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Asymmetric phase transfer Darzens reactions catalyzed by D-glucose- and D-mannose-based chiral crown ethers

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ABSTRACT

Liquid–liquid phase asymmetric Darzens condensations were carried out in the presence of D-glucose- and D-mannose-based crown ethers **1** and **2** as the catalyst. The use of D-glucose-based lariat ether **1** as the catalyst gave the best results. The reaction of 4-phenyl-α-chloroacetophenone, 2-chloro-1-tetralone, and 2-chloro-1-indanone with various aromatic aldehydes afforded the corresponding aromatic α,β-epoxyketones in moderate to high enantiomeric excess (ee up to 96%) under mild reaction conditions. The substituents of the benzaldehyde used as the reactants had a significant impact on the chemical yields and enantiomeric excess. The absolute configuration of some epoxyketone products was determined by single-crystal X-ray analysis.

1. Introduction

The Darzens reaction, which allows the generation of new stereogenic centers with complete diastereocontrol, is one of the most powerful methodologies for the synthesis of α,β-epoxy carbonyl and related compounds, and therefore has been recognized as one of the most significant C–C bond forming processes in synthetic organic chemistry. While epoxides are important functional groups in organic synthesis as targets in their own right, they are perhaps more important as intermediates that yield bifunctional compounds after stereoselective ring-opening by a nucleophile.[1a] The Darzens condensation may also be performed under phase-transfer conditions, which has several advantages, such as a simple reaction procedure, mild conditions, inexpensive and safe reagents, and solvents.[1b,c] Optically active α,β-epoxy carbonyl compounds can be easily converted into many types of useful chiral compounds such as chiral building blocks and synthetic intermediates for biologically active compounds (e.g., Diltiazem, Avermectin synthon, etc.). Starting from an enantiopure epoxide, the absolute stereochemistry at the two adjacent stereogenic centers can be controlled. The chiral epoxyketones can be produced by a variety of catalytic asymmetric reactions;[2] one of the simplest methods for the preparation of chiral epoxides involves a Darzens condensation carried out under phase transfer catalytic conditions in the presence of optically active catalysts.[3]

Although many examples are known with diastereoselective control in the Darzens reaction, only a few successful cases involving enantiocontrol, accomplished in the presence of chiral catalysts or reagents have been reported. North et al. used a cobalt(salen) complex to catalyze the asymmetric Darzens condensation of α-haloamides and aldehydes. The *cis*-epoxides were obtained in up to 50% enantiomeric excess, while the *trans*-epoxides were formed with an up to 43% enantiomeric excess.[4] Aggarwal et al. have developed a highly enantioselective variation of the Darzens condensation to give *trans*-glycidic amides by replacement of the halide leaving group with a chiral sulfonium salt.[5] Arai et al. used cinchona alkaloid derivatives as chiral phase transfer catalysts in asymmetric Darzens condensations resulting in enantioselectives of up to 86% in the reaction of cyclic α-chloroketone substrates,[6] up to 79% ee in the reactions of α-chloroacetophenone,[6,7] and up to 83% ee in the reactions of chloromethyl phenyl sulfone.[7] Recently, Arai et al. reported the use of a synthetic bis-ammonium salt as an asymmetric phase transfer catalyst in the Darzens condensation of *N*,*N*-diphenyl α-haloamides, predominantly giving the *cis*-epoxides with up to 64% ee for the *cis*-epoxide, and up to 70% ee for the *trans*-epoxide.[8] Jew and Jeong synthesized chiral α,β-epoxysulfones by the phase transfer catalytic Darzens reaction of chloromethyl phenyl sulfone with various aromatic aldehydes in the presence of a new cinchona alkaloid derivative as the catalyst, resulting in high (up to 97% ee) enantioselectivities.[9]

One of the most attractive methods in catalytic asymmetric synthesis is the phase transfer catalytic approach in which the enantioselectivity is generated by a chiral crown catalyst.[3]

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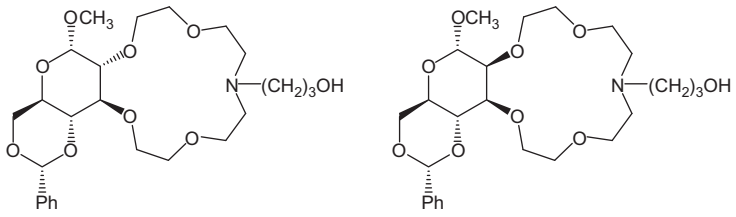


Figure 1. Crown ethers incorporating an α-D-glucopyranoside **1** and an α-D-mannopyranoside **2** unit.

Earlier, chiral monoaza-15-crown-5 type macrocycles incorporating an α-D-glucopyranoside or α-D-mannopyranoside units **1** and **2** were synthesized in our laboratory, and proved to be efficient catalysts in a few asymmetric reactions.[10] The Darzens condensation between benzaldehyde and α-chloroacetophenone took place in up to 72% ee.[11] Chiral heteroaromatic epoxyketones were formed in good (up to 86% ee) enantioselectivities in the presence of catalyst **1** (Fig. 1).[12]

Herein we report the asymmetric Darzens condensation of 4-phenyl-α-chloroacetophenone, 2-chloro-1-tetralone, and 2-chloro-1-indanone with various aromatic aldehydes (there was not any asymmetric induction with aliphatic aldehydes). Our preliminary results concerning the enantioselective Darzens reactions using catalysts **1** and **2** have already been reported.[12a]

2. Results and discussion

The Darzens reactions were carried out in a liquid–liquid two-phase system in toluene, employing 30% aq NaOH as the base and 7 mol % of chiral crown catalysts **1** and **2** at temperatures of −10 to 20 °C. Generally, the reactions were complete within a short period of time (20 min–2 h). The products were isolated by preparative TLC. The *trans*-epoxyketones were all obtained in diastereomeric excesses (de) of >98%. The high diastereoselectivity observed in this reaction system is probably due to the generation of a single *Z*-enolate species (the intermediate sodium enolate would necessarily be in the *Z*-form).[1c,6b] The asymmetric induction expressed in the term of enantiomeric excess was determined by ^{1}H NMR analysis in the presence of Eu(hfc)$_3$ as a chiral shift reagent.

First, the reaction of 4-phenyl-α-chloroacetophenone **3** and aromatic aldehydes **4a–m** was studied (Scheme 1). We wished to study the effect of the substituents of the phenyl ring of the benzaldehyde on the preparative yield and enantiomeric purity. The experimental data are listed in Table 1.

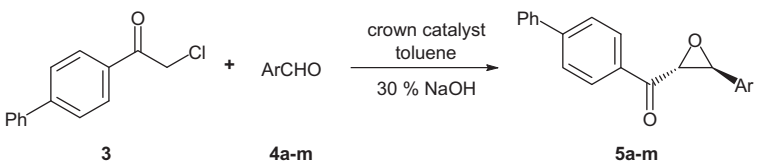
The *trans*-epoxyketones **5a–m** (with one exception) had negative specific rotation values and were obtained in yields of 54–76%. The maximum selectivity was detected in the reaction of compound **3** with benzaldehyde **4a**, giving epoxide **5a** in 96% ee (and after recrystallization in an ee of 100%) (Table 1, entry 1). The use of substituted benzaldehydes **4b–k** led to lower ee values that were dependent on the substitution pattern of the phenyl ring (40–84%). In the series, the use of 2-chlorobenzaldehyde **4b** led to the best enantiomeric purity (84% ee). After recrystallization, this value increased to 90% (Table 1, entry 2). The degree of asymmetric induction was affected by the position of the chloroatom in the phenyl ring: 2-Cl-, 3-Cl-, and 4-Cl-derivatives **5b**, **5c**, **5d** were formed with ee values of 84%, 60%, and 64%. Comparison of the ee values of the 4-chloro- **5d** and 4-fluoro- **5e** derivatives showed that the electronic effect is also responsible for the asymmetric induction reflected in the ee values of 64% and 55%, respectively. In the reaction of 4-phenyl-α-chloroacetophenone **3** with nitrobenzaldehydes, the epoxyketones **5f–h** were formed in a lower (40–51%) enantioselectivity (Table 1, 6–8 entries). The methyl derivatives **5i–k** were obtained in 60–70% ee. In the case of the nitro-substitution, as in **5f–h**, and methyl-substitution, as in **5i–k**, we observed that the further substituent on the benzaldehyde was placed from the reaction center, the more considerable the extent of the asymmetric induction. Hence, within the series, the highest enantiomeric excesses were obtained with *para*-substitution (Table 1, entries 8 and 11). The 1-naphthyl **5l** and 2-naphthyl **5m** products were obtained with ee values of 66% and 74%, respectively. It is noteworthy that the 1-naphthyl derivative **5l** had a positive specific rotation (Table 1, entry 12).

Table 1
Asymmetric reaction of 4-phenyl-α-chloroacetophenone with aromatic aldehydes in the presence of catalyst **1** at 20 °C

Entry	Ar	Product and yield[a] (%)	$[\alpha]_D^{22}$[b]	ee[c] (%)
1	Ph	**5a**: 54	−173	96 (100)
2	2-Cl-C_6H_4	**5b**: 71	−5	84 (90)
3	3-Cl-C_6H_4	**5c**: 61	−110	60
4	4-Cl-C_6H_4	**5d**: 68	−108	64 (68)
5	4-F-C_6H_4	**5e**: 48	−81	55
6	2-NO_2-C_6H_4	**5f**: 76	−63	40 (43)
7	3-NO_2-C_6H_4	**5g**: 51	−63	45
8	4-NO_2-C_6H_4	**5h**: 65	−119	51
9	2-H_3C-C_6H_4	**5i**: 59	−32	60 (66)
10	3-H_3C-C_6H_4	**5j**: 55	−122	64
11	4-H_3C-C_6H_4	**5k**: 54	−130	70 (77)
12	1-Naphthyl	**5l**: 59	+75	66 (72)
13	2-Naphthyl	**5m**: 56	−129	74 (86)

[a] Reaction times 1–2 h; Yield based after isolation by preparative TLC.
[b] In CH_2Cl_2, *c* 1.
[c] Determined by ^{1}H NMR spectroscopy; the ee given in parentheses is that obtained after one recrystallization from EtOH.

The pure levorotatory enantiomer of epoxyketone **5b** obtained from 2-chlorobenzaldehyde was subjected to single crystal X-ray analysis. According to this, the absolute configuration was (2*R*,3*S*)



Scheme 1.

(Fig. 2). It is reasonable to assume that the other epoxyketone derivatives with a negative specific rotation also had the same (2*R*,3*S*)-absolute configuration.

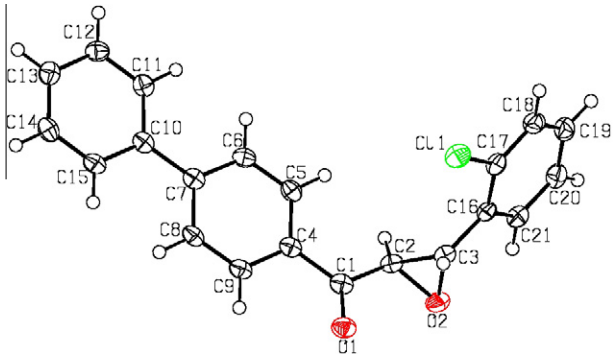


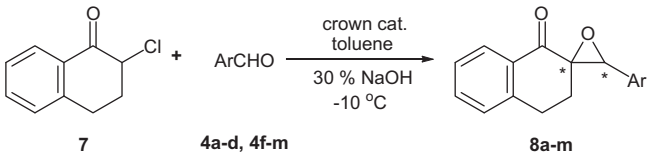
Figure 2. ORTEP representation of compound **5b** at a 50% probability level.

In the Darzens condensation studied, we isolated a by-product in an optically active form, which was found to be the base initiated self-condensation product of 4-phenyl-α-chloroacetophenone. The by-product can be formulated as epoxyketone **6** (Scheme 2). The self-condensation of compound **3** was then studied in a blank experiment carried out under the previously described conditions (toluene, 30% sodium hydroxide) in the presence of glucose-based crown-ether catalyst **1**. The ^{1}H NMR spectroscopy showed that the ratio of the *cis*:*trans* isomers of the condensed by-product **6** was 2:8. The *trans*-isomer was separated by chromatography in which the levorotatory enantiomer was in 10% excess.

The mannose-based crown ether **2** generated lower enantioselectivities and promoted the formation of the enantiomer with a positive specific rotation. For example, the epoxyketones **5b** and **5k** were obtained with ee values of 70% and 59%, respectively.

The reaction of cyclic α-chloroketones with aromatic aldehydes was studied under the conditions described above in the presence of catalysts **1** and **2**. Starting materials **7** and **9** were readily prepared from 1-tetralone and 1-indanone, respectively. The reactions of 2-chloro-1-tetralone **7** with various aromatic aldehydes **4** were complete after stirring for 20–40 min at −10 °C in the presence of catalyst **1** (Scheme 3). The *trans*-epoxyketones **8a–m** were obtained in good yields and with high diastereoselectivites (de of >98%) and with moderate to good enantioselectivities. With one exception, all of the products had a negative specific rotation. The results are listed in Table 2.

In the reaction of cyclic chloroketone **7** with benzaldehyde, epoxyketone **8a** was formed in a yield of 84% and with 74% ee.[13] On the basis of the negative specific rotation, the absolute configuration of product **8a** was assigned as (2*R*,3′*S*).[6b] The effect of the substituents of the benzaldehyde was evaluated next. With one exception, the substituted derivatives were formed with lower ee values. The *ortho*-, *meta*-, and *para*-chloro derivatives **8b**, **8c**, **8d** were obtained in 36%, 44%, and 59% ee, respectively, (Table 2, entries 2–4). The reactions with nitro-benzaldehydes resulted in higher enantioselectivities, with the corresponding products **8f**,



7 4a-d, 4f-m 8a-m

Scheme 3.

8g, and **8h** being obtained in 54%, 43%, and 75% ee, respectively (Table 2, entries 5–7). The ee value of 75% measured in the case of 4-nitro-epoxyketone represents a maximum regarding the whole series. It can be seen that with regards to asymmetric induction, the *para*-position is optimal, at least in the case of electron-withdrawing chloro and nitro substituents (entries 4 and 7). Methyl derivatives **8i–k** were formed in 40–65% ee. The best ee values were in the reactions of *m*-methylbenzaldehyde (Table 2, entries 8–10). There was a significant difference between the ee values of products **8l** and **8m** obtained in the reaction of 1-naphthaldehyde and 2-naphthaldehyde, respectively. In the former case, the ee was 32%, while in the latter it was 59% (entries 11 and 12, respectively). It is noteworthy that in contrast to all of the other cases, compound **8l** had a positive specific rotation. In the case of naphthyl derivatives the steric effect may be responsible for the asymmetric induction.

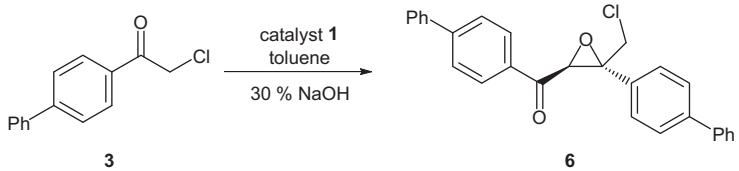
Table 2
Asymmetric reaction of 2-chloro-1-tetralone with aromatic aldehydes in the presence of catalyst **1** at −10 °C

Entry	Ar	Product and yield[a] (%)	$[\alpha]_D^{22}$[b]	ee[c] (%)
1	Ph	**8a**: 84	−144	74
2	2-Cl-C_6H_4	**8b**: 84	−15	36
3	3-Cl-C_6H_4	**8c**: 88	−122	44 (68)
4	4-Cl-C_6H_4	**8d**: 84	−137	59 (69)
5	2-O_2N-C_6H_4	**8f**: 71	−83	54
6	3-NO_2-C_6H_4	**8g**: 58	−83	43 (23)
7	4-NO_2-C_6H_4	**8h**: 51	−145	75
8	2-H_3C-C_6H_4	**8i**: 83	−32	40
9	3-H_3C-C_6H_4	**8j**: 83	−142	65 (69)
10	4-H_3C-C_6H_4	**8k**: 65	−133	55
11	1-Naphthyl	**8l**: 90	+36	32
12	2-Naphthyl	**8m**: 77	−225	59

[a] Based on isolation by preparative TLC.
[b] In $CHCl_3$, *c* 1.
[c] Determined by ^{1}H NMR spectroscopy, ee given in parentheses is that obtained after one recrystallization from EtOH.

Repeated recrystallization of products **8d** and **8m** led to pure enantiomers whose absolute configurations were determined by single crystal X-ray crystallography. In both cases the configuration of the stereogenic centers was found to be (2*R*,3′*S*) (Figs. 3 and 4).

We next investigated if the ring size of the cyclic chloro-ketone had an impact on the enantioselectivity. Hence, the Darzens reaction of 2-chloro-1-indanone **9** with aromatic aldehydes was studied in the presence of crown ether **1** under the conditions described above (Scheme 4). Completion of the reactions required 20–40 min at 0 °C. Products **10a–d** and **10f–m** were isolated in



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Scheme 2.

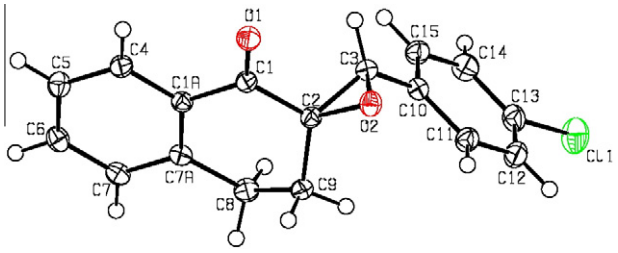


Figure 3. ORTEP representation of compound **8d** at a 50% probability level.

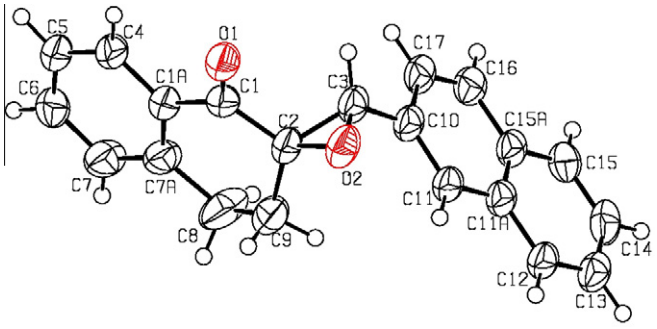


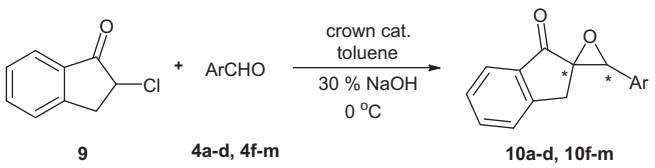
Figure 4. ORTEP representation of compound **8m** at a 50% probability level.

variable yields and displayed negative specific rotations. The data are summarized in Table 3.

It can be seen that a change in the ring size (i.e., replacing 6-ring compound **7** with 5-ring species **9**) had a dramatic impact on the isolated yields and enantiomeric purities. The reaction of chloroketone **9** and benzaldehyde gave epoxyketone **10a** in a yield of 59% with an ee value of 65%.[14] The substituted derivatives **10b–k**, with one exception, were formed in lower ee values. Chloro derivatives **10b**, **10c,** and **10d** were obtained in 85%, 59%, and 37% ee values, respectively (Table 3, entries 2–4). The nitro derivatives **10f–10h** were obtained in low yields (18–36%) and in variable ee values (0–62%). Products **10f** and **10g** were formed in 20% and 62% ee values, respectively, while *p*-nitro derivative **10h** was obtained practically as a racemate (Table 3, entries 5–7). Using crown catalyst **1**, methyl derivatives **10i–k** were obtained in good yields and with 49–63% ee (Table 3, entries 8–10). Among the substituted benzaldehydes, the best results were obtained in the reaction with 2-chlorobenzaldehyde; in this case, product **10b** was formed with an ee of 85%. Product **10l** formed from 1-naphthaldehyde and compound **10m** formed from 2-naphthaldehyde were obtained with ee values of 47% and 15%, respectively. The yields were rather low (Table 3, entries 11 and 12).

In the reactions shown in Schemes 3 and 4, the mannose-based crown ether **2** generated lower ee values and the chiral epoxyketones formed, had positive specific rotations. For example in the presence of catalyst **2**, products **8a** and **10b** were formed with ee values of 64% and 71%, respectively.

To the best of our knowledge, there are only a few examples of α,β-epoxy ketones prepared in phase-transfer catalytic asymmetric



Scheme 4.

Table 3
Asymmetric reaction of 2-chloro-1-indanone with aromatic aldehydes in the presence of catalyst **1** at 0 °C

Entry	Ar	Product and yield[a] (%)	$[\alpha]_D^{22}$[b]	ee[c] (%)
1	Ph	**10a**: 59	−246	65 (70)
2	2-Cl-C_6H_4	**10b**: 52	−31	85
3	3-Cl-C_6H_4	**10c**: 74	−229	59 (67)
4	4-Cl-C_6H_4	**10d**: 48	−140	37
5	2-NO_2-C_6H_4	**10f**: 36	−69	20
6	3-NO_2-C_6H_4	**10g**: 18	−152	62 (73)
7	4-NO_2-C_6H_4	**10h**: 16	0	—
8	2-H_3C-C_6H_4	**10i**: 84	−104	49
9	3-H_3C-C_6H_4	**10j**: 72	−233	63
10	4-H_3C-C_6H_4	**10k**: 76	−240	58 (54)
11	1-Naphthyl	**10l**: 20	−29	47
12	2-Naphthyl	**10m**: 25	−72	15

[a] Based on isolation by preparative TLC.
[b] In $CHCl_3$, *c* 1.
[c] Determined by ^1H NMR spectroscopy; the ee given in parentheses is that obtained after one recrystallization from EtOH.

Darzens reactions and obtained with ee values higher than 80%. Only Arai et al. have reported high enantioselectivities of up to 86% ee for the reaction of cyclic α-chloro ketones and aldehydes in the presence of a cinchonine derivative after prolonged (40–80 h) reaction times.[6]

3. Conclusion

The monosaccharide-based crown ethers used as phase transfer catalysts act as asymmetric inductors in the Darzens condensation only with aromatic aldehydes. In the presence of D-mannose-based crown ether **2**, the chiral epoxyketones were obtained in 20–30% lower ee values, than those obtained with glucose-based catalyst **1**. For this, crown catalyst **1** was applied to the test reactions. As compared to the cinchona alkaloid-catalyzed reactions, milder conditions could be applied, the reaction times were shorter (20 min–2 h), and the ee values were variable or high; in a few cases, the ee values were higher compared to those reported in the literature. We have shown that the substituents on the aromatic ring of the benzaldehyde had a significant impact on the yields and enantiomeric purity. In some cases, the steric factors controlled the extent of the asymmetric induction, while in other cases, it was electronic factors. The monosaccharide unit of the catalyst is decisive with respect to the configuration of the epoxyketone formed. The glucose-based catalyst **1** promoted mostly the formation of the enantiomer with a negative specific rotation [(2*R*,3*S*) and (2*R*,3′*S*)] while the mannose-based crown **2** enhanced the predominant formation of the enantiomer with a positive specific rotation. However, it should be emphasized that the sign of the specific rotation cannot be reliably used to determine the absolute configuration.

4. Experimental

4.1. General procedures

Melting points were taken on using a Büchi 510 apparatus and are uncorrected. Melting points of the epoxyketones were determined after recrystallization from ethanol. Specific rotations were measured with a Perkin–Elmer 241 polarimeter at 20 °C. ^1H and ^{13}C NMR spectra were recorded on a Bruker 300 and a Bruker DRX-500 or a Varian Inova 500 instrument in $CDC1_3$ with TMS as the internal standard. Analytical and preparative thin layer chromatography was performed on silica gel plates (60 GF-254, Merck), while column chromatography was carried out using 70–230 mesh

silica gel (Merck). Chemicals and the shift reagent Eu(hfc)$_3$ were purchased from Aldrich Chem. Co. The exact mass measurements were performed using Q-TOF Premier mass spectrometer (Waters Corporation, 34 Maple St, Milford, MA, USA) in positive electrospray ionization mode.

X-ray analysis: the absolute configuration of the crystals is described in most cases by two crystallographic data: the Flack *x* parameter[15] and the Hooft *y* parameter.[16] These parameters show the probability of the correct absolute configuration. If the value is near 0, with a correspondingly small uncertainty, the absolute configuration is correct. If the value is near 1, then one must invert the structure. If the standard uncertainty is large or the parameter value is near 0.5 the crystal may be racemic twin or we cannot prove the real configuration.

Other important factors for the determination of the absolute configuration are, for example, the wavelength of the radiation used, completeness of the data, and the presence of heavy atoms in the crystal.

4.2. General procedure for the Darzens condensation

A toluene solution (3 mL) of aromatic 2-chloroketone (1.87 mmol), aromatic aldehyde (2.8 mmol), and the crown ether (0.14 mmol) was cooled to the corresponding temperature and then treated with 30% NaOH (1 mL). The mixture was then stirred at this temperature. After complete conversion (1–2 h), a mixture of toluene (7 mL) and water (3 mL) was added and the mixture stirred for 10 min. The organic phase was washed with cold 10% HCl (3 × 10 mL) and then with water (10 mL), dried (Na_2CO_3) and concentrated. The crude product was purified on silica gel by preparative TLC using hexane–EtOAc (10:1) as an eluent. The enantioselectivities were determined by ^{1}H NMR spectroscopy in the presence of Eu(hfc)$_3$ as a chiral shift reagent.

4.2.1. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-phenylpropan-1-one 5a

Yield: 54%; $[\alpha]_D^{22} = -173$ (*c* 1, CH_2Cl_2) 96% ee; mp 68–74 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.10 (d, *J* = 8 Hz, 2H), 7.71 (d, *J* = 8.5 Hz, 2H), 7.64–7.61 (m, 2H), 7.50–7.45 (m, 1H), 7.44–7.38 (m, 7H), 4.33 (d, *J* = 2 Hz, 1H), 4,11 (d, *J* = 2 Hz, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 192.74, 146.66, 139.60, 139.05, 134.20, 129.47, 129.01, 128.96, 128.46, 127.46, 127.28, 126.50, 125.79, 61.15, 59.47. HRMS calcd for $C_{21}H_{16}O_2$ 300.1150, found 300.1152.

4.2.2. (−)-(2*R*,3*S*)-2,3-Epoxy-1-(biphen-4-yl)-3-(2-chlorophenyl)propan-1-one 5b

Yield: 71%; $[\alpha]_D^{22} = -5$ (*c* 1, CH_2Cl_2) 84% ee; mp 176–177 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 8.13 (d, *J* = 8.1 Hz, 2H), 7.73 (d, *J* = 8.1 Hz, 2H), 7.63 (d, *J* = 7.5 Hz, 2H), 7.52–7.38 (m, 5H), 7.37–7.31 (m, 2H), 4.41 (d, *J* = 1.5 Hz, 1H), 4.21 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}ClO_2$ 334.0761, found 334.0757. Crystal data for **5b**: CCDC 868833 contains the supplementary crystallographic data for this structure. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. Absolute configuration crystal data: Rigaku R-AXIS Rapid Diffractometer, Cu Kα radiation, λ = 1.54187 Å, *T* = 93(2) K, R_1 = 3.10, Rw^2 = 7.26, *N* = 2681, Friedel Pair Coverage = 92%, Flack parameter:[15] 0.024(16), Hooft parameter:[16] 0.03(1).

4.2.3. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(3-chlorophenyl)-propan-1-one 5c

Yield: 61%; $[\alpha]_D^{22} = -110$ (*c* 1, CH_2Cl_2) 60% ee; mp 90–92 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.09 (d, *J* = 8.5 Hz, 2H), 7.72 (d, *J* = 8.5 Hz, 2H), 7.62 (d, *J* = 7.5 Hz, 2H), 7.48 (t, *J* = 7.5 Hz, 2H), 7.42 (t, *J* = 7.5 Hz, 1H), 7.39–7.33 (m, 3H), 7.29 (dt, *J* = 6.5 Hz, 1.5 Hz, 1H), 4.29 (d, *J* = 1.5 Hz, 1H), 4.09 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}ClO_2$ 334.0761, found 334.0756.

4.2.4. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(4-chlorophenyl)-propan-1-one 5d

Yield: 68%; $[\alpha]_D^{22} = -108$ (*c* 1, CH_2Cl_2) 64% ee; mp 154–160 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.09 (d, *J* = 8.5 Hz, 2H), 7.72 (d, *J* = 8 Hz, 2H), 7.62 (d, *J* = 7.5 Hz, 2H), 7.48 (t, *J* = 7.5 Hz, 2H), 7.42 (d, *J* = 7.5 Hz, 1H), 7.39 (d, *J* = 8.5 Hz, 2H), 7.33 (d, *J* = 8.5 Hz, 2H), 4.27 (d, *J* = 1.5 Hz, 1H), 4.10 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}ClO_2$ 334.0761, found 334.0762.

4.2.5. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(4-fluorophenyl)-propan-1-one 5e

Yield: 48%; $[\alpha]_D^{22} = -81$ (*c* 1, CH_2Cl_2, 55% ee); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.09 (d, *J* = 8 Hz, 2H), 7.72 (d, *J* = 8.5 Hz, 2H), 7.62 (d, *J* = 7.5 Hz, 2H), 7.48 (t, *J* = 7.5 Hz, 2H), 7.42 (t, *J* = 7.5 Hz, 1H), 7.38 (d, *J* = 7.5 Hz, 1H), 7.37 (d, *J* = 7.5 Hz, 1H), 7.11 (t, *J* = 8.5 Hz, 2H), 4.28 (d, *J* = 1.5 Hz, 1H), 4.10 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}FO_2$ 318.1056, found 318.1059.

4.2.6. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(2-nitrophenyl)-propan-1-one 5f

Yield: 76%; $[\alpha]_D^{22} = -63$ (*c* 1, CH_2Cl_2) 40% ee; mp 156–162 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.23 (dd, *J* = 8.5 Hz, 1 Hz, 1H), 8.11 (d, *J* = 8.5 Hz, 2H), 7.78–7.76 (m, 1H), 7.71 (d, *J* = 8.5 Hz, 2H), 7.65–7.61 (m, 2H), 7.58 (ddd, *J* = 7.5 Hz, 6.5 Hz, 2 Hz, 1H), 7.48 (t, *J* = 7.5 Hz, 2H), 7.41 (tt, *J* = 7.5 Hz, 1 Hz, 1H), 4.68 (d, *J* = 1.5 Hz, 1H), 4.25 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}NO_4$ 345.1001, found 345.1004.

4.2.7. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(3-nitrophenyl) propan-1-one 5g

Yield: 51%; $[\alpha]_D^{22} = -63$ (*c* 1, CH_2Cl_2) 45% ee; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.26 (s, 1H), 8.25 (d, *J* = 8.5 Hz, 1H), 8.11 (d, *J* = 8.5 Hz, 2H), 7.76–7.71 (m, 3H), 7.65–7.61 (m, 3H), 7.49 (t, *J* = 7.5 Hz, 2H), 7.24 (tt, *J* = 7.5 Hz, 1 Hz, 1H), 4.34 (d, *J* = 1.5 Hz, 1H), 4.25 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}NO_4$ 345.1001, found 345.0998.

4.2.8. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(4-nitrophenyl)-propan-1-one 5h

Yield: 65%; $[\alpha]_D^{22} = -119$ (*c* 1, CH_2Cl_2) 51% ee; mp 140–146 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 8.27 (d, *J* = 8.7 Hz, 2H), 8.09 (d, *J* = 8.5 Hz, 2H), 7.72 (d, *J* = 8.1 Hz, 2H), 7.62 (d, *J* = 7.5 Hz, 2H), 7.57 (d, *J* = 8.7 Hz, 2H), 7.52–7.40 (m, 3H), 4.29 (d, *J* = 1.8 Hz, 1H), 4.24 (d, *J* = 1.5 Hz, 1H). HRMS calcd for $C_{21}H_{15}NO_4$ 345.1001, found 345.1002.

4.2.9. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(2-methylphenyl)-propan-1-one 5i

Yield: 59%; $[\alpha]_D^{22} = -32$ (*c* 1, CH_2Cl_2) 60% ee; mp 88–90 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.13 (d, *J* = 8 Hz, 2H), 7.72 (d, *J* = 8.5 Hz, 2H), 7.63 (d, *J* = 7.5 Hz, 2H), 7.48 (t, *J* = 7.5 Hz, 2H), 7.41 (t, *J* = 7.5 Hz, 1H), 7.36 (dd, *J* = 6 Hz, 3 Hz, 1H), 7.29–7.25 (m, 2H), 2.38 (s, 1H), 7.20 (dd, *J* = 6 Hz, 3 Hz, 1H), 4.25 (d, *J* = 2 Hz, 1H), 4.23 (d, *J* = 2 Hz, 1H), 2.38 (s, 3H). HRMS calcd for $C_{22}H_{18}O_2$ 314.1307, found 314.1309.

4.2.10. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(3-methyl-phenyl) propan-1-one 5j

Yield: 55%; $[\alpha]_D^{22} = -122$ (*c* 1, CH_2Cl_2) 64% ee; mp 122–126 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.10 (d, *J* = 8.5 Hz, 2H), 7.71 (d, *J* = 8.5 Hz, 2H), 7.62 (d, *J* = 7.5 Hz, 2H), 7.48 (t, *J* = 8 Hz, 2H), 7.41 (t, *J* = 7.5 Hz, 1H), 7.30 (t, *J* = 8 Hz, 1H), 7.22–7.18 (m, 3H), 4.32 (d,

J = 1.5 Hz, 1H), 4.07 (d, J = 1.5 Hz, 1H), 2.39 (s, 3H). HRMS calcd for $C_{22}H_{18}O_2$ 314.1307, found 314.1306.

4.2.11. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(4-methyl-phenyl) propan-1-one 5k

Yield: 54%; $[\alpha]_D^{22} = -130$ (c 1, CH_2Cl_2) 70% ee; mp 144–150 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.09 (d, J = 8.5 Hz, 2H), 7.70 (d, J = 8.5 Hz, 2H), 7.62 (d, J = 7.5 Hz, 2H), 7.48 (t, J = 8 Hz, 2H), 7.41 (t, J = 7.5 Hz, 1H), 7.28 (d, J = 8 Hz, 2H), 7.23 (d, J = 8 Hz, 2H), 4.31 (d, J = 1.5 Hz, 1H), 4.07 (d, J = 1.5 Hz, 1H), 2.39 (s, 3H). HRMS calcd for $C_{22}H_{18}O_2$ 314.1307, found 314.1304.

4.2.12. *trans*-(+)-2,3-Epoxy-1-(biphen-4-yl)-3-(naphth-1-yl)-propan-1-one 5l

Yield: 59%; $[\alpha]_D^{22} = +75$ (c 1, CH_2Cl_2) 66% ee; mp 143–146 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.16 (d, J = 8.5 Hz, 2H), 8.02 (d, J = 8.5 Hz, 1H), 7.93 (d, J = 7 Hz, 1H), 7.88 (d, J = 8 Hz, 1H), 7.72 (d, J = 8 Hz, 2H), 7.65–7.61 (m, 3H), 7.56–7.50 (m, 2H), 7.48 (t, J = 7.5 Hz, 2H), 7.41 (t, J = 7.5 Hz, 1H), 4.76 (d, J = 3 Hz, 1H), 4.34 (d, J = 3 Hz, 1H). HRMS calcd for $C_{25}H_{18}O_2$ 350.1307, found 350.1305.

4.2.13. *trans*-(−)-2,3-Epoxy-1-(biphen-4-yl)-3-(naphth-2-yl)-propan-1-one 5m

Yield: 56%; $[\alpha]_D^{22} = -129$ (c 1, CH_2Cl_2) 74% ee; mp 178–182 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.11 (d, J = 8 Hz, 2H), 7.90 (d, J = 8.5 Hz, 2H), 7.87 (d, J = 4.5 Hz, 1H), 7.86 (d, J = 4.5 Hz, 1H), 7.71 (d, J = 8 Hz, 2H), 7.61 (d, J = 7.5 Hz, 2H), 7.55–7.50 (m, 2H), 7.49–7.38 (m, 4H), 4.43 (d, J = 1.5 Hz, 1H), 4.28 (d, J = 1.5 Hz, 1H). HRMS calcd for $C_{25}H_{18}O_2$ 350.1307, found 350.1308.

4.2.14. *trans*-(−)-2,3-Epoxy-1,3-di(biphen-4-yl)-4-chlorobutan-1-one 6

Yield: 45% $[\alpha]_D^{22} = -35$ (c 1, CH_2Cl_2) 10% ee; mp 112–114 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 8.00 (d, J = 8.4 Hz, 2H), 7.67 (d, J = 8.4 Hz, 2H), 7.61 (dd, J = 8.1 Hz, 2H), 7.52–7.30 (m, 12H), 4.70 (s, 1H), 4.13 (s, 1H). Anal. Calcd for $C_{28}H_{21}ClO_2$: C, 79.14; H, 4.98; Cl, 8.34. Found: C, 79.10; H, 5.03; Cl, 8.28.

4.2.15. (−)-(2*R*,3′*S*)-3′-Phenyl-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8a

Yield:84%; $[\alpha]_D^{22} = -144$ (c 1, $CHCl_3$) 74%; ^{1}H NMR ($CDCl_3$, 300 MHz), δ 8.12 (d, J = 7.5 Hz, 1H), 7.52 (td, J = 7.5 Hz, 1.2 Hz, 1H), 7.41–7.36 (m, 6H), 7.23 (d, J = 7.5 Hz, 1H), 4.36 (s, 1H), 2.83 (dd, J = 8.4 Hz, 4.2 Hz, 2H), 2.45 (dt, J = 13.5 Hz, 8.4 Hz, 1H), 1.86 (dt, J = 13.5 Hz, 4.2 Hz, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 193.58, 143.35, 134.23, 134.14, 132.69, 128.74, 128.36, 128.32, 127.64, 126.99, 126.63, 64.32, 64.09, 27.34, 25.34. HRMS calcd for $C_{17}H_{14}O_2$ 250.0994, found 250.0991.

4.2.16. *trans*-(−)-3′-(2-Chlorophenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8b

Yield: 84%; $[\alpha]_D^{22} = -15$ (c 1, $CHCl_3$) 36%; mp 132–134 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.14 (d, J = 8 Hz, 1H), 7.53 (td, J = 7.5 Hz, 1 Hz, 1H), 7.46–7.42 (m, 1H), 7.41–7.31 (m, 4H), 7.25 (d, J = 8 Hz, 1H), 4.44 (s, 1H), 3.01 (ddd, J = 16.5 Hz, 7.5 Hz, 4 Hz, 1H), 2.86 (dt, J = 16.5 Hz, 4 Hz, 1H), 2.40 (td, J = 13 Hz, 4.5 Hz, 1H), 1.66 (dt, J = 13 Hz, 4 Hz, 1H). HRMS calcd for $C_{17}H_{13}ClO_2$ 284.0604, found 284.0600.

4.2.17. *trans*-(−)-3′-(3-Chlorophenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8c

Yield: 88%; $[\alpha]_D^{22} = -122$ (c 1, $CHCl_3$) 44% ee; mp 94–97 °C; ^{1}H NMR ($CDCl_3$, 300 MHz), δ 8.11 (d, J = 7.8 Hz, 1H), 7.54 (td, J = 7.5 Hz, 1.2 Hz, 1H), 7.38 (t, J = 7.5 Hz, 2H), 7.36–7.32 (m, 2H), 7.28 (t, J = 5.1 Hz, 1H), 7.24 (d, J = 7.5 Hz, 1H), 4.34 (s, 1H), 2.90–2.81 (m, 2H), 2.44 (ddd, J = 13.8 Hz, 10.8 Hz, 6.3 Hz, 1H), 1.84 (dt, J = 13.5 Hz, 4.5 Hz, 1H). HRMS calcd for $C_{17}H_{13}ClO_2$ 284.0604, found 284.0606.

4.2.18. (−)-(2*R*,3′*S*)-3′-(4-Chlorophenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8d

Yield: 84%; $[\alpha]_D^{22} = -137$ (c 1, $CHCl_3$) 59% ee; mp 138–142 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.11 (d, J = 7.5 Hz, 1H), 7.53 (td, J = 7.5 Hz, 1 Hz, 1H), 7.40–7.35 (m, 3H), 7.32 (d, J = 8.5 Hz, 2H), 7.23 (d, J = 7.5 Hz, 1H), 4.34 (s, 1H), 2.90–2.79 (m, 2H), 2.44 (ddd, J = 13.5 Hz, 8.5 Hz, 5 Hz, 1H), 1.81 (dt, J = 14 Hz, 4.5 Hz, 1H). HRMS calcd for $C_{17}H_{13}ClO_2$ 284.0604, found 284.0603. Crystal data for **8d**: CCDC 867376 contains the supplementary crystallographic data for this structure. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. Absolute configuration crystal data: Rigaku R-AXIS Rapid Diffractometer, Mo Kα radiation, λ = 0.71075 Å, T = 93(2) K, R_1 = 3.57, Rw^2 = 8.92, N = 4640, Friedel Pair Coverage = 100%, Flack parameter:[15] 0.01(4), Hooft parameter:[16] 0.02(1).

4.2.19. *trans*-(−)-3′-(2-Nitrophenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8f

Yield: 71%; $[\alpha]_D^{22} = -83$ (c 1, $CHCl_3$) 54% ee; mp 144–148 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.25 (d, J = 8 Hz, 1H), 8.16 (d, J = 7.5 Hz, 1H), 7.76 (d, J = 4 Hz, 2H), 7.61–7.56 (m, 1H), 7.53 (td, J = 7.5 Hz, 1 Hz, 1H), 7.38 (t, J = 7.5 Hz, 1H), 7.22 (d, J = 7.5 Hz, 1H), 4.75 (s, 1H), 2.86–2.81 (m, 2H), 2.42 (ddd, J = 13.5 Hz, 10 Hz, 7.5 Hz, 1H), 1.63 (dt, J = 13.5 Hz, 4 Hz, 1H). HRMS calcd for $C_{17}H_{13}NO_4$ 295.0845, found 295.0849.

4.2.20. *trans*-(−)-3′-(3-Nitrophenyl)-3,4-dihydro-1*H*-spiro (naphthalene-2,2′-oxiran)-1-one 8g

Yield: 58%; $[\alpha]_D^{22} = -83$ (c 1, $CHCl_3$) 43% ee; mp 147–150 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.27–8.25 (m, 1H), 8.24 (d, J = 8 Hz, 1H), 8.12 (d, J = 7.5 Hz, 1H), 7.74 (d, J = 7.5 Hz, 1H), 7.61 (t, J = 8 Hz, 1H), 7.55 (td, J = 7.5 Hz, 1 Hz, 1H), 7.39 (t, J = 7.5 Hz, 1H), 7.25 (d, J = 7 Hz, 1H), 4.48 (s, 1H), 2.90 (dt, J = 16.5 Hz, 4.5 Hz, 1H), 2.82 (ddd, J = 16.5 Hz, 12 Hz, 4.5 Hz, 1H), 2.47 (ddd, J = 13.5 Hz, 12 Hz, 4.5 Hz, 1H), 1.80 (dt, J = 13.5 Hz, 4.5 Hz, 1H). HRMS calcd for $C_{17}H_{13}NO_4$ 295.0845, found 295.0844.

4.2.21. *trans*-(−)-3′-(4-Nitrophenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8h

Yield: 51%; $[\alpha]_D^{22} = -145$ (c 0.5, $CHCl_3$) 75% ee; mp 192–195 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.28 (d, J = 8.5 Hz, 2H), 8.12 (d, J = 7.5 Hz, 1H), 7.58 (d, J = 8.5 Hz, 2H), 7.55 (td, J = 7.5 Hz, 1 Hz, 1H), 7.40 (t, J = 7.5 Hz, 1H), 7.25 (d, J = 7.5 Hz, 1H), 4.47 (s, 1H), 2.90 (dt, J = 16.5 Hz, 4.5 Hz, 1H), 2.80 (ddd, J = 16.5 Hz, 12 Hz, 4.5 Hz, 1H), 2.47 (ddd, J = 13.5 Hz, 12 Hz, 4.5 Hz, 1H), 1.80 (dt, J = 13.5 Hz, 4.5 Hz, 1H). HRMS calcd for $C_{17}H_{13}NO_4$ 295.0845, found 295.0847.

4.2.22. *trans*-(−)-3′-(2-Methylphenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8i

Yield: 83%; $[\alpha]_D^{22} = -32$ (c 1, $CHCl_3$) 40% ee; mp 114–116 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.14 (d, J = 7.5 Hz, 1H), 7.54 (td, J = 7.5 Hz, 1.5 Hz, 1H), 7.38 (t, J = 7.5 Hz, 1H), 7.36 (dd, J = 7.5 Hz, 2.5 Hz, 1H), 7.28–7.22 (m, 3H), 7.20–7.16 (m, 1H), 4.36 (s, 1H), 2.87 (td, J = 16.5 Hz, 4.5 Hz, 1H), 2.82 (dd, J = 12 Hz, 4.5 Hz, 1H), 2.38 (ddd, J = 16.5 Hz, 12 Hz, 5 Hz, 1H), 2.25 (s, 3H), 1.74 (dt, J = 13.5 Hz, 4.5 Hz, 1H). HRMS calcd for $C_{18}H_{16}O_2$ 264.1150, found 264.1147.

4.2.23. *trans*-(−)-3′-(3-Methylphenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8j

Yield: 83%; $[\alpha]_D^{22} = -142$ (c 1, $CHCl_3$) 65% ee; mp 96–98 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.12 (d, J = 7.5 Hz, 1H), 7.52 (td, J = 7.5 Hz, 1 Hz, 1H), 7.37 (t, J = 7.5 Hz, 1H), 7.27 (t, J = 7.5 Hz, 1H),

7.22 (d, J = 7.5 Hz, 1H), 7.20–7.15 (m, 3H), 4.33 (s, 1H), 2.84 (dd, J = 8.5 Hz, 4 Hz, 2H), 2.44 (dt, J = 13.5 Hz, 8.5 Hz, 1H), 2.38 (s, 3H), 1.88 (dt, J = 13.5 Hz, 4 Hz, 1H). HRMS calcd for $C_{18}H_{16}O_2$ 264.1150, found 264.1154.

4.2.24. *trans*-(−)-3′-(4-Methylphenyl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8k

Yield: 65%; $[\alpha]_D^{22} = -133$ (c 1, $CHCl_3$) 55% ee; mp 165–169 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.11 (d, J = 8 Hz, 1H), 7.51 (td, J = 7.5 Hz, 1.5 Hz, 1H), 7.36 (t, J = 8 Hz, 1H), 7.26 (d, J = 7.5 Hz, 2H), 7.22 (d, J = 8 Hz, 1H), 7.19 (d, J = 7.5 Hz, 2H), 4.33 (s, 1H), 2.83 (dd, J = 8.5 Hz, 4 Hz, 2H), 2.44 (dt, J = 13.5 Hz, 8.5 Hz, 1H), 2.38 (s, 3H), 1.86 (dt, J = 13.5 Hz, 4 Hz, 1H). HRMS calcd for $C_{18}H_{16}O_2$ 264.1150, found 264.1151.

4.2.25. *trans*-(+)-3′-(Naphth-1-yl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8l

Yield: 90%; $[\alpha]_D^{22} = +36$ (c 1, $CHCl_3$) 32% ee; mp 120–121 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.21 (d, J = 7.5 Hz, 1H), 7.91 (d, J = 8 Hz, 1H), 7.87 (d, J = 8.5 Hz, 1H), 7.79 (d, J = 8.5 Hz, 1H), 7.61 (d, J = 7 Hz, 1H), 7.56–7.49 (m, 3H), 7.44 (td, J = 8 Hz, 1 Hz, 1H), 7.41 (t, J = 7.5 Hz, 1H), 7.18 (d, J = 7.5 Hz, 1H), 4.86 (s, 1H), 2.78–2.65 (m, 2H), 2.38 (ddd, J = 13.5 Hz, 12 Hz, 6 Hz, 1H), 1.70 (dt, J = 13.5 Hz, 4 Hz, 1H). HRMS calcd for $C_{21}H_{16}O_2$ 300.1150, found 300.1154.

4.2.26. (−)-(2*R*,3′*S*)-3′-(Naphth-2-yl)-3,4-dihydro-1*H*-spiro-(naphthalene-2,2′-oxiran)-1-one 8m

Yield: 77%; $[\alpha]_D^{22} = -225$ (c 1, $CHCl_3$) 59% ee; mp 139–140 °C; ^{1}H NMR ($CDCl_3$, 500 MHz), δ 8.15 (dd, J = 8 Hz, 1 Hz, 1H), 7.89–7.84 (m, 4H), 7.55–7.49 (m, 3H), 7.48 (dd, J = 7.5 Hz, 1.5 Hz, 1H), 7.38 (t, J = 7.5 Hz, 1H), 7.21 (d, J = 7.5 Hz, 1H), 4.52 (s, 1H), 2.82–2.78 (m, 2H), 2.48 (ddd, J = 13.5 Hz, 10.5 Hz, 8 Hz, 1H), 1.90 (dt, J = 13.5 Hz, 4.5 Hz, 1H). HRMS calcd for $C_{21}H_{16}O_2$ 300.1150, found 300.1148. Crystal data for **8m**: CCDC 867377 contains the supplementary crystallographic data for this structure. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif. *Absolute configuration crystal data*: Rigaku R-AXIS Rapid Diffractometer, Cu Kα radiation, λ = 1.54187 Å, T = 93(2) K, R_1 = 6.86, Rw^2 = 19.06, N = 2306, Friedel Pair Coverage = 96%, Flack parameter:[15] −0.1(6), Hooft parameter:[16] 0.1(1).

4.2.27. *trans*-(−)-3′-Phenylspiro(inden-2,2′-oxiran)-1(3*H*)-one 10a

Yield: 59%; $[\alpha]_D^{22} = -246$ (c 1, $CHCl_3$) 65% ee; mp 152–154 °C (Lit. 95–96 °C);[17] ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.85 (d, J = 7.5 Hz, 1H), 7.62 (td, J = 7.5 Hz, 1.2 Hz, 1H), 7.46–7.30 (m, 7H), 4.48 (s, 1H), 3.26 (d, J = 18.3 Hz, 1H), 2.94 (d, J = 18.3 Hz, 1H). ^{13}C NMR ($CDCl_3$, 75 MHz) δ 199.53, 151.12, 135.81, 135.60, 134.65, 128.63, 128.52, 127.97, 126.66, 126.46, 124.11, 67.15, 63.06, 29.05. HRMS calcd for $C_{16}H_{12}O_2$ 236.0837, found 236.0833.

4.2.28. *trans*-(−)-3′-(2-Chlorophenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10b

Yield: 52%; $[\alpha]_D^{22} = -31$ (c 1, $CHCl_3$) 85% ee; mp 160–164 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.87 (d, J = 7.5 Hz, 1H), 7.63 (td, J = 7.5 Hz, 1 Hz, 1H), 7.47–7.29 (m, 6H), 4.68 (s, 1H), 3.11 (d, J = 18 Hz, 1H), 2.80 (d, J = 18 Hz, 1H). HRMS calcd for $C_{16}H_{11}ClO_2$ 270.0448, found 270.0443.

4.2.29. *trans*-(−)-3′-(3-Chlorophenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10c

Yield: 74%; $[\alpha]_D^{22} = -229$ (c 1, $CHCl_3$) 59% ee; mp 120–124 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.85 (d, J = 7.5 Hz, 1H), 7.64 (td, J = 7.5 Hz, 1 Hz, 1H), 7.46–7.41 (m, 2H), 7.35–7.33 (m, 2H), 7.33–7.31 (m, 1H), 7.24–7.21 (m, 1H), 4.45 (s, 1H), 3.26 (d, J = 18 Hz, 1H), 2.93 (d, J = 18 Hz, 1H). HRMS calcd for $C_{16}H_{11}ClO_2$ 270.0448, found 270.0450.

4.2.30. *trans*-(−)-3′-(4-Chlorophenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10d

Yield: 48%; $[\alpha]_D^{22} = -140$ (c 1, $CHCl_3$) 37% ee; mp 162–164 °C; (Lit. mp 168–169 °C)[17] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.85 (d, J = 7.5 Hz, 1H), 7.63 (td, J = 7.5 Hz, 1 Hz, 1H), 7.46–7.39 (m, 2H), 7.36 (d, J = 8 Hz, 2H), 7.27 (d, J = 8 Hz, 2H), 4.46 (s, 1H), 3.24 (d, J = 18 Hz, 1H), 2.91 (d, J = 18 Hz, 1H). HRMS calcd for $C_{16}H_{11}ClO_2$ 270.0448, found 270.0444.

4.2.31. *trans*-(−)-3′-(2-Nitrophenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10f

Yield: 36%; $[\alpha]_D^{22} = -69$ (c 1, $CHCl_3$) 20% ee; mp 136–140 °C; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 8.22 (d, J = 8.1 Hz, 1H), 7.89 (d, J = 7.8 Hz, 1H), 7.79–7.74 (m, 2H), 7.62 (td, J = 7.5 Hz, 1.2 Hz, 1H), 7.62–7.54 (m, 1H), 7.45 (t, J = 7.5 Hz, 1H), 7.36 (d, J = 7.5 Hz, 1H), 4.91 (s, 1H), 3.10 (d, J = 18 Hz, 1H), 2.72 (d, J = 18 Hz, 1H). HRMS calcd for $C_{16}H_{11}NO_4$ 281.0688, found 281.0690.

4.2.32. *trans*-(−)-3′-(3-Nitrophenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10g

Yield: 18%; $[\alpha]_D^{22} = -152$ (c 1, $CHCl_3$) 62% ee; mp 176–180 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.27–8.21 (m, 2H), 7.87 (d, J = 7.5 Hz, 1H), 7.69 (d, J = 7.5 Hz, 1H), 7.65 (t, J = 8 Hz, 1H), 7.61 (t, J = 8 Hz, 1H), 7.46 (t, J = 7.5 Hz, 1H), 7.42 (d, J = 7.5 Hz, 1H), 4.58 (s, 1H), 3.31 (d, J = 18 Hz, 1H), 2.88 (d, J = 18 Hz, 1H). HRMS calcd for $C_{16}H_{11}NO_4$ 281.0688, found 281.0693.

4.2.33. *trans*-3′-(4-Nitrophenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10h

Yield: 18%; $[\alpha]_D^{22} = 0$ (c 1, $CHCl_3$) racemic; mp 204–206 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 8.28 (d, J = 8.5 Hz, 2H), 7.87 (d, J = 7.5 Hz, 1H), 7.66 (td, J = 7.5 Hz, 1 Hz, 1H), 7.53 (d, J = 8.5 Hz, 2H), 7.46 (t, J = 7.5 Hz, 1H), 7.42 (d, J = 8 Hz, 1H), 4.58 (s, 1H), 3.27 (d, J = 18 Hz, 1H), 2.87 (d, J = 18 Hz, 1H). HRMS calcd for $C_{16}H_{11}NO_4$ 281.0688, found 281.0689.

4.2.34. *trans*-(−)-3′-(2-Methylphenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10i

Yield: 84%; $[\alpha]_D^{22} = -104$ (c 1, $CHCl_3$) 49% ee; mp 112–114 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.86 (d, J = 7.5 Hz, 1H), 7.62 (td, J = 7 Hz, 1 Hz, 1H), 7.44 (t, J = 7.5 Hz, 1H), 7.38 (d, J = 7.5 Hz, 1H), 7.35–7.32 (m, 1H), 7.28–7.26 (m, 2H), 7.19–7.15 (m, 1H), 4.54 (s, 1H), 3.12 (d, J = 18 Hz, 1H), 2.76 (d, J = 18 Hz, 1H), 2.19 (s, 3H). HRMS calcd for $C_{17}H_{14}O_2$ 250.0994, found 250.0997.

4.2.35. *trans*-(−)-3′-(3-Methylphenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10j

Yield: 72%; $[\alpha]_D^{22} = -233$ (c 1, $CHCl_3$) 63% ee; mp 110–112 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.84 (d, J = 7.5 Hz, 1H), 7.62 (td, J = 7.5 Hz, 1 Hz, 1H), 7.45–7.38 (m, 2H), 7.29 (t, J = 7.5 Hz, 1H), 7.17 (d, J = 7.5 Hz, 1H), 7.15–7.11 (m, 2H), 4.45 (s, 1H), 3.25 (d, J = 18 Hz, 1H), 2.95 (d, J = 18 Hz, 1H), 2.38 (s, 3H). HRMS calcd for $C_{17}H_{14}O_2$ 250.0994, found 250.0993.

4.2.36. *trans*-(−)-3′-(4-Methylphenyl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10k

Yield: 76%; $[\alpha]_D^{22} = -240$ (c 1, $CHCl_3$) 58% ee; mp 102–104 °C (lit. 116–118 °C);[17] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.84 (d, J = 7.5 Hz, 1H), 7.61 (td, J = 7.5 Hz, 1 Hz, 1H), 7.45–7.37 (m, 2H), 7.22–7.20 (m, 4H), 4.45 (s, 1H), 3.24 (d, J = 18 Hz, 1H), 2.95 (d, J = 18 Hz, 1H), 2.38 (s, 3H). HRMS calcd for $C_{17}H_{14}O_2$ 250.0994, found 250.0991.

4.2.37. *trans*-(−)-3′-(Naphth-1-yl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10l

Yield: 20%; $[\alpha]_D^{22} = -29$ (*c* 1, $CHCl_3$) 47% ee; mp 128–130 °C; ^1H NMR ($CDCl_3$, 500 MHz) δ 7.93–7.89 (m, 2H), 7.87 (d, *J* = 8 Hz, 1H), 7.76 (d, *J* = 8.5 Hz, 1H), 7.59 (t, *J* = 7.5 Hz, 2H), 7.54 (t, *J* = 7.5 Hz, 1H), 7.50 (t, *J* = 7.5 Hz, 1H), 7.46–7.41 (m, 2H), 7.29 (d, *J* = 7.5 Hz, 1H), 5.05 (s, 1H), 3.12 (d, *J* = 18.5 Hz, 1H), 2.72 (d, *J* = 18.5 Hz, 1H). HRMS calcd for $C_{20}H_{14}O_2$ 286.0994, found 286.0999.

4.2.38. *trans*-(−)-3′-(Naphth-2-yl)spiro(inden-2,2′-oxiran)-1(3*H*)-one 10m

Yield: 25%; $[\alpha]_D^{22} = -72$ (*c* 1, $CHCl_3$) 15% ee; mp 152–154 °C; ^1H NMR ($CDCl_3$, 500 MHz) δ 7.88 (d, *J* = 8 Hz, 1H), 7.88–7.84 (m, 3H), 7.84–7.82 (m, 1H), 7.61 (td, *J* = 7.5 Hz, 1 Hz, 1H), 7.55–7.49 (m, 2H), 7.45–7.40 (m, 2H), 7.36 (d, *J* = 8 Hz, 1H), 4.65 (s, 1H), 3.31 (d, *J* = 18.5 Hz, 1H), 2.95 (d, *J* = 18.5 Hz, 1H). HRMS calcd for $C_{20}H_{14}O_2$ 286.0994, found 286.0992.

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