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Enantioenriched (*S*)-6,6′-diphenylBinol-Ca: a novel and efficient chirally modified metal complex for asymmetric epoxidation of α,β-unsaturated enones

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Abstract—A novel enantioenriched-Ca complex was generated using low cost commercially available $CaCl_2$ and the potassium salt of (*S*)-6,6′-diphenylBINOL and its application to α,β-unsaturated enone epoxidation is described. Furthermore the absolute stereochemistry of (*S*)-6,6′-diphenylBINOL has been corrected and unequivocally established by single crystal X-ray analysis, 500 MHz NMR spectroscopy and mass spectra. The enantiomeric excess (ee) was determined by ^{1}H NMR spectroscopy of its corresponding MTPA ester and was found to be >98%.

1. Introduction

Asymmetric epoxidation of α,β-unsaturated enones is a powerful strategy for the synthesis of enantiomerically enriched organic compounds.[1] Early studies by Wynberg revealed that catalytic amount of cinchona alkaloids of quaternary ammonium salts could effect the epoxidation of α,β-unsaturated ketones with moderate enantioselectivity.[2] Following this report, a variety of methods have been developed[3] for this reaction including the use of biphasic system using hydrogen peroxide in the presence of polyaminoacids.[4] Impressive practical methods developed recently for this transformation include (a) stoichiometric diethylzinc-*N*-methylpseudoephedrine using molecular oxygen;[5] (b) chirally modified magnesium–diethyltartrate with *tert*-butylhydroperoxide;[6] (c) lanthanoid-BINOL derivatives using *tert*-butylhydroperoxide or cumene hydroperoxide[7] and triphenylphosphine oxide as synergistic additive.[8]

2. Results and discussion

Recently, we described the first Lewis acid-Bronsted base BINOL-Ca complex for the promotion of the Michael reaction.[9] Further, we envisioned examining the BINOL-Ca complex for the asymmetric epoxidation of α,β-unsaturated ketones. Herein, we report our results on the asymmetric epoxidation of substituted chalcones using the 6,6′-diphenylBINOL–Ca complex and alkylhydroperoxides. Initially we chose chalcone **5a** as the substrate and BINOL-Ca (*S*)-**2a** (10 mol%) complex. The complexes (*S*)-**2a**–**g** were generated from potassium salt of the corresponding alcohols (*S*)-**1a**–**g** and $CaCl_2$ in absolute ethanol as shown in Scheme 1.

The epoxidation reaction was carried out in toluene at −10°C using *tert*-butylhydroperoxide in the presence of activated MS 4 Å. The product **6a** was obtained in 88% yield with moderate enantioselectivity (55%) after 48 h (Scheme 2).

Introduction of substituents on the BINOL (i.e. 3-position and 6,6′-position) has been shown to have profound effects not only on the activity but also on the enantioselectivities of the product **6a**.[10] En route to the synthesis of substituted BINOL ligands, we have initiated the synthesis of (*S*)-6,6′-diphenylBINOL (*S*)-**1d** following the Qian et al., procedure.[11] We were able to produce the ligand in good yield, the absolute configuration of **4** {$[\alpha]_D^{25}=+100$ (*c* 1, $CHCl_3$); lit.[11] −89.6 (*c* 0.67, $CHCl_3$)} and the specific rotation of (*S*)-**1d**

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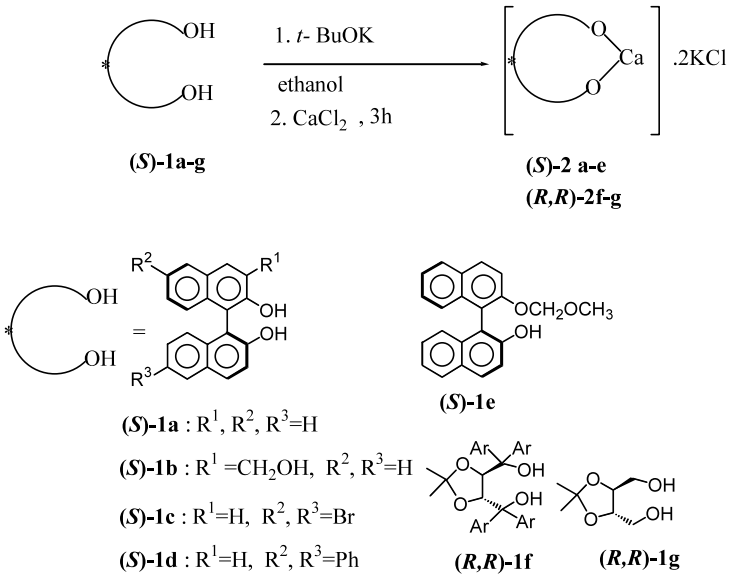
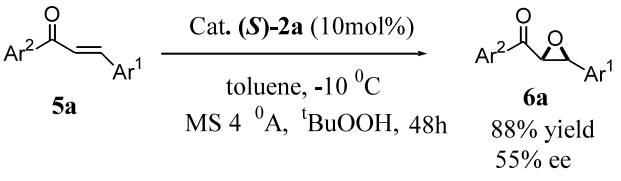


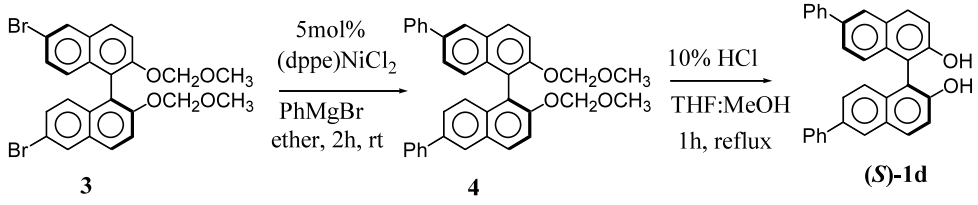
Scheme 1.



Scheme 2.

$\{[\alpha]_D^{25} = +215$ (c 1, $CHCl_3$); lit.[11] -19.5 (c 1.3, $CHCl_3$)$\}$ did not match with those reported in the literature. Surprisingly, [1,2-bis(diphenylphosphino)ethane]dichloronickel(II) (dppe)$NiCl_2$ as a catalyst exhibits remarkable activity for the transformation of **3** to **4** over bis[triphenylphosphino]dichloronickel(II) $Ni[P(C_6H_5)_3]_2Cl_2$. The above transformation using 5 mol% of $Ni[P(C_6H_5)_3]_2Cl_2$ as catalyst needs the reaction to be refluxed for 22 h in ether whereas, with 5 mol% of (dppe)$NiCl_2$ as catalyst the reaction proceeded at ambient temperature in only 2 h (Scheme 3). Our experiments on arylation with (dppe)$NiCl_2$ or $Ni[P(C_6H_5)_3]_2Cl_2$ as catalyst resulted in the product **4** with identical absolute configuration which was contrary to the original report.[11,12] Furthermore, single crystal X-ray analysis, 500 MHz NMR and mass spectral data have unequivocally established the structure of the product as (*S*)-**1d** (Fig. 1). This is the first attempt to resolve the crystal structure of this compound. The dihedral angle between the naphthalene rings (C8–C12 and C15–C23) is 84.4°, which is larger than that of BINOL (82°). The enantiomeric purity of (*S*)-**1d** was determined by ^1H NMR spectroscopy of its corresponding MTPA monoester and was found to be >98%.

In an effort to increase the enantioselectivity of the product **6a**, a range of substituted BINOL catalyst (*S*)-**2b–e** and C_2-symmetric ligands (*R*,*R*)-**2f–g** were screened. As expected, a remarkable improvement in enantioselectivity was observed with (*S*)-**2d** (70% *ee*, 85% yield) over (*S*)-**2a** (55% *ee*, 88% yield).[10] The increase in enantioselectivity by (*S*)-**2d** catalyst is not only due to the electronic effect of 6,6′-arylsubstitution as predicted by de Vries et al.,[10] but also due to the increase in bond angle between two naphthyl rings, which may provide favorable coordination environment at metal-ligand site. The catalysts (*S*)-**2b** and (*S*)-**2e** possessing strong coordinating groups at the reaction site showed substantial decreases in enantioselectivity {(*S*)-**2b**; 10% *ee*, 70% yield and (*S*)-**2e**; 5% *ee*, 89% yield}. This is in sharp contrast to the lanthanoid based catalyst wherein hydroxymethyl group substituted at 3-position of BINOL strongly influenced the enantioselectivity of the product **6a**.[7a] 6,6′-Bromosubstituted catalyst (*S*)-**2c** also gave the product with low stereoselectivity (40% *ee*, 60% yield). C_2-Symmetric cat-



Scheme 3.

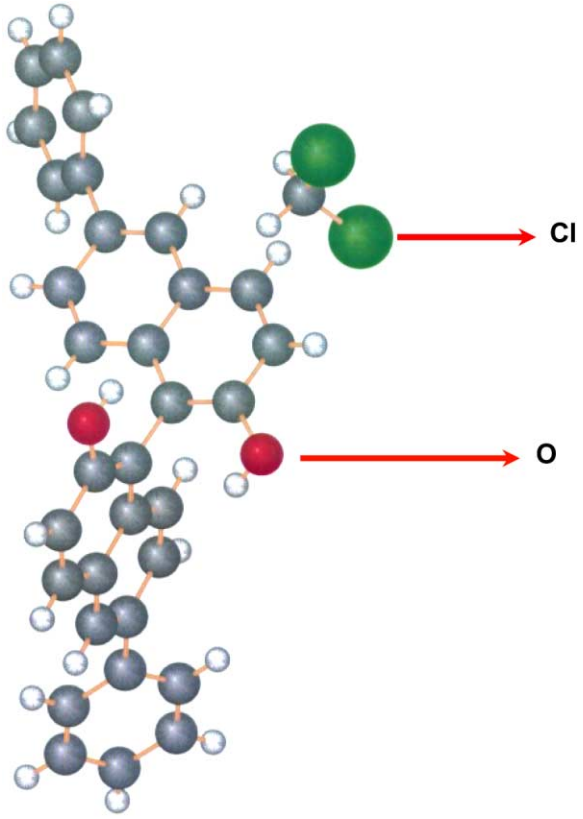


Figure 1. X-Ray crystal structure of *S*-6,6′-diphenyl-1,1′-bi-2-naphthol. A suitable crystal of X-ray crystallography was grown on slow evaporation of a mixture of hexane and dichloromethane solvent. The crystal structure showed a molecule of dichloromethane. Crystal data: $C_{36}H_{30}O_4.CH_2Cl_2$, $M=523.00$, orthorhombic, $a=8.841(1)$, $b=10.051(1)$, $c=29.202(2)$ A°, $U=2594.7(4)$, $T=173$ K, space group $P2_12_12_1$ (no. 19), $Z=4$, μ(Mo-Kα)$=0.28$ mm^{-1}, 16453 reflections measured, 6022 unique ($R_{int}=0.0181$), $WR(F^2)=0.1659$, $S=1.043$, $R_1=0.0558$ for 5425, $F_o>4\sigma(F_o)$, 0.0612 for all 6.022 data. Crystal and atomic data may be obtained free of charge from The Director CCDC, 12 Union Road, Cambridge CB2 1EZ, UK, on quoting the deposition number CCDC 209446, the names of the authors and the journal citation (fax: +44-1223-336-033; e-mail: deposit@ccdc.cam.ac.uk; web site: http://www.ccdc.cam.ac.uk). Method used for absolute configuration: Flack HD, *Acta cryst*. **1983**, *39*, 876–881.

alysts (*R*,*R*)-**2f** and (*R*,*R*)-**2g** gave excellent yields of product **6a** but almost negligible *ee*s (6% *ee*, 88% yield, and 2% *ee*, 95% yield, respectively). Addition of additives such as triphenylphosphine oxide lowered the enantioselectivity of product **6a** (20% *ee*). In marked contrast to our previous report,[9] ethanol as additive has a detrimental effect on the epoxidation of **6a** (45% *ee*, 40% yield). Water as additive gave racemic product with 95% yield.

Next, we investigated the effect of solvents and found that the coordinating solvents such as THF, DMF, DME showed deleterious effects on the enantioselectivity of the product. The best choice of solvent appeared to be toluene:cyclohexane (1:9) mixture. The optimum temperature range was found to be −5 to −10°C. In line with previous reports,[7a] activated MS 4 Å (260–280°C/10 mmHg, 3 h) is essential for the initiation of the reaction. Although satisfactory yields were obtained with as less as 5 mol% of catalyst (5 mol% of (*S*)-**2d**; 60% *ee*), good levels of enantiomeric excess was achieved with 10 mol% catalyst.[13] The catalyst prepared from (*S*)-**1d** and various CaX_2 (X= OTf, F, Br) were also evaluated for **5a** to **6a** and found to be inferior to $CaCl_2$.[14] No significant change in enantioselectivity of the product 6a was observed on varying the $CaCl_2$ ratio to ligand (*S*)-**1d** (1:1 mol equivalent $CaCl_2$: (*S*)-**1d**=68% *ee*, 80% yield; 2:1 mol equivalent $CaCl_2$: (*S*)-**1d**=66% *ee*, 78% yield). On the other hand, variation in ligand to $CaCl_2$ showed detrimental effect on enantioselectivity of product **6a** (2:1 mol equivalent of (*S*)-**1d**: $CaCl_2$=10% *ee*, 70% yield). We then sought to explore the generality of the process using 10 mol% of complex (*S*)-**2d** to a range of enone substrates (Table 1).

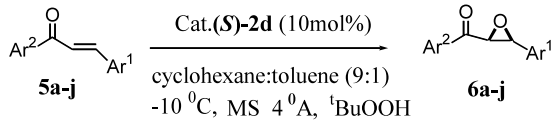
The results obtained show that, the catalyst tolerates a variety of substituents on the phenyl group. Simple enone substrates like chalcone (entry 1), phenyl group bearing substituents like chloro and methyl lead to moderate to good *ee*s with good product yield (entries 2 and 3). Strong coordinating groups substituted at 2-position of phenacyl gave very high yield of the product but drastically decreased the enantioselectivity (entries 7 and 8). 2-Naphthylketo enone also epoxidized under standard condition with moderate enantioselectivity (entry 4).

The precise nature of the catalyst structure of (*S*)-**2d** is presently not known, however, we believe that the oligomeric structure of (*S*)-**2d** appears to be responsible for the observed enantioselectivity as predicted by Shibasaki et al.[7a] The catalyst prepared from 1 equiv. of each (*S*)-**1d** and $CaCl_2$ gave MALDI-TOF spectrum that exhibits a major peak at m/z 1429 and minor peak at m/z 1906, indicating the possible existence of trimeric (A) and tetrameric oligomers. Activation by hydroperoxide can generate monomeric-Ca hydroperoxide (B) from oligomers. These chirally modified Ca-hydroperoxide in turn controls the orientation of the enone which when followed by oxygen transfer (C) leads to the observed enantioselectivity of the product as shown in Scheme 4.

3. Conclusion

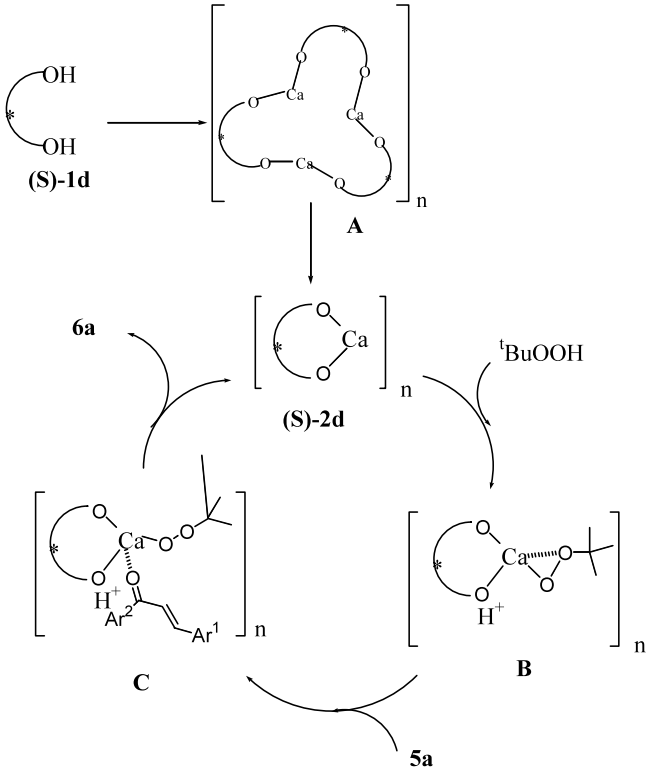
In conclusion, we have developed a simple and practical method for the enantioselective epoxidation of α,β-unsaturated ketones using low cost commercially available eco-friendly $CaCl_2$ as the metal source. To the best of our knowledge, it is for the first time that chirally modified Ca has been used for epoxidation.[15]

Table 1. Enantioenriched (*S*)-6,6′-diphenylBINOL-Ca catalyzed epoxidation of α,β-unsaturated enones[a]



Entry	Ar^1	Ar^2	Product[b]	Temp. (°C)	Time (h)	%ee[c]	Config.[d]	% Yield[e]
1	Ph	Ph	**6a**	−10	48	70	(2*R*,3*S*)	85
2	*p*-ClPh	Ph	**6b**	−15	48	74	(2*R*,3*S*)	91
3	*p*-MePh	Ph	**6c**	−10	48	80	(2*R*,3*S*)	78
4	Ph	2-Naphthyl	**6d**	0	58	73	(2*R*,3*S*)	72
5	Ph	*p*-MePh	**6e**	5	48	62	(2*R*,3*S*)	68
6	*m*-PhO-Ph	Ph	**6f**	0	48	74		82
7	Ph	*o*-NH_2Ph	**6g**	0	48	26		60
8	Ph	*o*-MeO-Ph	**6h**	0	48	22	(2*R*,3*S*)	70
9	1-Naphthyl	Ph	**6i**	0	52	25	(2*R*,3*S*)	76
10	Ph	*p*-BrPh	**6j**	−15	48	32		82

[a] Unless otherwise stated, all reactions were conducted using 2.5 mmol substrate, 3.75 mmol of TBHP (3.2 M in toluene), MS 4 Å powder (750 mg, activated at 260–280°C/10 mmHg, 3 h).
[b] Characterized by NMR, mass.
[c] The ee was determined by HPLC using Chiralpak AD-H column.
[d] The sign of optical rotation of products[10] determined the absolute configurations.
[e] Isolated yields.



Scheme 4.

4. Experimental

All reactions were carried out under an inert atmosphere of dry nitrogen and were followed by TLC. Glassware was flame dried before use. Standard syringe techniques were applied to transfer dry solvents and reagents. ^1H and ^{13}C NMR spectra were recorded on a Varian 200, 500 spectrometer. Chemical shifts (a) are given in ppm and are referenced to residual solvent peaks. Mass spectra and accurate mass measurement were carried out with a VG MICROMASS instrument. Elemental analyses were performed on an Elementar Vario EL spectrometer. Optical rotations were recorded on a Perkin–Elmer 341 polarimeter in a 10 cm cell. Melting points were measured on a BUCHI Melting Point machine. HPLC analyses were performed using a SHIMADZU LC-10AT VP Model SPD-10AVP 486 UV detector. THF and Ether were freshly distilled from sodium/benzophenone ketyl, while toluene, heptane were distilled from CaH_2. All other chemicals were used as received.

4.1. A typical procedure for the asymmetric epoxidation of enone, 6a

A mixture of (*S*)-6,6-diphenylBINOL (98.5 mg, 0.224 mmol), pot.*t*-butoxide (50.4 mg, 0.449 mmol) in absolute ethanol (6 ml) was stirred under argon for 0.5 h. The ethanol was evaporated under reduced pressure and to the residue, solid $CaCl_2$ (99%) (24.9 mg, 0.224 mmol) was added. Then the combined components were dried under vacuum (10 mmHg, 15 min) followed by the addition of absolute ethanol (6 ml) to give a white suspension. After being stirred for 3 h at ambient temperature, ethanol was evaporated under reduced pressure to give a white solid powder. To this solid complex, cyclohexane (10 ml) and toluene (1 ml) were added sequentially and allowed to stir for 3 h. Then MS 4 Å powder (750 mg, activated at 260–280°C/10 mmHg, 3 h) was added, the reaction mixture was cooled to −10°C followed by the addition of TBHP (1.12 ml, 3.75 mmol, 3.3 M solution in toluene). After 15 min, a toluene solution of chalcone **5a** (520 mg, 2.5

mmol) 1 ml was added and the reaction mixture was maintained at −10°C for 48 h. The reaction mixture was quenched with saturated NH_4Cl solution (15 ml) and extracted with ethylacetate (3×20 ml). The combined organic layers were dried over anhydrous Na_2SO_4 and evaporated under reduced pressure. The residue was purified by column chromatography (SiO_2, hexane/acetone, 25/2) to give epoxy ketone **6a** (476 mg), as a solid (85%).

4.2. *trans*-(2*R*,3*S*)-Epoxy-1,3-diphenylpropan-1-one, 6a

Mp = 89–91°C; Enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 97:3); t_r = 17.98 min, (2*R*,3*S* minor), t_r = 18.73 min, (2*S*,3*R* major); $[\alpha]_D^{25}$ = −188 (*c* 1, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 4.09 (d, 1H, *J* = 1.96 Hz), 4.18 (d, 1H, *J* = 1.96 Hz), 7.22–7.52 (m, 7H), 7.58–7.65 (m,1H), 8.01–8.03 (m, 2H); EIMS 224 (M^+).

4.3. *trans*-(2*R*,3*S*)-Epoxy-3-(4-chlorophenyl)-1-phenylpropan-1-one, 6b

Yield: 91% (588 mg); mp = 68–70°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 97:3); t_r = 18.67 min, (2*R*,3*S* minor), t_r = 20.48 min (2*S*,3*R* major); $[\alpha]_D^{25}$ = −172 (*c* 1, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 4.06 (d, 1H, *J* = 1.8 Hz), 4.19 (d, 1H, *J* = 1.8 Hz), 7.25–7.68 (m, 7H), 7.97–8.08 (m, 2H); EIMS 258 (M^+).

4.4. *trans*-(2*R*,3*S*)-Epoxy-3-(4-methylphenyl)-1-phenylpropan-1-one, 6c

Yield: 78% (464.1 mg); mp = 89–91°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 95:5); t_r = 17.48 min (2*R*,3*S* minor), t_r = 18.11 min (2*S*,3*R* major); $[\alpha]_D^{25}$ = −190 (*c* 1, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 2.39 (s, 3H), 4.01 (d, 1H, *J* = 1.85 Hz), 4.19 (d, 1H, *J* = 1.85 Hz), 7.16–7.29 (m, 4H), 7.42–7.51 (m, 2H), 7.56–7.62 (m, 1H), 8.01–8.03 (m, 2H); EIMS 238 (M^+).

4.5. *trans*-(2*R*,3*S*)-Epoxy-3-phenyl-1-(2-naphthyl)-propan-1-one, 6d

Yield: 72% (493.2 mg); mp = 110–112°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 97:3); t_r = 22.69 min (2*R*,3*S* major), t_r = 24.12 min (2*S*,3*R* minor); $[\alpha]_D^{25}$ = −100 (*c* 1, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 4.15 (d, 1H, *J* = 2.0 Hz), 4.36 (d, 1H, *J* = 2.0 Hz), 7.32–7.65 (m, 6H), 7.81–7.96 (m, 4H), 8.01–8.12 (d, 1H, *J* = 8.10 Hz), 8.58 (s, 1H); EIMS 274 (M^+).

4.6. *trans*-(2*R*,3*S*)-Epoxy-3-phenyl-1-(4-methylphenyl)-propan-1-one, 6e

Yield: 68% (404.6 mg); mp = 60–62°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 95:5); t_r = 18.40 min (2*R*,3*S* minor), t_r = 19.23 min (2*S*,3*R* major); $[\alpha]_D^{25}$ = −141 (*c* 1, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 2.41 (s, 3H), 4.05 (d, 1H, *J* = 1.8 Hz), 4.20 (d, 1H, *J* = 1.8 Hz), 7.2–7.24 (d, 2H, *J* = 8.2 Hz), 7.30–7.38 (m, 5H), 7.82–7.92 (m, 2H); EIMS 238 (M^+).

4.7. *trans*-2,3-Epoxy-3-(3-phenoxyphenyl)-1-phenylpropan-1-one, 6f

Yield: 82% (647.8 mg); enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 95:5); t_r = 17.95 min (2*R*,3*S* major), t_r = 21.15 min (2*S*,3*R* minor); mp = 74–76°C; $[\alpha]_D^{25}$ = −133 (*c* 1, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 4.02 (d, 1H, *J* = 1.92 Hz), 4.16 (d, 1H, *J* = 1.92 Hz), 6.92–7.18 (m, 6H), 7.27–7.62 (m, 6H), 7.95–8.05 (d, 2H, *J* = 8.00 Hz); EIMS 298 (M^+).

4.8. *trans*-2,3-Epoxy-3-phenyl-1-(2-aminophenyl)-propan-1-one, 6g

Yield: 60% (358.5 mg); mp = 124–126°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 95:5); t_r = 17.45 min (minor), t_r = 18.45 min (major); $[\alpha]_D^{25}$ = −162 (*c* 1, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 4.02 (d, 1H, *J* = 2.00 Hz), 4.21 (d, 1H, *J* = 2.00 Hz), 6.30 (bs, 2H), 6.57–6.72 (m, 2H), 7.22–7.40 (m, 6H), 7.69–7.75 (d, 1H, *J* = 8.00 Hz); EIMS 239 (M^+).

4.9. *trans*-(2*R*,3*S*)-Epoxy-3-phenyl-1-(2-methoxyphenyl)-propan-1-one, 6h

Yield: 70% (444.5 mg); mp = 122–124°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 95:5); t_r = 17.89 min (2*R*,3*S* minor), t_r = 18.52 min (*2S*,*3R* major); $[\alpha]_D^{25}$ = −30 (*c* 1, CH_2Cl_2); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 3.6 (s, 3H), 3.98 (d, 1H, *J* = 1.82 Hz), 4.22 (d, 1H, *J* = 1.82 Hz), 6.89–7.90 (m, 9H); EIMS 254 (M^+).

4.10. *trans*-(2*R*,3*S*)-Epoxy-3-(1-naphthyl)-1-phenylpropan-1-one, 6i

Yield: 76% (520.6 mg); mp = 106–107°C; enantiomeric excess was determined by HPLC analysis, using DAICEL Chiralpak AD-H column, (hexane/2-propanol, 94:6); t_r = 17.55 min (2*R*,3*S* minor), t_r = 18.32 min (2*S*,3*R* major); $[\alpha]_D^{25}$ = +25 (*c* 1, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 200 MHz): δ 4.22 (d, 1H, *J* = 2.00 Hz), 4.7 (d, 1H, *J* = 2.00 Hz), 7.45–7.62 (m, 7H), 7.70–7.98 (m, 3H), 8.05–8.12 (d, 2H, *J* = 7.80 Hz); EIMS 274 (M^+).

4.11. *trans*-2,3-Epoxy-3-phenyl-1-(4-bromophenyl)-propan-1-one, 6j

Yield: 82% (620.9 mg); mp = 90–91°C; enantiomeric excess was determined by HPLC analysis, using

DAICEL Chiralpak AD-H column, (hexane/2-propanol, 95:5); $t_r = 18.78$ min (minor), $t_r = 20.58$ min (major); $[\alpha]_D^{25} = -71$ (c 1, $CHCl_3$); ^1H NMR ($CDCl_3$, 200 MHz): δ 4.01 (d, 1H, $J = 2.00$ Hz), 4.15 (d, 1H, $J = 2.00$ Hz), 7.28–7.35 (m, 5H), 7.58–7.62 (m, 2H), 7.85–7.89 (m, 2H); EIMS 302 (M^+).

4.12. (*S*)-2,2-Bis(methoxymethoxy)-6,6′-dibromo-1,1′-binaphthalene, 3

To NaH (60%) (6.4 g, 16 mmol) in dry DMF (15 ml), (*S*)-6,6′-dibromo-1,1′-binaphthol (10 g, 22.5 mmol) dissolved in DMF (150 ml) was added slowly at 0°C. The reaction mixture stirred for 30 min and then chloromethyl methylether (6.34 g, 78.9 mmol) was added dropwise. After 3h stirring at same temperature, 100 ml water added and the precipitate formed was filtered off. The crude product was purified by column chromatography over silica gel (hexane:EtOAc) to give 10.5 g (87%yield). Mp = 130–131°C; $[\alpha]_D^{25} = -17.3$ (c 1, $CHCl_3$) [lit.[12] $[\alpha]_D^{20} = -16.3$ (c 1, $CHCl_3$)]; ^1H NMR ($CDCl_3$, 200 MHz) δ 3.15 (s, 6H), 4.98 (d, 2H, $J = 6.8$ Hz), 5.07 (d, 2H, $J = 6.8$ Hz), 6.98 (d, 2H, $J = 9.0$ Hz), 7.29 (dd, 2H, $J = 9.0$, 2.1 Hz), 7.60 (d, 2H, $J = 9.0$ Hz), 7.88 (d, 2H, $J = 9.0$ Hz), 8.03 (d, 2H, $J = 9.01$ Hz). Anal calcd for $C_{24}H_{20}Br_2O_2$ requires C, 54.16; H, 3.79, found C, 55.38; H, 3.62.

4.13. (*S*)-2,2-Bis(methoxymethoxy)-6,6′-bis(2-phenyl)-1,1′-binaphthalene, 4

To a suspension of (*S*)-6,6′-dibromo-2,2′-bis(methoxymethoxy)1,1′-binaphthalene (9 g, 16.8 mmol), (dppe)-$NiCl_2$ (445 mg, 0.84 mmol) in 150 ml of dry ether, was added slowly 50.4 mmol of phenyl magnesium bromide in 85 ml ether. On addition of PhMgBr, the suspension turned into a clear brown solution. The reaction mixture was stirred for 3h at room temperature. The reaction mixture was quenched with water, filtered the salts through Celite. The organic layer was separated, dried over anhydrous Na_2SO_4 and concentrated under reduced pressure gave the crude product. Then, the crude product was subjected to column chromatography over silica gel gave **4** (7.3 g) as solid (82% yield). Mp = 82–84°C; $[\alpha]_D^{25} = +100.0$ (c 1, $CHCl_3$); ^1H NMR ($CDCl_3$, 200 MHz) δ 3.2 (s, 6H), 5.05 (q, 4H), 7.70–7.23 (m, 16H), 8.02 (d, $J = 8.2$, 2H), 8.10 (s, 2H). Anal calcd for $C_{36}H_{30}O_4$ requires C, 82.13; H, 5.70, found C, 81.94; H, 5.77.

4.14. (*S*)-6,6′-Diphenyl-1,1′-bi-2-naphthol, (*S*)-1d

To a solution of MeOH:THF (10:1) containing (*S*)-2,2-bis(methoxymethoxy)-6,6′-bis(2-phenyl)-1,1′-binaphthalene (4.8 g, 9.125 mmol) was added 10% HCl. The reaction mixture was heated to reflux 1 h, cooled and the solvent was evaporated under vacuum. The residue was purified by flash chromatography yielded (*S*)-**1d** (3.0 g) as solid (75%). Recrystallized from DCM to give 2.85 g. Mp = 127–129°C; $[\alpha]_D^{25} = +215.0$ (c 1, $CHCl_3$), ^1H NMR ($CDCl_3$, 500 MHz) δ 5.01 (s), 7.27 (d, $J = 8.5$ Hz), 7.36 (tt, $J = 8.5$, 1.2 Hz), 7.43 (d, $J = 8.8$ Hz), 7.46 (t, $J = 8.5$ Hz), 7.59 (dd, $J = 8.5$, 2.0 Hz), 7.67 (dd, $J = 8.5$, 1.2 Hz), 8.05 (d, $J = 8.8$ Hz), 8.10 (d, $J = 2$ Hz); ^{13}C NMR ($CDCl_3$) δ 152.96, 140.91, 137.07, 132.70, 131.86, 129.86, 129.00, 127.36, 126.49, 124.92, 118.38, 110.89; m/z (EI) 438 (M^+); EI HRMS calcd for $C_{32}H_{22}O_2$ 438.16198, obsd 438.16060.

4.15. (*S*)-MTPA-monoester

^1H NMR ($CDCl_3$, 200 MHz) δ 2.89 (s, 3H, 1×OCH_3), 5.21 (s, 1H, 1×OH), 7.09–8.2 (m, 25H, Ar).

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