N, 6.54. Found: C, 78.65; H, 7.52; N, 6.26.

4.2.2.3. (*S*,*S*)-1,8-Bis[4-(1,1-dimethylethyl)oxazolin-2-yl]anthracene 2c. Yellow crystals, yield 56%; mp 142–144 °C; $R_f = 0.22$ (ethyl acetate/petroleum ether 1:8, v/v, silica gel plate); $[\alpha]_D^{20} = -10.9$ (*c* 0.96, $CHCl_3$); IR (KBr) (cm^{-1}): 1641 (C=N); ^1H NMR (200 MHz, $CDCl_3$): δ 1.07 (s, 18H, $6CH_3$), 4.23–4.38 (m, 4H, $2CH_2$), 4.49 (dd, 2H, $J = 7.8$, 9.4 Hz, 2CHN), 7.48 (dd, $J = 7.2$, 8.6 Hz, 2H, ArH), 8.06–8.13 (m, 4H, ArH), 8.45 (s, 1H, ArH), 10.45 (s, 1H, ArH); ^{13}C NMR (50 MHz, $CDCl_3$): δ 26.1, 34.1, 68.4, 76.7, 124.5, 124.9, 126.2, 127.6, 129.5, 129.5, 131.6, 131.7, 164.0; MS (EI) *m*/*z* (rel. intensity, %): 428 (M^+, 25), 371 ($M^+-C_4H_9$, 80), 344 (51), 313 (3.2), 287 (4.3), 271 (100), 244 (14), 216 (18), 202 (11), 190 (4.1), 176 (4.7). Anal. Calcd for $C_{28}H_{32}N_2O_2$: C, 78.47; H, 7.53; N, 6.54. Found: C, 78.42; H, 7.83; N, 6.23.

4.2.2.4. (*S*,*S*)-1,8-Bis(4-benzyloxazolin-2-yl)anthracene 2d. Yellow crystals, yield 52%; mp 166–168 °C; $R_f = 0.26$ (ethyl acetate/petroleum ether 1:2, v/v, silica gel plate); $[\alpha]_D^{20} = +50.7$ (*c* 0.92, $CHCl_3$); IR (KBr) (cm^{-1}): 1638 (C=N); ^1H NMR (300 MHz, $CDCl_3$): 2.91 (dd, $J = 9.0$, 13.8 Hz, 2H in $2CH_2Ph$), 3.45 (dd, $J = 4.8$, 13.8 Hz, 2H in $2CH_2Ph$), 4.23 (dd, $J = 7.8$, 8.1 Hz, 2H in $2CH_2O$), 4.43 (dd, $J = 8.1$, 9.3 Hz, 2H in $2CH_2O$), 4.75 (dddd, $J = 4.8$, 7.8, 9.0, 9.3 Hz, 2H, 2CHN), 7.24–7.53 (m, 12H, ArH), 8.1–8.15 (m, 4H, ArH), 8.50 (s, 1H, ArH), 10.92 (s, 1H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 42.0, 68.6, 71.1, 124.5, 125.1, 125.5, 126.5, 127.6, 128.6, 129.3, 129.5, 131.5, 132.0, 138.0, 164.1; MS (EI) *m*/*z* (rel. intensity, %): 496 (M^+, 28), 405 (M^+-PhCH_2, 65), 378 (82), 313 (3.0), 287 (20), 271 (100), 244 (22), 228 (48), 216 (21), 202 (16), 189 (4.6), 176 (4.6), 117 (8.8), 105 (13), 91 ($PhCH_2^+$, 40); Anal. Calcd for $C_{34}H_{28}N_2O_2$: C, 82.23; H, 5.68; N, 5.64. Found: C, 82.47; H, 5.67; N, 5.62.

4.2.2.5. (*S*,*S*)-1,8-Bis(4-phenyloxazolin-2-yl)anthracene 2e. Yellow crystals, yield 72%, mp 147–148 °C; $R_f = 0.43$ (ethyl acetate/petroleum ether 1:2, v/v, silica gel plate); $[\alpha]_D^{23} = +113$ (*c* 0.56, $CHCl_3$); IR (KBr) *v* (cm^{-1}): 1638 (C=N); ^1H NMR (300 MHz, $CDCl_3$): 4.09 (dd, $J = 8.4$, 8.4 Hz, 2H, 2CHN), 4.62 (dd, $J = 8.4$, 10.2 Hz, 2H in CH_2O), 5.37 (dd, $J = 10.2$, 8.4 Hz, 2H in CH_2O), 7.21–7.32 (m, 10H, ArH), 7.53 (dd, $J = 7.2$, 8.1 Hz, 2H, ArH), 8.15–8.23 (m, 4H, ArH), 8.53 (s, 1H, ArH), 11.08 (s, 1H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 70.5, 74.1, 124.6, 125.3, 126.9, 127.5, 127.6, 128.6, 129.6, 129.9, 131.5, 132.2, 136.3, 142.5, 165.0. MS (EI) *m*/*z* (rel. intensity, %): 468 (M^+, 28), 405 (M^+-PhCH_2, 65), 378 (82), 313 (3.0), 287 (20), 271 (100), 244 (22), 228 (48), 216 (21), 202 (16), 189 (4.6), 176 (4.6), 117 (8.8), 105 (13), 91 ($PhCH_2^+$, 40); Anal. Calcd for $C_{32}H_{24}N_2O_2$: C, 82.03; H, 5.16; N, 5.98. Found: C, 82.25; H, 5.19; N, 5.71.

4.2.3. Synthesis of (*S*,*S*)-*N*,*N*′-bis[1-(hydroxymethyl)-benzyl]anthraquinone-1,8-dicarboxamide 5. To a solution of anthraquinone-1,8-dicarbonyl dichloride (0.71 g, 2.1 mmol) in 20 mL of dry THF was added dropwise a solution of L-phenylalaninol (0.91 g, 6.0 mmol) in 20 mL of dry THF at 0 °C in an ice bath. The resulting mixture was allowed to warm to room temperature and was stirred overnight. After filtration, the solution was concentrated to give a solid residue, which was purified by column chromatography (silica gel, acetone/petroleum ether 3:2, v/v) to afford yellow crystals, yield 50%, mp 275–276 °C; $R_f = 0.50$ (acetone/petroleum ether 3:2, v/v, silica gel plate); $[\alpha]_D^{24} = -111.5$ (*c* 0.85, CH_3OH); IR (KBr) *v* (cm^{-1}): 3367 (O–H), 1676 ($C_{9,10}$=O), 1626 (C=O); ^1H NMR (200 MHz, DMSO-d_6): 2.78 (dd, $J = 8.0$, 13.6 Hz, 2H in $2CH_2Ph$), 2.95

(dd, $J = 6.4$, 13.6, 2H in $2CH_2Ph$), 3.45–3.63 (m, 4H, $2CH_2O$), 4.11–4.14 (m, 2H, 2CHN), 7.17–7.27 (m, 10H, ArH), 7.46 (d, $J = 7.6$ Hz, 2H, ArH), 7.88 (dd, $J = 7.6$, 7.6 Hz, 2H, ArH), 8.21–8.27 (m, 4H, 2H in ArH and 2NH); ^{13}C NMR (75.5 MHz, DMSO-d_6): 36.2, 52.8, 62.0, 126.0, 127.2, 128.2, 129.3, 131.3, 132.7, 133.8, 139.0, 139.4, 168.2, 182.05, 182.11; MS (EI) m/z (rel. intensity, %): 544 (M^+-H_2O, 3.8), 531 (7.0), 513 (6.3), 471 (M^+-PhCH_2, 39), 453 (40), 435 (22), 413 (54), 395 (25), 320 (18), 302 (70), 279 (77), 263 (57), 248 (10), 234 (100), 206 (13), 178 (13), 150 (28). Anal. Calcd for $C_{34}H_{30}N_2O_6$: C, 72.58; H, 5.37; N, 4.98. Found: C, 72.66; H, 5.38; N, 4.74.

4.2.4. Synthesis of (*S*,*S*)-1,8-bis[(4-phenylmethyl)oxazolin-2-yl]anthraquinone 4. To a solution of above dihydroxy diamide **5** (0.60 g, 1.1 mmol) in 30 mL of dry THF was added 5.0 mL (68.6 mmol) of $SOCl_2$. The resulting mixture was heated to reflux for 4 h to give clear yellow solution. After removal of solution and excess $SOCl_2$ in vacuo, the residue was dissolved in 50 mL of ethyl acetate, then washed with 20 mL of 2 mol/L K_2CO_3, water, and brine, respectively. The organic layer was dried over Na_2SO_4, filtered, and concentrated in vacuo to yield yellow solid, which was used in further reaction without purification. The yellow solid was dissolved in 45 mL of acetonitrile, 10.5 g (76.1 mmol) of K_2CO_3, and 4.0 mL of water were added. After refluxing for 8 h, the resulting solution was cooled to room temperature and concentrated, then 200 mL of ethyl acetate and 70 mL of water were added. The organic extract was dried over Na_2SO_4, filtered, and concentrated to give crude product, which was purified by column chromatography (silica gel, acetone/petroleum ether 1:1, v/v) to afford yellow crystals, yield 68%; mp 185–186 °C; $R_f = 0.57$ (acetone/petroleum ether 1:1, v/v, silica gel plate); $[\alpha]_D^{20} = -121$ (c 0.51, acetone); IR (KBr) ν (cm^{-1}): 1684 (C=N), 1670 ($C_{9,10}$=O); ^1H NMR (300 MHz, $CDCl_3$): 2.93 (dd, $J = 8.4$, 13.6 Hz, 2H in $2CH_2Ph$), 3.31 (dd, $J = 5.7$, 13.6 Hz, 2H in $2CH_2Ph$), 4.23 (dd, $J = 7.2$, 8.2 Hz, 2H in $2CH_2O$), 4.42 (dd, $J = 8.2$, 9.0 Hz, 2H in $2CH_2O$), 4.62–4.70 (m, 2H, 2CHN), 7.21–7.33 (m, 10H, ArH), 7.77–7.89 (m, 4H, ArH), 8.41 (dd, $J = 1.5$, 7.5 Hz, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): 44.4, 68.2, 73.1, 126.5, 128.6, 129.2, 129.8, 133.2, 133.4, 136.1, 138.0, 164.7, 181.6, 181.8; MS (EI) m/z (rel. intensity, %): 526 (M^+, 9.7), 512 (8.9), 435 (M^+-PhCH_2, 89), 381 (3.7), 378 (4.2), 343 (4.2), 301 (100), 287 (6.7), 260 (7.6), 246 (18), 235 (3.3), 218 (5.3), 190 (11), 176 (6.5). Anal. Calcd for $C_{34}H_{26}N_2O_4$: C, 77.55; H, 4.98; N, 5.32. Found: C, 77.78; H, 4.90; N, 5.11.

4.3. General procedure for the asymmetric aziridination of chalcones or olefins

A three-necked flask (25 mL) was charged with chalcone **6** or olefin (1.50 mmol), AnBOX **2** (0.06 mmol), and CuOTf·1/2PhH (13 mg, 0.05 mmol) under nitrogen atmosphere. Dichloromethane (8 mL) was added by syringe and the resulting mixture was stirred for 1 h at 24 °C. PhI=NTs (373 mg, 1.00 mmol) was added portionwise to the mixture over 2 h. After the addition, the reaction mixture was kept stirring for another 3 h. The aziridine product was obtained after flash silica gel chromatography with a mixture of petroleum ether (60–90 °C) and ethyl acetate (6:1, v/v) as an eluent. For analytic data of known chiral aziridines **7a**, **7b**, **7e**, **7i**, **7j**, **7o**, **7p**, **7q**, and **7r**, see the electronic supporting information in Ref. 18; *ent*-**7a**, *ent*-**7k**, and *ent*-**7l**, see the supporting information in Ref. 40.

4.3.1. (2*S*,3*R*)-2-Benzoyl-3-(4-phenylphenyl)-1-(4-toluenesulfonyl)aziridine 7c. Colorless crystals, yield 35%; mp 152.5–154.0 °C; $R_f = 0.29$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 87% ee determined by HPLC with Chiralcel OD-H column with hexane/2-propanol (70:30, v/v) as an eluent at a flow rate of 0.6 mL/min ($\tau_{major} = 22.4$ min; $\tau_{minor} = 37.5$ min); $[\alpha]_D^{20} = +1.3$ (c 0.64, $CHCl_3$, 87% ee); IR (KBr) ν (cm^{-1}): 1689 (s), 1332 (s), 1161 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.40 (s, 3H, CH_3), 4.34 (d, $J = 4.2$ Hz, 1H, CH), 4.55 (d, $J = 4.2$ Hz, 1H, CH), 7.24 (d, $J = 5.7$ Hz, 2H, ArH), 7.36–7.63 (m, 12H, ArH), 7.74 (d, $J = 5.7$ Hz, 2H, ArH), 8.05–8.09 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 47.4, 50.2, 127.1, 127.3, 127.6, 127.7, 128.0, 128.80, 128.84, 128.9, 129.5, 131.8, 134.1, 135.9, 140.3, 141.8, 144.4, 190.3; MS (EI) m/z (rel. intensity, %): 453 (M^+, 11), 298 (M^+-Ts, 11), 105 ($PhCO^+$, 100), 77 (Ph^+, 41). Anal. Calcd for $C_{28}H_{23}NO_3S$: C, 74.15; H, 5.11; N, 3.09. Found: C, 74.14; H, 5.08; N, 2.91.

4.3.2. (2*S*,3*R*)-2-Benzoyl-3-(4-fluorophenyl)-1-(4-toluenesulfonyl)aziridine 7d. Colorless crystals, yield 72%; mp 130.5–131.5 °C; $R_f = 0.19$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 62% ee determined by HPLC with Chiralcel OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 23.7$ min; $\tau_{minor} = 32.3$ min); $[\alpha]_D^{20} = +1.7$ (c 0.77, $CHCl_3$, 62% ee); IR (KBr) ν (cm^{-1}): 1689 (s), 1332 (s), 1162 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.40 (s, 3H, CH_3), 4.28 (d, $J = 4.2$ Hz, 1H, CH), 4.49 (d, $J = 4.2$ Hz, 1H, CH), 7.00–7.05 (m, 2H, ArH), 7.22–7.35 (m, 4H, ArH), 7.46–7.51 (m, 2H, ArH), 7.60–7.72 (m, 3H, ArH), 8.02–8.06 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 46.8, 45.0, 115.6 (d, $^2J_{F-C-C} = 27.9$ Hz), 127.7, 128.6, 128.8, 128.9, 129.4, 129.5, 129.5, (d, $^1J_{F-C} = 288.8$ Hz), 134.1, 135.8, 136.4, 144.5, 190.2; MS (EI) m/z (rel. intensity, %): 395 (M^+, 2), 240 (M^+-Ts, 78), 105 ($PhCO^+$, 100), 77 (Ph^+, 79). Anal. Calcd for $C_{22}H_{18}FNO_3S$: C, 66.82; H, 4.59; N, 3.54. Found: C, 66.67; H, 4.67; N, 3.29.

4.3.3. (2*S*,3*R*)-2-Benzoyl-3-(4-bromophenyl)-1-(4-toluenesulfonyl)aziridine 7f. Colorless crystals, yield 58%; mp 150–152 °C; $R_f = 0.23$ (ethyl acetate/petroleum ether 1:6, v/v, silica gel plate); 52% ee determined by HPLC with chiral OD column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{minor} = 32.25$ min; $\tau_{major} = 48.16$ min); $[\alpha]_D^{20} = +3.8$ (c 1.02, $CHCl_3$, 52% ee); IR (KBr) ν (cm^{-1}): 1686 (s), 1332 (s), 1161 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.40 (s, 3H, CH_3), 4.24 (d, $J = 4.2$ Hz, 1H, CH), 4.48 (d, $J = 4.2$ Hz, 1H, CH), 7.0–7.27 (m, 4H, ArH), 7.45–7.52 (m, 4H, ArH), 7.61–7.73 (m, 3H, ArH), 8.02–8.06

(m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 46.5, 50.2, 123.0, 127.6, 128.8, 128.9, 129.1, 129.6, 131.8, 132.0, 134.2, 135.8, 136.3, 144.6, 190.0; MS (EI) m/z (rel. intensity, %) 455 (M^+, 15), 299 (M^+-Ts, 12), 105 ($PhCO^+$, 100), 77 (Ph^+, 31). Anal. Calcd for $C_{22}H_{18}BrNO_3S$: C, 57.90; H, 3.98; N, 3.07. Found: C, 57.89; H, 4.02; N, 2.92.

4.3.4. (2*S*,3*R*)-2-Benzoyl-3-(4-methoxyphenyl)-1-(4-toluenesulfonyl)aziridine 7g. Yellow crystals, yield 61%; mp 43–45 °C; $R_f = 0.21$ (ethyl acetate/petroleum ether 1:4, v/v, silica gel plate); 37% ee determined by HPLC with chiral OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.7 mL/min ($\tau_{minor} = 27.44$ min; $\tau_{major} = 35.07$ min); $[\alpha]_D^{20} = +23.8$ (c 0.98, $CHCl_3$, 37% ee); IR (KBr) ν (cm^{-1}): 1694 (s), 1329 (s), 1162 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 2.42 (s, 3H, CH_3), 3.67 (s, 3H, CH_3), 4.33 (d, $J = 7.5$ Hz, 1H, CH), 4.38 (d, $J = 7.5$ Hz, 1H, CH), 6.67–6.70 (m, 2H, ArH), 7.14–7.17 (m, 2H, ArH), 7.33–7.41 (m, 4H, ArH), 7.50–7.53 (m, 1H, ArH), 7.84–7.87 (m, 2H, ArH), 7.95–7.98 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.7, 46.3, 48.3, 55.1, 113.7, 123.1, 128.0, 128.3, 128.5, 128.7, 129.8, 133.8, 134.4, 135.6, 145.0, 159.6, 189.1; MS (EI) m/z (rel. intensity, %): 407 (M^+, 6), 251 (M^+-Ts-H, 100), 236 ($M^+-Ts-H-CH_3$, 18), 105 ($PhCO^+$, 27), 77 (Ph^+, 32). Anal. Calcd for $C_{23}H_{21}NO_4S$: C, 67.79; H, 5.19; N, 3.44. Found: C, 67.75; H, 5.11; N, 3.13.

4.3.5. (2*S*,3*R*)-2-Benzoyl-3-(2-methoxyphenyl)-1-(4-toluenesulfonyl)aziridine 7h. Colorless crystals, yield 21%; mp 143–145 °C; $R_f = 0.24$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 27% ee determined by HPLC with chiral OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 27.29$ min; $\tau_{minor} =$ 32.05 min); $[\alpha]_D^{20} = -13.6$ (c 0.45, $CHCl_3$, 27% ee); IR (KBr) ν (cm^{-1}): 1693 (s), 1328 (s), 1162 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 3.73 (s, 3H, CH_3), 4.41 (d, $J = 4.5$ Hz, 1H, CH), 4.64 (d, $J = 4.5$ Hz, 1H, CH), 6.84–6.92 (m, 2H, ArH), 7.20–7.34 (m, 4H, ArH), 7.48–7.51 (m, 2H, ArH), 7.61–7.64 (m, 1H, ArH), 7.72–7.74 (m, 2H, ArH), 8.09–8.13 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 44.9, 48.2, 55.2, 110.3, 120.3, 120.7, 127.8, 128.0, 128.7, 128.9, 129.3, 130.1, 133.9, 136.0, 136.6, 144.1, 158.8, 190.9; MS (EI) m/z (rel. intensity, %): 407 (M^+, 28), 376 (M^+-OMe, 4.5), 252 (M^+-Ts, 20), 155 (Ts^+, 3.3), 105 ($PhCO^+$, 100), 77 (Ph^+, 8.9). Anal. Calcd for $C_{23}H_{21}NO_4S$: C, 67.79; H, 5.19; N, 3.44. Found: C, 67.87; H, 5.11; N, 3.13.

4.3.6. (2*S*,3*R*)-2-(4-Fluorobenzoyl)-3-phenyl-1-(4-toluenesulfonyl)aziridine 7l. Colorless needle crystals, yield 72%; mp 123.5–125.5 °C; $R_f = 0.34$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 54% ee determined by HPLC with chiral OD-H column with hexane/2-propanol (94:6, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 35.06$ min; $\tau_{minor} = 38.21$ min); $[\alpha]_D^{25} = +7.9$ (c 0.68, $CHCl_3$, 54% ee); IR (KBr) ν (cm^{-1}): 1687 (s), 1333 (s), 1160 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 4.20 (d, $J = 4.2$ Hz, 1H, CH), 4.52 (d, $J = 4.2$ Hz, 1H, CH), 7.13–7.33 (m, 9H, ArH), 7.72 (d, $J = 8.1$ Hz, 2H, ArH), 8.08–8.13 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 47.2, 50.2, 115.9, 116.2, 127.4, 127.7, 128.6, 128.9, 129.5, 131.7, 131.8, 132.9, 136.5, 144.5, 188.8; MS (EI) m/z (rel. intensity, %): 395 (M^+, 19), 240 (M^+-Ts, 100), 155 (Ts^+, 21), 123 ($4\text{-}FC_6H_4CO^+$, 100). Anal. Calcd for $C_{22}H_{18}FNO_3S$: C, 66.82; H, 4.59; N, 3.54. Found: C, 66.70; H, 4.61; N, 3.55.

4.3.7. (2*S*,3*R*)-2-(4-Chlorobenzoyl)-3-phenyl-1-(4-toluenesulfonyl)aziridine 7m. Colorless crystals, yield 74%; mp 145–147 °C; $R_f = 0.32$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 58% ee determined by HPLC with Chiral OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.5 mL/min ($\tau_{major} = 46.79$ min; $\tau_{minor} = 51.26$ min); $[\alpha]_D^{20} = +10.6$ (c 1.01, $CHCl_3$, 58% ee); IR (KBr) ν (cm^{-1}): 1687 (s), 1330 (s), 1161 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 4.18 (d, $J = 4.0$ Hz, 1H, CH), 4.52 (d, $J = 4.4$ Hz, 1H, CH), 7.24 (d, $J = 8.2$ Hz, 2H, CH), 7.33 (s, 5H, ArH), 7.45 (d, $J = 8.8$ Hz, 2H, ArH), 7.71 (d, $J = 8.2$ Hz, 2H, ArH), 8.00 (d, $J = 8.4$ Hz, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 47.2, 50.3, 127.3, 127.7, 128.7, 128.9, 129.1, 129.5, 130.3, 132.8, 134.3, 136.3, 140.7, 144.6, 189.2; MS (EI) m/z (rel. intensity, %): 411 (M^+, 5), 255 (M^+-Ts-H, 100), 139 ($ClC_6H_4CO^+$, 71), 111 ($C1C_6H_4^+$, 35), 77 (Ph^+, 24). Anal. Calcd for $C_{22}H_{18}ClNO_3S$: C, 64.15; H, 4.40; N, 3.40. Found: C, 64.10; H, 4.53; N, 3.12.

4.3.8. (2*S*,3*R*)-2-(4-Bromobenzoyl)-3-phenyl-1-(4-toluenesulfonyl)aziridine 7n. Colorless needle crystals, yield 64%; mp 143–145 °C; $R_f = 0.32$ (ethyl acetate/petroleum ether 1:6, v/v, silica gel plate); 50% ee determined by HPLC with chiral OD-H column with hexane/2-propanol (93:7, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 36.2$ min; $\tau_{minor} = 39.7$ min); $[\alpha]_D^{20} = +10.8$ (c 1.00, $CHCl_3$, 50% ee); IR (KBr) ν (cm^{-1}): 1688 (s), 1329 (s), 1160 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 4.17 (d, $J = 4.2$ Hz, 1H, CH), 4.52 (d, $J = 4.2$ Hz, 1H, CH), 7.22–7.33 (m, 7H, ArH), 7.62 (d, $J = 8.7$ Hz, 2H, ArH), 7.70 (d, $J = 8.4$ Hz, 2H, ArH), 7.91 (d, $J = 8.7$ Hz, 2H, ArH),; ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 47.1, 50.2, 126.4, 127.3, 127.7, 128.6, 128.9, 129.5, 130.3, 132.1, 132.8, 134.6, 136.3, 144.5, 189.4; MS (EI) m/z (rel. intensity, %): 455 (M^+, 22), 300 (M^+-Ts, 7.8), 185 (95), 183 ($4\text{-}BrC_6H_4CO^+$, 100), 155 (Ts^+, 39). Anal. Calcd for $C_{22}H_{18}BrNO_3S$: C, 57.90; H, 3.98; N, 3.07. Found: C, 57.85; H, 4.09; N, 3.06.

4.3.9. (2*S*,3*R*)-2-(4-Nitrobenzoyl)-3-phenyl-1-(4-toluenesulfonyl)aziridine 7o. Colorless needle crystals, yield 61%; mp 146–148 °C; $R_f = 0.28$ (ethyl acetate/petroleum ether 1:6, v/v, silica gel plate); The ee value cannot be determined due to very poor solubility; $[\alpha]_D^{25} = +6.3$ (c 0.73, $CHCl_3$); IR (KBr) ν (cm^{-1}): 1697 (s), 1335 (s), 1159 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 2.42 (s, 3H, CH_3), 4.17 (d, $J = 4.2$ Hz, 1H, CH), 4.58 (d, $J = 4.2$ Hz, 1H, CH), 7.25–7.35 (m, 7H, ArH), 7.72 (d, $J = 8.4$ Hz, 2H, ArH), 8.23 (d, $J = 9.0$ Hz, 2H, ArH), 8.34 (d, $J = 9.0$ Hz, 2H, ArH); ^{13}C NMR (50 MHz, $CDCl_3$): δ 21.6, 47.2, 50.5, 123.9, 127.2, 127.7, 128.8,

129.1, 129.7, 130.0, 132.6, 138.0, 140.2, 144.9, 189.5; MS (EI) *m/z* (rel. intensity, %): 422 (M^+, 20), 267 (M^+-Ts, 14), 155 (Ts^+, 17), 150 (100, 4-$NO_2C_6H_4CO^+$, 100) HRMS (EI) *m/z* calcd for $C_{22}H_{18}N_2O_5S$ (M^+) 422.0936; Found 422.0924.

4.3.10. (2*S*,3*R*)-2-(4-Methoxybenzoyl)-3-phenyl-1-(4-toluenesulfonyl)aziridine 7p. Colorless needle crystals, yield 74%; mp 123–125 °C; $R_f = 0.22$ (ethyl acetate/petroleum ether 1:4, v/v, silica gel plate); 62% ee determined by HPLC with chiral OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 48.75$ min; $\tau_{minor} = 62.22$ min); $[\alpha]_D^{20} = +3.4$ (*c* 1.02, $CHCl_3$, 62% ee); IR (KBr) *v* (cm^{-1}): 1677 (s), 1332 (s), 1164 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.40 (s, 3H, CH_3), 3.88 (s, 3H, CH_3), 4.26 (d, $J = 4.2$ Hz, 1H, CH), 4.50 (d, $J = 4.2$ Hz, 1H, CH), 6.93–6.96 (m, 2H, ArH), 7.21–7.30 (m, 7H, ArH), 7.71 (d, $J = 8.4$ Hz, 2H, ArH), 8.03–8.06 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 47.3, 50.1, 55.6, 114.0, 127.5, 127.7, 128.6, 128.8, 129.1, 129.5, 131.4, 133.0, 136.6, 144.3, 164.3, 188.4; MS (EI) *m/z* (rel. intensity, %): 407 (M^+, 12), 251 (M^+-Ts-H, 100), 135 ($CH_3OC_6H_4CO^+$, 60), 107 ($CH_3OC_6H_4^+$, 10), 77 (Ph^+, 42). Anal. Calcd for $C_{23}H_{21}NO_4S$: C, 67.79; H, 5.19; N, 3.44. Found: C, 67.76; H, 5.21; N, 3.50.

4.3.11. (2*S*,3*R*)-2-(4-Chlorobenzoyl)-3-(4-chlorophenyl)-1-(4-toluenesulfonyl)aziridine 7q. Colorless crystals, yield 68%; mp 161–163 °C; $R_f = 0.30$ (ethyl acetate/petroleum ether 1:6, v/v, silica gel plate); 43% ee determined by HPLC with Chiralcel OD column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 35.46$ min; $\tau_{minor} = 42.53$ min); $[\alpha]_D^{20} = +9.25$ (*c* 1.01, $CHCl_3$, 43% ee); IR (KBr) *v* (cm^{-1}): 1695 (s), 1330 (s), 1162 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.42 (s, 3H, CH_3), 4.14 (d, $J = 4.2$ Hz, 1H, CH), 4.49 (d, $J = 4.2$ Hz, 1H, CH), 7.24–7.32 (m, 6H, ArH), 7.44–7.47 (m, 2H, ArH), 7.69–7.71 (m, 2H, ArH), 7.97–8.00 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 46.3, 50.3, 127.7, 128.7, 128.9, 129.2, 129.6, 130.3, 131.4, 134.1, 134.9, 136.1, 140.8, 144.8, 188.9; MS (EI) *m/z* (rel. intensity, %): 445 (M^+, 22), 290 (M^+-Ts, 59), 255 ($M^+-Ts-Cl$, 3), 139 ($ClC_6H_4CO^+$, 100), 111 ($C1C_6H_4^+$, 42). Anal. Calcd for $C_{22}H_{17}Cl_2NO_3S$: C, 59.20; H, 3.84; N, 3.14. Found: C, 59.20; H, 3.90; N, 2.99.

4.3.12. (2*S*,3*R*)-2-(4-Methylbenzoyl)-3-(4-chlorophenyl)-1-(4-toluenesulfonyl)aziridine 7r. Colorless crystals, yield 66%; mp 163.5–165 °C; $R_f = 0.30$ (ethyl acetate/petroleum ether 1:6, v/v, silica gel plate); 39% ee determined by HPLC with chiral OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.5 mL/min ($\tau_{major} = 39.00$ min; $\tau_{minor} = 56.87$ min); $[\alpha]_D^{20} = +3.6$ (*c* 1.04, $CHCl_3$ 39% ee); IR (KBr) *v* (cm^{-1}): 1683 (s), 1331 (s), 1162 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 2.44 (s, 3H, CH_3), 4.23 (d, $J = 4.2$ Hz, 1H, CH), 4.46 (d, $J = 4.0$ Hz, 1H, CH), 721–7.29 (m, 8H, ArH), 7.71 (d, $J = 8.2$ Hz, 2H, ArH), 7.94 (d, $J = 8.2$ Hz, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 21.8, 46.6, 50.2, 127.7, 128.8, 128.9, 129.1, 129.5, 131.6, 133.4, 134.8, 136.4, 144.5, 145.4, 189.5; MS (EI) *m/z* (rel. intensity, %): 425 (M^+, 11), 269 (M^+-Ts-H, 100), 179 ($M^+-Ts-CH_3C_6H_4$, 49), 119 ($CH_3C_6H_4CO^+$, 76), 91 (CH_3Ph^+, 84). Anal. Calcd for $C_{23}H_{20}ClNO_3S$: C, 64.86; H, 4.73; N, 3.29. Found: C, 64.79; H, 4.76; N, 3.10.

4.3.13. (2*S*,3*R*)-2-Benzoyl-3-(4-trifluoromethylphenyl)-1-(4-toluenesulfonyl)aziridine 7w. Colorless crystals, yield 69%; mp 156.0–158.0 °C; $R_f = 0.36$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 67% ee determined by HPLC with Chiralcel OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 23.0$ min; $\tau_{minor} = 34.8$ min); $[\alpha]_D^{20} = +9.0$ (*c* 0.55, $CHCl_3$, 67% ee); IR (KBr) *v* (cm^{-1}): 1694 (s), 1325 (s), 1164 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.42 (s, 3H, CH_3), 4.22 (d, $J = 4.2$ Hz, 1H, CH), 4.60 (d, $J = 4.2$ Hz, 1H, CH), 7.24–7.26 (m, 2H, ArH), 7.45–7.53 (m, 4H, ArH), 7.59–7.65 (m, 3H, ArH), 7.71–7.74 (m, 2H, ArH), 8.03–8.07 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 46.0, 50.8, 125.6, 125.6, 127.7, 128.8, 129.0, 129.6, 134.2, 135.8, 136.2, 137.3, 144.7, 189.7; MS (EI) *m/z* (rel. intensity, %): 445 (M^+, 1), 290 (M^+-Ts, 56), 105 ($PhCO^+$, 100), 77 (Ph^+, 62). Anal. Calcd for $C_{23}H_{18}F_3NO_3S$: C, 62.01; H, 4.07; N, 3.14. Found: C, 62.05; H, 4.06; N, 2.94.

4.3.14. (*R*,*R*)-2-Benzyl-3-phenyl-1-(4-toluenesulfonyl)aziridine 14. Colorless crystals, yield 41%; mp 113–114 °C; $R_f = 0.45$ (ethyl acetate/petroleum ether 1:6, v/v, silica gel plate); 6% ee determined by HPLC with Daicel Chiralcel OJ column with hexane/2-propanol (70:30, v/v) as an eluent at a flow rate of 0.6 mL/min ($\tau_{major} = 40.95$ min; $\tau_{minor} = 54.46$ min); $[\alpha]_D^{20} = -2.45$ (*c* 1.06, $CHCl_3$, 6% ee), the configuration was assigned tentatively on the basis of the configuration of aziridine **16**; ^1H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 3.06 (ddd, $J = 9.6$, 4.2, 4.2 Hz, 1H, *CH*CH_2), 3.41 (dd, $J = 14.4$, 9.6 Hz, 1H, CH_2), 3.61 (dd, $J = 14.4$, 4.2 Hz, 1H, CH_2), 4.01 (d, $J = 4.2$ Hz, 1H, CH), 7.09–7.13 (m, 3H, ArH), 7.22–7.24 (m, 4H, ArH), 7.29–7.31 (m, 5H, ArH), 7.84 (d, $J = 8.4$ Hz, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 34.7, 49.1, 52.8, 126.5, 126.8, 127.3, 128.1, 128.5, 128.6, 128.7, 129.6, 135.0, 137.5, 137.7, 144.1; MS (EI) *m/z* (rel. intensity, %): 363 (M^+, 0.72), 208 (M^+-Ts, 100), 117 ($M^+-Ts-PhCH_2$, 36), 103 ($M^+-Ts-PhCH_2CH-H$, 15), 91 ($PhCH_2^+$, 100), 77 (Ph^+, 15). Anal. Calcd for $C_{22}H_{21}NO_2S$: C, 72.70; H, 5.82; N, 3.85. Found: C, 72.71; H, 5.84; N, 3.65.

4.3.15. (2*S*,3*R*)-2-Phenyl-3-phenoxylmethyl-1-(4-toluenesulfonyl)aziridine 16. Colorless crystals, yield 24%; mp 108–109 °C; $R_f = 0.27$ (ethyl acetate/petroleum ether 1:10, v/v, silica gel plate); 40% ee determined by HPLC with Chiralcel OD column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 20.4$ min; $\tau_{minor} = 29.8$ min); $[\alpha]_D^{20} = -10.8$ (*c* 1.05, $CHCl_3$, 40% ee); IR (KBr) *v* (cm^{-1}): 1598 (s), 1325 (s), 1161 (s), 1089 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3), 3.29 (ddd, $J = 5.8$, 6.4,

4.4 Hz, 1H, CHCH_2), 4.01 (d, $J = 4.4$ Hz, 1H, CH), 4.53 (dd, $J = 10.6$, 6.4 Hz, 1H, CH_2), 4.73 (dd, $J = 10.6$, 5.8 Hz, 1H, CH_2), 6.89–7.02 (m, 3H, ArH), 7.20–7.29 (m, 9H, ArH), 7.84 (d, $J = 8.2$ Hz, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 46.9, 49.6, 114.7, 116.0, 121.4, 126.8, 127.6, 128.4, 128.6, 129.5, 134.3, 136.7, 144.3, 158.0; MS (EI) *m*/*z* (rel. intensity, %): 379 (M^+, 1), 286 (M^+−PhO, 3), 272 (M^+−PhOCH_2, 2), 224 (M^+−Ts, 44), 155 (Ts^+, 12), 130 (M^+−Ts−PhO−H, 52); Anal. Calcd for $C_{22}H_{21}NO_3S$: C, 69.63; H, 5.58; N, 3.69. Found: C, 69.60; H, 5.63; N, 3.45.

4.3.16. (2*S*,3*R*)-2-Benzoyl-3-methyl-1-(4-toluenesulfonyl)-aziridine 32. Colorless viscous oil, yield 42%; $R_f = 0.28$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 9% ee determined by HPLC with Chiralcel OD column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 14.93$ min; $\tau_{minor} = 18.30$ min); $[\alpha]_D^{20} = -5.4$ (*c* 0.21, $CHCl_3$, 9% ee); IR (KBr) (cm^{-1}): 1689 (s), 1325 (s), 1162 (s); ^{1}H NMR (300 MHz, $CDCl_3$): 1.83 (d, $J = 6.0$ Hz, 3H, CH_3), 2.38 (s, 3H, CH_3), 3.25 (qd, $J = 6.0$ Hz, 5.2 Hz, 1H, C*H*CH_3), 4.15 (d, $J = 5.2$ Hz, 1H, C*H*CH), 7.25–7.28 (m, 2H, ArH), 7.43–7.60 (m, 3H, ArH), 7.84–8.97 (m, 4H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 13.6, 21.5, 45.4, 46.9, 127.4, 128.5, 128.7, 129.5, 134.0, 135.5, 136.9, 144.4, 191.6; MS (EI) *m*/*z* (rel. intensity, %): 315 (M^+, 0.14), 160 (M^+−Ts, 47), 105 ($PhCO^+$, 100), 77 (Ph^+, 54). HRMS (EI) *m*/*z* calcd for $C_{17}H_{17}NO_3S$ (M^+) 315.0929; Found 315.0921.

4.3.17. 2-Acetyl-3,3-dimethyl-1-(4-toluenesulfonyl)aziridine 33. Colorless viscous oil, yield 20%; $R_f = 0.21$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); 6% ee determined by HPLC with Chiralcel OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{minor} = 10.7$ min; $\tau_{major} = 11.4$ min); $[\alpha]_D^{20} = -1.8$ (*c* 0.85, $CHCl_3$, 6% ee); ^{1}H NMR (300 MHz, $CDCl_3$): 1.30 (s, 3H, CH_3), 1.82 (s, 3H, CH_3), 1.97 (s, 3H, CH_3), 2.45 (s, 3H, CH_3), 3.48 (s, 1H, CH), 7.33–7.36 (m, 2H, ArH), 7.86–7.88 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.0, 21.6, 21.9, 28.7, 53.3, 55.2, 127.4, 129.7, 137.2, 144.4, 202.1. Racemate was reported in the literature.[41]

4.4. Determination of the absolute configuration of (2*S*,3*R*)-2-phenyl-3-phenoxylmethyl-1-(4-toluenesulfonyl)aziridine 16

tert-Butyldimethylsilyl cinnamyl ether **19** was prepared in the yield of 84% according to the literature method,[34] and was aziridinated asymmetrically by using general procedure as mentioned above to afford (2*S*,3*R*)-2-*tert*-butyldimethylsiloxymethyl-3-phenyl-1-(4-toluenesulfonyl)aziridine (**20**), colorless oil, yield 27%; $R_f = 0.43$ (ethyl acetate/petroleum ether 1:10, v/v, silica gel plate); 27% ee, $[\alpha]_D^{20} = -10.7$ (*c* 0.37, $CHCl_3$, 27% ee), lit.[34] $[\alpha]_D^{20} = +35.7$ (*c* 1.29, $CHCl_3$, >98% ee) for (2*R*,3*S*)-enantiomer; ^{1}H NMR (200 MHz, $CDCl_3$): δ 0.095 (s, 6H, $2CH_3$), 0.90 (s, 9H, $3CH_3$), 2.39 (s, 3H, CH_3), 3.10 (1H, ddd, $J = 4.5$, 6.8, 6.9 Hz, 1H, CH), 3.89 (d, $J = 4.4$ Hz, CH), 4.14 (dd, $J = 7.1$, 11.3 Hz, 1H in CH_2), 4.35 (dd, $J = 4.9$, 11.3 Hz, 1H in CH_2), 7.15–7.28 (m, 7H, ArH), 7.82 (d, $J = 8.2$ Hz, 2H, ArH); ^{13}C NMR (50 MHz, $CDCl_3$): δ −5.3, 18.2, 21.6, 25.8, 47.5, 52.3, 60.7, 126.8, 127.4, 128.2, 128.4, 129.5, 134.7, 137.2, 144.0.

4.4.1. Preparation of (2*S*,3*R*)-2-hydroxymethyl-3-phenyl-1-(4-toluenesulfonyl)aziridine 21. To a stirred solution of **20** (0.147 g, 0.36 mmol) in 2.5 mL of THF was added tetrabutylammonium fluoride (0.36 mL, 0.36 mmol, 1 mol/L solution in THF) by syringe at −78 °C, and the resulting mixture was allowed to warm to 0 °C then stirred at this temperature for an additional 1 h. The mixture was poured into ice-water and extracted with Et_2O. The extract was washed successively with 5% citric acid, water, 5% $NaHCO_3$, and water, and dried over anhydrous Na_2SO_4. Concentration under reduced pressure gave an oily residue, which was purified by flash chromatography over silica gel with ethyl acetate/petroleum ether (1:4, v/v) to give colorless oil 69 mg of **21**, yield 65%. $R_f = 0.12$ (ethyl acetate/petroleum ether 1:4, v/v, silica gel plate); $[\alpha]_D^{20} = -12.9$ (*c* 0.51, $CHCl_3$, 27% ee), lit.[34] $[\alpha]_D^{15} = +48.4$ (*c* 1.5, $CHCl_3$, >98% ee) for (2*R*,3*S*)-enantiomer; ^{1}H NMR (200 MHz, $CDCl_3$): δ 2.41 (s, 3H, CH_3), 3.15 (dd, $J = 4.9$, 9.8 Hz, 1H, OH), 3.19 (ddd, $J = 3.1$, 4.4, 8.4 Hz, 1H, CH), 4.03 (d, $J = 4.4$ Hz, 1H, CH), 4.19 (ddd, $J = 4.9$, 8.4, 13.3 Hz, 1H in CH_2), 4.32 (ddd, $J = 3.2$, 9.8, 13.3 Hz, 1H in CH_2), 7.13–7.31 (m, 7H, ArH), 7.82 (d, $J = 8.2$ Hz, 2H, ArH); ^{13}C NMR (50 MHz, $CDCl_3$): δ 21.6, 46.3, 54.7, 60.7, 126.4, 127.1, 128.4, 128.6, 129.7, 134.5, 137.0, 144.4.

4.4.2. Preparation of (2*S*,3*R*)-3-phenyl-1-(4-toluenesulfonyl)aziridin-2-ylmethyl tosylate 22. To a stirred solution of **21** (69 mg, 0.23 mmol) in 4 mL of CH_2Cl_2 were added 0.035 mL (0.25 mmol) of Et_3N and 46 mg (0.24 mmol) of TsCl at 0 °C. The mixture was allowed to stir overnight with warming to room temperature, then diluted with 5 mL of water and extracted with CH_2Cl_2. The combined organic layer was washed with brine and dried over anhydrous Na_2SO_4. The usual work-up was followed by flash chromatography over silica gel with ethyl acetate/petroleum ether (1:5, v/v) as an eluent to give colorless oil 65 mg of **22**, yield 63%. $R_f = 0.23$ (ethyl acetate/petroleum ether 1:5, v/v, silica gel plate); $[\alpha]_D^{20} = -2.3$ (*c* 0.27, $CHCl_3$); ^{1}H NMR (200 MHz, $CDCl_3$): 2.41 (s, 3H, CH_3, 27% ee), 2.45 (s, 3H, CH_3), 3.14 (ddd, $J = 4.0$, 5.8, 7.2 Hz, 1H, CH), 3.89 (d, $J = 4.0$ Hz, CH), 4.60 (dd, $J = 7.2$, 11.4 Hz, 1H in CH_2), 4.71 (dd, $J = 5.8$, 11.6 Hz, 1H in CH_2), 7.13–7.31 (m, 9H, ArH), 7.79 (d, $J = 8.2$ Hz, 2H, ArH), 7.81 (d, $J = 8.6$ Hz, 2H, ArH); ^{13}C NMR (50 MHz, $CDCl_3$): δ 21.59, 21.64, 47.3, 47.9, 66.7, 126.8, 127.6, 128.0, 128.6, 129.7, 130.0, 133.6, 136.4, 144.6, 145.2.

4.4.3. Substitution reaction of (2*S*,3*R*)-3-phenyl-1-(4-toluenesulfonyl)aziridin-2-ylmethyl tosylate 22 and sodium phenolate for the preparation of (2*S*,3*R*)-2-phenyl-3-phenoxylmethyl-1-(4-toluenesulfonyl)aziridine 16. Seven milligrams (0.175 mmol) of 60% NaH in mineral oil was added to 1.5 mL of dry DMF at 0 °C. After

10 min, to the above white suspension 14 mg (0.149 mmol) of PhOH in 1 mL of dry DMF was added dropwise at the same temperature. The resulting mixture was stirred for 30 min to give the clear solution. Then 65 mg (0.142 mmol) of **22** in 1 mL of dry DMF was added dropwise to the solution. The mixture was allowed to stir overnight with warming to room temperature, and diluted with 10 mL of water. The mixture was extracted with EtOAc and the organic layer was washed with brine, dried over anhydrous Na_2SO_4. Concentration under reduced pressure gave an oily residue, which was separated by flash chromatography over silica gel with ethyl acetate/petroleum ether (1:10, v/v) to give colorless oil 13 mg of **16**, yield 24%; colorless oil 16 mg of **23**, yield 30%; white solid 23 mg of **24**, yield 34%, respectively.

4.4.3.1. (2*S*,3*R*)-2-Phenyl-3-phenoxymethyl-1-(4-toluenesulfonyl)aziridine 16 (from 22). Yield 24%; 26% ee determined by HPLC with Chiralcel OD column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{major} = 20.9$ min; $\tau_{minor} = 30.3$ min); $[\alpha]_D^{20} = -7.1$ (*c* 1.00, $CHCl_3$, 26% ee).

4.4.3.2. (*S*,*S*)2-(1-Phenoxy-phenylmethyl)-1-(4-toluenesulfonyl)aziridine 23. Colorless crystals, yield 30%; mp 92.5–94 °C; $R_f = 0.12$ (ethyl acetate/petroleum ether 1:10, v/v, silica gel plate); 19% ee determined by HPLC with Chiralcel OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{minor} = 12.05$ min; $\tau_{major} = 19.59$ min); $[\alpha]_D^{20} = +10.7$ (*c* 0.45, $CHCl_3$, 19% ee); IR (KBr) (cm^{-1}): 1598 (s), 1494 (s), 1327 (s), 1234 (s), 1163 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.40 (d, $J = 4.2$ Hz, 1H in CH_2N), 2.43 (s, 3H, CH_3), 2.81 (d, $J = 6.9$ Hz, 1H in CH_2N), 3.14 (ddd, $J = 4.2$, 6.0, 6.9 Hz, 1H, CHN), 4.87 (d, $J = 6.0$ Hz, 1H, CHO), 6.70–6.73 (m, 2H, ArH), 6.85–6.90 (m, 1H, ArH), 7.12–7.19 (m, 9H, ArH), 7.61–7.64 (m, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.6, 31.0, 43.8, 78.8, 116.0, 121.4, 126.3, 127.9, 128.0, 128.5, 129.3, 129.5, 134.4, 137.7, 144.4; MS (EI) *m*/*z* (rel. intensity, %): 379 (M^+, 0.25), 286 (M^+−PhO, 35), 166 (13), 155 (Ts^+, 27), 130 (100), 91 (CH_3Ph^+, 78), 77 (Ph^+, 22). HRMS (EI) *m*/*z* calcd for $C_{22}H_{21}NO_3S$ (M^+) 379.1242; Found 379.1249.

4.4.3.3. (*S*,*S*)-1,3-Diphenoxy-1-phenyl-*N*-(4-toluenesulfonyl)propan-2-amine 24. Colorless crystals, yield 34%; mp 162–164 °C; $R_f = 0.08$ (ethyl acetate/petroleum ether 1:10, v/v, silica gel plate); 23% ee determined by HPLC with Chiralcel OD-H column with hexane/2-propanol (90:10, v/v) as an eluent at a flow rate of 0.8 mL/min ($\tau_{minor} = 12.01$ min; $\tau_{major} = 14.83$ min); $[\alpha]_D^{20} = -5.8$ (*c* 0.45, $CHCl_3$); IR (KBr) (cm^{-1}): 1599 (s), 1494 (s), 1330 (m), 1235 (s), 1161 (s); ^1H NMR (300 MHz, $CDCl_3$): 2.40 (s, 3H, CH_3), 3.90 (dd, $J = 5.1$, 9.9 Hz, 1H in CH_2O), 4.06 (dddd, $J = 4.5$, 5.1, 5.7, 9.0 Hz, 1H, CHN), 4.23 (dd, $J = 5.7$, 9.9 Hz, 1H in CH_2O), 5.00 (d, $J = 9.0$ Hz, 1H, CHO), 5.45 (d, $J = 4.5$ Hz, 1H, NH), 6.63–6.68 (m, 4H, ArH), 6.84–6.95 (m, 2H, ArH), 7.10–7.29 (m, 11H, ArH), 7.69 (d, $J = 8.4$ Hz, 2H, ArH); ^{13}C NMR (75.5 MHz, $CDCl_3$): δ 21.5, 57.6, 65.5, 78.9, 114.4, 115.7, 121.2, 121.3, 126.5, 127.2, 128.3, 128.8, 129.3, 129.4, 129.5, 136.6, 137.5, 143.3, 157.9; MS (EI) *m*/*z* (rel. intensity, %): 473 (M^+, 0.67), 380 (M^+−PhO, 4.25), 290 (23), 209 (14), 183 (52), 172 (94), 155 (Ts^+, 50), 130 (36), 119 (41), 91 (CH_3Ph^+, 100), 77 (Ph^+, 49). HRMS (EI) *m*/*z* calcd for $C_{28}H_{27}NO_4S$ (M^+) 473.1661; Found 473.1660.

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