SUPPLEMENTARY INFORMATION

Dramatic synergistic effect of a flexible achiral linker on a rigid chiral cis-1,2-diamine bifunctional organocatalyst

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Experimental Procedures. Melting points were determined using the Yanaco micro melting point apparatus and are uncorrected. Optical rotations were measured with a JASCO P-1010 polarimeter. $^1$H NMR spectra were recorded in CDCl$_3$ with tetramethylsilane as an internal standard on a JEOL JNM-AL300 (300 MHz), JEOL JNM-GX400 (400 MHz) and Bruker Avance 600 (600 MHz) spectrometers. $^{13}$C NMR spectra were recorded in CDCl$_3$ with tetramethylsilane as an internal standard on a JEOL JNM-AL300 (75 MHz), JEOL JNM-GX400 (100 MHz) and Bruker Avance 600 (150 MHz) spectrometers using broad band proton decoupling. Infrared spectra were measured with a JASCO JIR-6500W FT-IR spectrometer. MS and HRMS (EI or FAB) were obtained with a JEOL JMS-700 mass spectrometer. HPLC analyses were carried out on a JASCO PU-1580 HPLC pump and a JASCO UV-1580 detector, using chiral columns (Daicel; 250 × 4.6 mm).

Flash chromatography was performed using Fuji Silysia silica gel PSQ60B. Methylene chloride (dehydrate) and THF (dehydrate) were purchased from Kanto Chemical Co., Inc. Other solvents and reagents were distilled prior to use. 

$(E)$-$\beta$-Aryl nitroolefins (4, 7a-7i), $(E)$-1-nitropent-1-ene (7j) and $(E)$-(4-nitrobut-3-en-1-yl)benzene (7k) were prepared according to literature procedures.
The preparation of chiral “roofed” cis-amine-thiourea organocatalysts A-D:

Planning the synthetic strategy for the preparation of chiral “roofed” amine-thiourea compounds, we started from the optically pure (-)-(2R,6S)-3-[(1S,2R)-methoxy-7,7-dimethylbicyclo[2.2.1]-heptane-1-carbonyl] (abbreviated as “MAC”) -3,5-diazadibenzo[h,k]tricyclo[5.2.2.2.6]undeca-8,10-dien-4-one (abbreviated as “DHALm”) (S1), which is readily available from the thermal [4+2] cycloaddition of 1,3-dihydro-2-imidazolone with anthracene followed by optical resolution using MAC acid (MAC-OH). Thus, N°-protection of S1 with 2-naphthalenesulfonyl (2-Nps) group and subsequent removal of MAC group by PhCH2SLi, followed by ring-opening and N-tert-butoxycarbonylation gave N,N°-diprotected “roofed” cis-1,2-diamine 2 as a key intermediate. Dimethylation of Boc-deprotected amine and subsequent removal of 2-Nps group by lithium naphthalenide followed by the condensation with N-Boc amino acids in the presence of diethyl phosphorocyanidate (DEPC) afforded corresponding amides S4. Removal of Boc group by TFA followed by the treatment of 3,5-bis(trifluoromethyl)phenyl isothiocyanate gave chiral “roofed” cis-amine-thiourea bifunctional compounds with three types of linker between chiral scaffold and thiourea moiety (A1-A3) (Scheme S1).

“Roofed” cis-amine-thiourea organocatalysts B, with four types of linker between chiral scaffold and amine moiety, were also prepared from key intermediate 2. Thus, the removal of 2-Nps group followed by the treatment with isothiocyanate gave thiourea compound 6, Boc

![Diagram S1](image1)

Scheme S1

![Diagram S2](image2)

Scheme S2
group of which was removed and the corresponding primary amine was condensed with \(N,N\)-dimethylamino acids to afford B1-B4 (Scheme S2).

“Roofed” \(cis\)-amine-thiourea organocatalyst with “double-elongated” functional groups using glycine as a linker, C, was synthesized from 2 by stepwise deprotection of Boc and 2-Nps groups followed by the condensation of amino groups with glycine moieties, respectively (Scheme S3).

Prototype of “roofed” \(cis\)-amine-thiourea organocatalysts D, without linker, was simply prepared from intermediate S3 by the removal of 2-Nps group followed by the treatment with isothiocyanate (Scheme S4).

The preparation of compound S2, \((+)-(2S,6R)-3-(2\text{-naphthalenesulfonyl})-3,5\text{-diazadibenzo}[h,k]\text{-tricyclo}[5.2.2.2^6]\text{-undeca}-8,10\text{-dien}-4\text{-one}, from S1.

Preparation of S7 from S1: To the solution of S1, \((+)-(2R,6S)-3-[/(1S,2R)\text{-methoxy}-7,7\text{-dimethylbicyclo[2.2.1]heptane-1-carbonyl}]-3,5\text{-diazadibenzo}[h,k]\text{-tricyclo}[5.2.2.2^6]\text{-undeca}-8,10\text{-dien}-4\text{-one} (24.88 g, 56.22 mmol), in THF (562 mL) was added NaH (60% in oil; 5.40 g, 134.93 mmol, 2.4 eq) at 0 \(^\circ\text{C}\) and stirred for 10 minutes. 2-Naphthalenesulfonyl chloride (19.12 g, 84.35
mmol, 1.5 eq) was added to the resulting mixture at 0 °C and the reaction mixture was stirred at room temperature for 1.5 h. The reaction was quenched with sat. NH₄Cl aq. at 0 °C and EtOAc (1200 mL) was added. The reaction solution was washed with brine (200 mL x 3) and dried over anhyd. Na₂SO₄. After the concentration of the organic layer in vacuo, the residue was purified by column chromatography on silica gel (CH₂Cl₂/hexane (3:7) to CH₂Cl₂) to afford the N-(2-naphthalenesulfonylated) compound S7 (34.39 g, 54.39 mmol, 97%) as a colorless amorphous solid; [α]D⁺20 +16.6 (c 1.26, CHCl₃); ¹H NMR (CDCl₃, 300 MHz) δ 8.59 (s, 1H), 7.98-7.91 (m, 4H), 7.68-7.60 (m, 2H), 7.40-7.37 (m, 2H), 7.23-7.02 (m, 3H), 7.61 (t, J = 7.1, 1.8 Hz, 1H), 6.93-6.85 (m, 2H), 5.03 (d, J = 3.3 Hz, 2H), 5.01 (d, J = 2.9 Hz, 1H), 4.56 (dd, J = 9.7, 3.3 Hz, 1H), 4.44 (dd, J = 9.7, 2.9 Hz, 1H), 4.20 (dd, J = 7.7, 3.7 Hz, 1H), 2.77 (s, 3H), 1.89-1.72 (m, 2H), 1.62-1.48 (m, 2H), 1.43-1.26 (m, 1H), 1.33 (s, 3H), 1.05 (s, 3H), 0.97-0.86 (m, 2H); ¹³C NMR (CDCl₃, 75 MHz) δ 172.8, 149.6, 140.3, 138.9, 137.9, 135.7, 135.3, 131.8, 129.6, 129.4, 129.3, 129.2, 127.9, 127.7, 127.1, 127.0, 126.9, 126.6, 126.5, 125.8, 125.3, 125.2, 122.5, 83.2, 61.9, 57.0, 56.8, 53.4, 50.8, 48.2, 45.6, 45.3, 37.4, 26.9, 26.7, 21.8, 21.3; IR (KBr, cm⁻¹): 3341, 2923, 1764, 1683, 1367, 1070, 750, 659, 626, 576. HRMS (FAB⁺): m/z calcd for C₃₈H₃₆N₂O₅SNa [M+Na]⁺ 655.2243, found 655.2228.

Preparation of S2 from S7: THF (690 mL) solution of benzyl mercaptan (24.3 mL, 206.73 mmol, 3.0 eq) under argon atmosphere was treated with n-BuLi (2.6 M in hexane; 66.3 mL, 172.28 mmol, 2.5 eq) at 0 °C and stirred for 10 minutes to form lithium benzylmercaptide. To this solution was added S7 (43.57 g, 68.91 mmol) in THF (690 mL) dropwise at 0 °C and stirred at rt for 1 hour. The reaction was quenched with sat. NH₄Cl aq. at 0 °C followed by evaporation in vacuo to remove THF. EtOAc (600 mL) was added to the residue and the solution was washed with brine (150 mL x 3) and dried over anhyd. Na₂SO₄. After the concentration of the organic layer in vacuo, the residue was purified by column chromatography on silica gel (CH₂Cl₂/hexane (3:7) to CH₂Cl₂/EtOAc (7:3)) to yield, in addition to MAC acid thiobenzyl ester (19.62 g, 64.44 mmol, 94%), the deacylated DHAIm S2 (31.19 g, 68.91 mmol, >99%) as colorless crystals; mp 268-270 °C; [α]D⁺20 +109.3 (c 1.32, CHCl₃); ¹H NMR (CDCl₃, 300 MHz) δ 8.56 (s, 1H), 7.99-7.85 (m, 4H), 7.65-7.54 (m, 2H),
7.43-7.40 (m, 1H), 7.28-7.00 (m, 5H), 6.91-6.86 (m, 2H), 5.95 (br s, 1H), 4.94 (d, J = 3.3 Hz, 1H), 4.56 (dd, J = 9.5, 3.3 Hz, 1H), 4.31, (d, J = 2.9 Hz, 1H), 3.89 (dd, J = 9.5 Hz, 2.9 Hz, 1H), 3.89 (dd, J = 9.5 Hz, 2.9 Hz, 1H), 3.89 (dd, J = 9.5 Hz, 2.9 Hz, 1H). IR (KBr, cm\(^{-1}\)): 3392, 3342, 3050, 2958, 1739, 1344, 1243, 1164, 1133, 1076, 765, 746, 659, 574.

HRMS (FAB\(^{+}\)): m/z calcd for C\(_{27}\)H\(_{21}\)N\(_2\)O\(_3\)S [M+H]\(^{+}\) 453.1273, found 453.1270.

The preparation of 2, tert-butyl [(2R,3S)-3-(2-naphthalenesulfonamido)dibenzo[e,h]bicyclo[2.2.2]octa-5,7-dien-2-ly]carbamate, from S2.

To the solution of compound S2 (2.26 g, 5.0 mmol) in EtOH/H\(_2\)O/DMSO (5/1/1; 50 mL) was added Ba(OH)\(_2\)•8H\(_2\)O (7.89 g, 25 mmol, 5 eq) and refluxed for 16 hours. The reaction mixture was poured into H\(_2\)O (250 mL) at 0 °C and the white precipitate was collecte by filtration and washed by H\(_2\)O to yield the mixture of ring-opened crude product and Ba(OH)\(_2\)•8H\(_2\)O as white powder. The crude product was subsequently treated with (Boc)\(_2\)O (1.72 mL, 7.5 mmol, 1.5 eq) in CH\(_2\)Cl\(_2\) (50 mL) and stirred at rt for 18 hours. The reaction mixture was passed through Celite\(^{®}\) pad to remove the precipitate and the pad was washed with CH\(_2\)Cl\(_2\). The filtrate was combined and concentrated in vacuo followed by column chromatography on silica gel (CH\(_2\)Cl\(_2\) to CH\(_2\)Cl\(_2\)/EtOAc (8:2)) to obtain 2 (2.24 g, 4.25 mmol, 86%) as a colorless amorphous solid; \([\alpha]_D^{20}\) +3.7 (c 1.06, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\)+CD\(_3\)OD 1 drop, 300 MHz, 50 °C) \(\delta\) 8.43 (s, 1H), 7.98 (d, J = 8.6 Hz, 2H), 7.92 (dd, J = 8.8, 1.8 Hz, 1H), 7.80 (dd, J = 8.8, 1.8 Hz, 1H), 7.67-7.58 (m, 2H), 7.31-7.18 (m, 5H), 7.11-7.06 (m, 3H), 4.38 (br s, 1H), 4.28 (d, J = 2.4 Hz, 1H), 4.16-4.08 (m, 2H), 3.92 (dd, J = 9.0, 2.4 Hz, 1H), 1.33 (s, 9H); \(^13\)C NMR (CDCl\(_3\), 75 MHz) \(\delta\) 155.1, 140.5, 139.9, 139.2,138.6, 135.0, 132.3, 129.6, 129.3, 128.9, 128.4, 128.0, 127.6, 127.2, 126.9, 126.7, 126.6, 126.0, 124.4, 122.4, 80.2, 53.4, 51.2,
The preparation of S3, N-[(2S,3R)-3-(dimethylamino)dibenzo[e,h]bicyclo[2.2.2]octa-5,7-dien-2-lyl]2-naphthalenesulfonamide, from 2.

To the solution of compound 2 (790 mg, 1.5 mmol) in CH₂Cl₂ (1.5 mL) was added TFA (7.5 mL) and stirred at rt for 30 minutes to remove Boc group. The reaction mixture was concentrated in vacuo and the residue was dissolved in CH₂Cl₂ (100 mL). The solution was washed (i) satd. NaHCO₃ aq (20 mL x 3), ii) brine (20 mL x 3)), dried (anhyd. Na₂SO₄) and concentrated in vacuo. The residue was dissolved in THF and K₂CO₃ (622 mg, 4.5 mmol, 3 eq) and MeI (0.94 mL, 15 mmol, 10 eq) were subsequently added and stirred at 40 °C for 24 hours. The reaction mixture was passed through Celite® pad to remove the precipitate and the pad was washed with CH₂Cl₂. The filtrate was combined and concentrated in vacuo followed by column chromatography on silica gel (hexane/EtOAc (7:3 to 6:4)) to yield S3 (547 mg, 1.20 mmol, 80%) as a colorless amorphous solid; [α]D²⁰ +69.5 (c 0.62, CHCl₃); ¹H NMR (CDCl₃, 300 MHz) δ 8.49 (d, J = 1.5 Hz, 1H), 8.00-7.96 (m, 2H), 7.92 (dd, J = 6.6, 2.6 Hz, 1H), 7.85 (dd, J = 8.8, 1.8 Hz, 1H), 7.67-7.58 (m, 2H), 7.27-7.05 (m, 7H), 6.97 (dd, J = 7.0, 1.5 Hz, 1H), 6.12 (br s, 1H), 4.41 (d, J = 3.7 Hz, 1H), 4.38 (d, J = 1.8 Hz, 1H), 3.75 (dd, J = 8.8, 3.7 Hz, 1H), 2.52 (dd, J = 8.8, 1.8 Hz), 2.16 (br s, 6H); ¹³C NMR (CDCl₃, 75 MHz) δ 142.7, 141.0, 140.2, 138.7, 138.4, 134.8, 132.3, 129.2, 129.1, 128.6, 128.1, 127.9, 127.5, 126.7, 126.50, 126.47, 126.2, 126.1, 125.2, 125.0, 123.4, 123.0, 66.6, 52.0, 51.1, 46.7, 44.2 (two carbons were overlapped); IR (KBr, cm⁻¹): 3172, 3043, 2989, 2829, 1375, 1338, 1326, 1160, 1133, 1074, 1029, 821, 755, 661. HRMS (FAB⁺): m/z calcd for C₂₈H₂₇N₂O₂S [M+H]⁺ 455.1793, found 455.1794.
The preparation of S4a-c from S3: General procedure.

To the solution of naphthalene (6 eq) in DME (10 mL / 1 mmol of S3) was added small pieces of Na (14 eq) under argon atmosphere and sonicated at 25 °C for 5 minutes to prepare sodium naphthalenide. A solution of S3 in THF (27 mL / 1 mmol of S3) was added dropwise to the solution of sodium naphthalenide at -30 °C and stirred at this temperature until the accomplishment of the reaction (approx. for 30 minutes ~ 2 hours). The reaction mixture was poured into the ice water to quench excess amount of Na metal and the product was extracted (Et₂O, x 3), washed (brine, x 3) and dried (anhyd. Na₂SO₄). The solution was concentrated under reduced pressure and the residue was dissolved in DMF (10 mL / 1 mmol of S3) and N-Boc-amino acid (1.1 eq) was added. To the solution were subsequently added diethyl cyanophosphonate (DEPC; 1.1 eq) and NEt₃ (2 eq) at 0 °C and stirred at 0 °C and rt for each 30 minutes. EtOAc was added to the reaction mixture and the solution was washed (i) satd. NaHCO₃ (x 2), ii) brine (x 3)) and dried (anhyd. Na₂SO₄). After the concentration in vacuo, the residue was purified to afford S4a-c.

*tert*-butyl [[[2S,3R]-3-(dimethylamino)dibenzo[e,h]bicyclo[2.2.2]octa-5,7-dien-2-ly]amino]-2-oxoethyl]carbamate (S4a).

Product was purified by column chromatography on silica gel (CH₂Cl₂ to CH₂Cl₂/EtOH (19:1) via CH₂Cl₂/EtOAc (9:1)) to afford S4a in 84% yield as a colorless amorphous solid; [α]D⁺23 +41.8 (c 1.42, CHCl₃); ¹H NMR (CDCl₃, 300 MHz) δ 7.37-7.09 (m, 8H), 6.71 (br s, 1H), 4.98 (br s, 1H), 4.73 (d, J = 3.3 Hz, 1H), 4.46 (d, J =1.8 Hz, 1H), 4.21 (ddd, J = 8.4, 6.6, 3.3 Hz, 1H), 3.65 (d, J = 2.6 Hz, 1H), 3.63 (d, J = 2.6 Hz, 1H), 2.57 (dd, J = 8.4, 1.8 Hz, 1H), 2.27 (s, 6H), 1.40 (s, 9H); ¹³C NMR (CDCl₃, 75 MHz) δ 168.4, 155.5, 142.4, 141.1, 140.4, 138.7, 126.5, 126.3, 126.2 (two carbons were overlapped), 125.8, 125.1 (two
carbons were overlapped), 123.5, 79.6, 66.9, 48.7, 48.3, 47.0, 44.6, 44.0, 28.2; IR (KBr, cm\(^{-1}\)): 3299, 3041, 2973, 2946, 2865, 2819, 1691, 1672, 1544, 1521, 1290, 1172, 767. HRMS (FAB\(^{+}\)): m/z calcd for C\(_{25}\)H\(_{32}\)N\(_{3}\)O\(_{3}\) [M+H]\(^{+}\) 422.2444, found 422.2441.

tert-butyl [[(2S,3R)-3-(dimethylamino)dibenzo[e,h]bicyclo[2.2.2]octa-5,7-dien-2-ly]amino]-3-oxopropyl]carbamate (S4b).

Product was purified by column chromatography on silica gel (hexane/EtOAc (8:2) to EtOAc) to afford S4b in 68% yield as a pale yellow oil; [\(\alpha\)]\(_D\)\(^{23}\) +42.7 (c 2.08, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\), 300 MHz) \(\delta\) 7.38-7.31 (m, 2H), 7.26-7.10 (m, 6H), 6.43 (br d, \(J = 6.0\) Hz, 1H), 5.15 (br s, 1H), 4.74 (d, \(J = 3.5\) Hz, 1H), 4.46 (d, \(J = 1.8\) Hz, 1H), 4.20 (ddd, \(J = 8.4, 6.6, 3.5\) Hz, 1H), 3.34 (q, \(J = 6.0\) Hz, 2H), 2.56 (dd, \(J = 8.4, 1.8\) Hz, 1H), 2.27 (s, 6H), 2.24-2.19 (m, 2H), 1.43 (s, 9H); \(^{13}\)C NMR (CDCl\(_3\), 75 MHz) \(\delta\) 170.8, 155.8, 142.3, 141.2, 140.4, 138.7, 126.5, 126.3, 126.19, 126.17, 125.7, 125.2, 125.1, 123.5, 79.0, 66.9, 48.7, 48.3, 47.0, 44.7, 44.6, 36.8, 36.1, 28.4.; IR (KBr, cm\(^{-1}\)): 3340, 2975, 2873, 2823, 1700, 1652, 1496, 1172, 757. HRMS (FAB\(^{+}\)): m/z calcd for C\(_{26}\)H\(_{34}\)N\(_{3}\)O\(_{3}\) [M+H]\(^{+}\) 436.2600, found 436.2587.

tert-butyl [[(2S,3R)-3-(dimethylamino)dibenzo[e,h]bicyclo[2.2.2]octa-5,7-dien-2-ly]amino]-4-oxobutyl]carbamate (S4c).

Product was purified by column chromatography on silica gel (hexane/EtOAc (2:8) to EtOAc) to afford S4c in 68% yield as a pale yellow oil; [\(\alpha\)]\(_D\)\(^{20}\) +53.2 (c 2.28, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\), 300 MHz) \(\delta\) 7.38-7.31 (m, 2H), 7.25-7.18 (m, 2H), 7.16-7.10 (m, 4H), 6.36 (d, \(J = 6.0\) Hz, 1H), 4.78 (br s, 1H), 4.72 (d, \(J = 3.3\) Hz, 1H), 4.46 (d, \(J = 1.8\) Hz, 1H), 4.26-4.19 (m, 1H), 3.18-3.06 (m, 2H), 2.55 (dd, \(J = 6.6, 1.8\) Hz, 1H), 2.27 (s, 6H), 2.14-1.99 (m, 2H), 1.74 (quintet, \(J = 7.1\) Hz, 2H), 1.44 (s, 9H); \(^{13}\)C NMR (CDCl\(_3\), 75 MHz, 50 °C) \(\delta\) 171.5, 155.9, 142.5, 141.4, 140.6, 138.8, 126.4, 126.2, 126.03, 126.01, 125.8, 125.1, 125.0, 123.4, 78.9, 67.1, 48.7, 48.6, 47.1, 44.6, 40.3 (two carbons were overlapped),
33.9, 28.4, 25.8; IR (KBr, cm\(^{-1}\)): 3349, 3070, 3041, 2973, 2935, 2869, 2827, 2780, 1703, 1657, 1495, 1417, 1365, 1290, 1255, 1172, 1024, 760, 730. HRMS (FAB\(^{+}\)): m/z calcd for C\(_{27}\)H\(_{36}\)N\(_3\)O\(_3\) [M+H]\(^{+}\) 450.2757, found 450.2743.

The preparation of catalyst A1-A3 from S4a-c: General procedure

To the solution of compound S4 in CH\(_2\)Cl\(_2\) (5 mL / 1 mmol of S4) was added TFA (5 mL / 1 mmol of S4) and stirred at rt for 30 minutes to remove Boc group. The reaction mixture was concentrated \textit{in vacuo} and the residue was dissolved in CH\(_2\)Cl\(_2\). The solution was washed (i) satd. NaHCO\(_3\) aq (x 3), ii) brine (x 3)), dried (anhyd. Na\(_2\)SO\(_4\)) and concentrated \textit{in vacuo}. The residue was dissolved in CH\(_2\)Cl\(_2\) (10 mL / 1 mmol of S4) and NEt\(_3\) (4 eq) and 3,5-bis(trifluoromethyl)phenyl isothiocyanate (1.25 eq) was added to the solution at 0 °C and stirred for 30 minutes. The reaction solution was concentrated under reduced pressure and the residue was purified to obtain catalyst A1-A3.


Product was purified by column chromatography on silica gel (CH\(_2\)Cl\(_2\) to CH\(_2\)Cl\(_2\)/EtOH (19:1)) to afford A1 (ca. 81% yield) as a pale yellow amorphous solid, together with slightly amount of inseparable impurities, observed in \(^1\)H NMR. The product was converted to its TFA salt by the addition of TFA and dissolved in MeOH followed by the addition of slightly amount of Et\(_2\)O to obtain the pure TFA salt of A1 as precipitate. The EtOAc solution of the salt was treated with NEt\(_3\), washed by brine, dried over anhyd. Na\(_2\)SO\(_4\) and concentrated \textit{in vacuo} to yield pure A1 in 48% yield as a pale yellow amorphous solid; \([\alpha]_D^{23} +52.9\) (c 1.82, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\), 300 MHz)
δ 9.23 (br s, 1H), 8.43 (br s, 1H), 8.03 (s, 2H), 7.45 (s, 1H), 7.39-7.36 (m, 1H), 7.29-7.18 (m, 4H), 7.16-7.06 (m, 3H), 4.66 (d, J = 3.3 Hz, 1H), 4.50 (d, J = 1.5 Hz, 1H), 4.38 (dd, J = 16.3, 5.1 Hz, 1H), 4.24-4.18 (m, 1H), 4.04 (dd, J = 16.3, 5.1 Hz, 1H), 2.61 (dd, J = 8.2, 1.5 Hz, 1H), 2.04 (s, 6H); 13C NMR (CDCl₃, 75 MHz, 50 °C) δ 181.8, 170.2, 142.1, 140.7, 140.3, 139.8, 138.7, 131.3 (q, J = 33.6 Hz; two carbons were overlapped), 126.64, 126.61, 126.5, 126.4, 125.9, 125.4, 124.8, 123.8, 123.0 (q, J = 272.8 Hz; two carbons were overlapped), 122.54, 122.49, 117.5 (m), 66.7, 49.2, 48.5, 47.4, 47.0, 44.7 (two carbons were overlapped); IR (KBr, cm⁻¹): 3313, 3072, 2957, 2877, 2831, 1652, 1506, 1473, 1384, 1278, 1176, 1133, 951, 887, 760. HRMS (FAB⁺): m/z calcd for C₂⁹H₂⁷F₆N₄OS [M+H]⁺ 593.1809, found 593.1816.

3-[3-[3,5-bis(trifluoromethyl)phenyl]thioureido]-N-[(2S,3R)-3-(dimethylamino)dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-lyl]propanamide (A2).

Product was purified by column chromatography on silica gel (hexane/EtOAc (1:9)) to afford A2 (75% yield) as a pale yellow amorphous solid; [α]D²³ +56.1 (c 1.40, CHCl₃); 1H NMR (CDCl₃, 300 MHz, 50 °C) δ 8.06 (br s, 2H), 7.69 and 7.52 (br s, 1H; the peaks of rotational isomers), 7.37-7.09 (m, 10H), 6.62 and 6.47 (br s, 1H; the peaks of rotational isomers), 4.75 and 4.70 (d, J = 3.3 Hz, 1H; the peaks of rotational isomers), 4.45 (br s, 1H), 4.21-4.08 (m, 1H), 3.89-3.75 (m, 1.36 H), 3.57 (dd, J = 11.3, 5.7 Hz, 0.64 H; one of the peaks of rotational isomers), 2.56 (d, J = 8.4 Hz, 1 H), 2.39-2.22 (m, 2H), 2.27 (s, 6H); 13C NMR (CDCl₃, 75 MHz, 50 °C; the peaks of rotational isomers were observed) δ 181.3, 171.6, 170.4, 142.5, 142.3, 141.2, 140.9, 140.7, 140.3, 140.1, 138.8, 138.7, 132.3 (q, J = 33.6 Hz), 126.71, 126.66, 126.59, 126.54, 126.43, 126.36, 126.30, 125.8, 125.6, 125.4, 125.1, 124.9, 123.7, 123.6, 123.2 (q, J = 272.4 Hz), 122.97, 122.93, 118.1 (m), 67.1, 67.0, 49.3, 49.0, 48.5, 48.4, 47.1, 46.2, 44.6, 40.8, 36.0, 35.3, 34.3, 29.7; IR (KBr, cm⁻¹): 3332, 3070, 2956, 2837, 2829, 1722, 1643, 1506, 1473, 1386, 1278, 1174, 10
1136, 885, 759, 680. HRMS (FAB\(^+\)): m/z calcd for C\(_{30}\)H\(_{29}\)F\(_6\)N\(_4\)OS [M+H]\(^+\) 607.1966, found 607.2000.

4-[3-[3,5-bis(trifluoromethyl)phenyl]thioureido]-N-[(2S,3R)-3-(dimethylamino)dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly]butanamide (A3).

Product was purified by column chromatography on silica gel (CH\(_2\)Cl\(_2\)/EtOH (99:1 to 97:3)) to afford A3 (63% yield) as a pale yellow amorphous solid; \([\alpha]\)\(_D\)\(^{20}\) +54.0 (c 1.46, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\), 300 MHz, 50 °C) \(\delta\) 8.25 (br s, 1H), 7.64 (s, 1H), 7.33-7.09 (m, 10H), 6.58 (br d, \(J = 3.6\) Hz, 1H), 4.64 (br s, 1H), 4.45 (br s, 1H), 4.08 (br s, 1H), 3.60 (m, 2H), 2.55 (d, \(J = 8.2\) Hz, 1H), 2.27 (br s, 7H), 2.17 (dd, \(J = 7.3, 4.4\) Hz, 2H), 1.93-1.81 (m, 2H); \(^{13}\)C NMR (CDCl\(_3\), 75 MHz, 50 °C) \(\delta\) 181.3, 172.7, 142.3, 141.1 (two carbons were overlapped), 140.1, 138.8, 132.0 (q, \(J = 33.6\) Hz; two carbons were overlapped), 131.0, 126.7, 126.6, 126.4, 126.3, 125.7, 125.4, 124.9, 123.6 (two carbons were overlapped), 123.3 (q, \(J = 273.2\) Hz; two carbons were overlapped), 118.1, 67.1, 49.2, 48.5, 47.1, 44.6 (two carbons were overlapped), 44.2, 33.3, 24.8; IR (KBr, cm\(^{-1}\)): 3323, 3091, 3074, 3047, 3025, 2954, 2873, 2829, 2785, 1643, 1506, 1473, 1383, 1330, 1281, 1172, 1133, 1128, 1049, 1024, 978, 950, 885, 848, 759, 730, 702, 680, 647, 638. HRMS (FAB\(^+\)): m/z calcd for C\(_{31}\)H\(_{31}\)F\(_6\)N\(_4\)OS [M+H]\(^+\) 621.2123, found 621.2138.

The preparation of 6, tert-butyl [(2R,3S)-3-[3-[3,5-bis(trifluoromethyl)phenyl]thioureido]-dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly]carbamate, from 2.

To the solution of naphthalene (1.92 g, 15 mmol, 6 eq) in DME (25 mL) was added small pieces of Na (805 mg, 35 mmol, 14 eq) under argon atmosphere and sonicated at 25 °C for 5 minutes to prepare sodium naphthalenide. A solution of 2 in DME (12.5 mL) was added dropwise to the
solution of sodium naphthalenide at -30 °C and stirred at this temperature for 2 hours. The reaction mixture was poured into the ice water to quench excess amount of Na metal and the product was extracted (Et₂O, 50 mL x 3), washed (brine, 25 mL x 3) and dried (anhyd. Na₂SO₄). The solution was concentrated under reduced pressure and the residue was purified by column chromatography on silica gel (CH₂Cl₂/EtOAc (7:3) to EtOAc) to afford desulfonylated amine, which was successively dissolved in CH₂Cl₂ (25 mL) and 3,5-bis(trifluoromethyl)phenyl isothiocyanate (0.47 mL, 2.75 mmol, 1.1 eq) was added to the solution at 0 °C and stirred for 30 minutes. The reaction solution was concentrated in vacuo followed by column chromatography on silica gel (hexane/CH₂Cl₂ (5:5) to CH₂Cl₂) to yield 6 (1.169 g, 1.92 mmol, 77%) as a colorless amorphous solid; [α]D⁺20 +2.5 (c 1.44, CHCl₃); ¹H NMR (CDCl₃, 300 MHz, 50 °C) δ 8.28 (br s, 1H), 7.79 (br s, 2H), 7.59 (br s, 1H), 7.38-7.16 (m, 8H), 5.81 (br d, J = 6.4Hz, 1H), 4.63 (br s, 1H), 4.52 (br s, 1H), 4.29 (m, 2H), 4.09 (br s, 1H), 1.29 (s, 9H); ¹³C NMR (CDCl₃, 100 MHz, 50 °C) δ 181.1, 156.1, 140.2, 139.9 (two carbons were overlapped), 138.9, 138.6, 132.5 (q, J = 33.6 Hz; two carbons were overlapped), 127.7, 127.6, 127.1, 127.0, 126.1, 125.9, 124.7, 124.3, 123.1 (two carbons were overlapped), 122.9 (q, J = 272.8 Hz; two carbons were overlapped), 118.4, 81.2, 55.4, 51.9, 49.3, 48.7, 28.1 (three carbons were overlapped); IR (KBr, cm⁻¹): 3344, 2979, 1683, 1519, 1469, 1383, 1278, 1176, 1135, 885, 759, 682. HRMS (FAB⁺): m/z calcd for C₃₀H₂₇F₆N₃O₂SNa [M+Na]⁺ 630.1626, found 630.1631.

The preparation of catalyst B1-B4 from 6: General procedure

To the solution of compound 6 in CH₂Cl₂ (2 mL / 1 mmol of 6) was added TFA (5 mL / 1 mmol of 6) and stirred at rt for 1 hour to remove Boc group. The reaction mixture was concentrated in vacuo and azeotroped with toluene for three times to ensure removal of all excess TFA to afford TFA salt of amine as a foam which was used in the next step without further purification. The residue was
dissolved in DMF (10 mL / 1 mmol of 6) and N,N-dimethylamino acid (1.1 eq) was added. To the solution were subsequently added diethyl cyanophosphonate (DEPC; 1.1 eq) and NEt₃ (4.4 eq) at 0 °C and stirred at rt for 1 hour. EtOAc was added to the reaction mixture and the solution was washed (i) satd. NaHCO₃ (x 2), ii) brine (x 3)) and dried (anhyd. Na₂SO₄). After the concentration in vacuo, the residue was purified to afford B₁-B₄.

**N-{(2R,3S)-3-[3,5-bis(trifluoromethyl)phenyl]thioureido}dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly}]-2-(dimethylamino)acetamide (B₁).**

Product was purified by column chromatography on silica gel (CH₂Cl₂ to CH₂Cl₂/EtOH (19:1)) to afford B₁ (ca. >99% yield) as a pale yellow amorphous solid, together with slightly amount of inseparable impurities, observed in ¹H NMR. The product was dissolved in EtOH and converted to its HCl salt by the addition of HCl solution. After removal of the solvent and excess amount of HCl by azeotrope with toluene, residue was solidified by adding Et₂O, suspended in small amount of Et₂O/EtOH (9/1), collected by filtration and washed (Et₂O/EtOH (9/1)). The collected salt was suspended in EtOAc and NEt₃ was added to convert HCl salt to free amine. The solution was washed (brine, x3), dried (anhyd. Na₂SO₄) and concentrated in vacuo to yield pure B₁ in 54% yield as a colorless amorphous solid; [α]D²₀ -35.3 (c 1.00, CHCl₃); ¹H NMR (DMSO-d₆, 300 MHz) δ 10.4 (s, 1H), 8.21 (s, 2H), 7.75 (s, 1H), 7.49-7.36 (m, 4H), 7.31-7.24 (m, 3H), 7.22-7.15 (m, 2H), 6.66 (d, J = 8.6 Hz, 1H), 4.85 (ddd, J = 8.6, 8.6, 2.2 Hz, 1H), 4.54 (d, J = 2.2 Hz, 1H), 4.42 (d, J = 2.7 Hz, 1H), 4.38 (ddd, J = 8.6, 8.6, 2.7 Hz, 1H), 2.77 (d, J = 15.4 Hz, 1H), 2.70 (d, J = 15.4 Hz, 1H), 2.01 (s, 6H); ¹³C NMR (CDCl₃, 100 MHz, 50 °C) δ 182.6, 171.7, 140.3, 139.3, 139.2, 138.3, (other one carbon was overlapped from 140.3 to 138.3), 132.4 (q, J = 37.4 Hz; two carbons were overlapped), 127.7, 127.3, 127.2, 125.9, 124.6, 124.5, 124.0, 123.0 (q, J = 273.2 Hz; two carbons were overlapped), 118.9 (m), (other three carbons were overlapped from 127.7 to 123.0), 62.8, 56.1, 50.1, 49.3, 49.2, 45.9 (two carbons were overlapped); IR (KBr, cm⁻¹): 3325, 3043, 2950, 2877, 1652,
1527, 1471, 1386, 1278, 1176, 1132, 956, 887, 761, 680. HRMS (FAB\(^+\)): m/z calcd for C\(_{29}\)H\(_{27}\)F\(_6\)N\(_4\)OS [M+H]\(^+\) 593.1810, found 593.1818.

\(N\)\{-\(2R,3S\)\}-3\{-3\{-3,5-bis(trifluoromethyl)phenyl\}thioureido\}dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly\}-3\{(dimethylamino)propanamide (B2).

Product was purified by column chromatography on silica gel (CH\(_2\)Cl\(_2\) to CH\(_2\)Cl\(_2\)/EtOH (8:2)) to afford B2 in 38% yield as a pale yellow amorphous solid; \([\alpha]_D^{21}\) -33.7 (c 1.04, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\), 300 MHz, 50 °C) \(\delta\) 8.92 (br s, 1H), 8.31 (br s, 1H), 8.04 (s, 2H), 7.56 (s, 1H), 7.52-7.49 (m, 1H), 7.39-7.28 (m, 5H), 7.22-7.15 (m, 2H), 5.71 (br s, 1H), 4.64 (dd, \(J = \) 8.6, 8.6, 2.6 Hz, 1H), 4.50 (d, \(J = \) 2.6 Hz, 1H), 4.34 (br s, 1H), 4.30 (d, \(J = \) 2.6 Hz, 1H), 2.47-2.35 (m, 3H), 2.24-2.13 (m, 1H), 2.01 (s, 6H); \(^{13}\)C NMR (CDCl\(_3\), 75 MHz, 50 °C) \(\delta\) 182.8, 174.5, 141.4, 140.5, 139.4, 139.3, 138.2, 131.8 (q, \(J = \) 33.6 Hz; two carbons were overlapped), 127.6, 127.4, 127.3, 127.2, 126.3, 126.0, 124.6, 124.3, 123.54, 123.48, 123.2 (q, \(J = \) 272.8 Hz; two carbons were overlapped), 118.1 (m), 56.1, 55.0, 51.0, 49.5, 49.1, 44.1 (two carbons were overlapped), 32.3; IR (KBr, cm\(^{-1}\)) 3309, 3023, 2948, 2829, 1616, 1558, 1572, 1471, 1384, 1278, 1176, 1133, 960, 887, 761, 680. HRMS (FAB\(^+\)): m/z calcd for C\(_{30}\)H\(_{29}\)F\(_6\)N\(_4\)OS [M+H]\(^+\) 607.1966, found 607.1979.

\(N\)\{-\(2R,3S\)\}-3\{-3\{-3,5-bis(trifluoromethyl)phenyl\}thioureido\}dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly\}-3\{(dimethylamino)propanamide (B3).

Product was purified by column chromatography on silica gel (CH\(_2\)Cl\(_2\) to CH\(_2\)Cl\(_2\)/EtOH (19:1); contains 0.1% of NEt\(_3\)) to afford B3 (ca. >99% yield) as a pale yellow amorphous solid, together with slightly amount of inseparable impurities, observed in \(^1\)H NMR. The product was again purified by column chromatography on Al\(_2\)O\(_3\) (CH\(_2\)Cl\(_2\) to CH\(_2\)Cl\(_2\)/MeOH (97:3)) to afford pure B3 in 74% yield as a colorless amorphous solid; \([\alpha]_D^{23}\) +30.6 (c 1.62, CHCl\(_3\)); \(^1\)H NMR (CDCl\(_3\), 300
MHz, 50 °C) δ 8.01 (s, 2H), 7.58 (s, 1H), 7.50-7.47 (m, 1H), 7.42-7.28 (m, 5H), 7.22-7.15 (m, 2H), 6.40 (br s, 1H), 5.75 (br s, 1H), 4.61 (br t, J = 6.0 Hz, 1H), 4.53 (d, J = 1.8 Hz, 1H), 4.44 (br s, 1H), 4.29 (d, J = 2.2 Hz, 1H), 2.31-2.13 (m, 3H), 2.02 (s, 6H), 1.74-1.52 (m, 2H); $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C) δ 182.5, 175.0, 141.2, 140.7, 139.4, 139.1, 138.6, 131.8 (q, J = 33.6 Hz; two carbons were overlapped), 127.8, 127.7, 127.2, 127.1, 126.4, 126.0, 124.6, 124.2, 123.39, 123.36, 123.2 (q, J = 272.8 Hz; two carbons were overlapped), 118.1 (m), 58.8, 55.7, 51.2, 49.4, 48.9, 45.0 (two carbons were overlapped), 34.6, 22.7; IR (KBr, cm$^{-1}$): 3324, 3070, 2952, 2827, 1652, 1521, 1471, 1384, 1278, 1180, 1135, 956, 885, 761, 680. HRMS (FAB$^+$): m/z calcd for C$_{31}$H$_{31}$F$_6$N$_4$OS [M+H]$^+$ 621.2123, found 621.2133.

$\text{N-}\{\text{2R,3S}-3-[3,5-\text{bis(trifluoromethyl)phenyl]thioureido}]\text{dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly}\}\{4-(\text{dimethylamino})\text{butanamide (B4).}}$

Product was purified by column chromatography on silica gel (CH$_2$Cl$_2$ to CH$_2$Cl$_2$/EtOH (8:2); contains 0.5% of NEt$_3$) to afford B4 in 67% yield as a colorless amorphous solid; [α]$^2_{D}$ +48.2 (c 1.11, CHCl$_3$); $^1$H NMR (DMSO-d$_6$, 300 MHz) δ 10.0 (br s, 1H), 8.26 (s, 2H), 7.71 (s, 1H), 7.42-7.37 (m, 4H), 7.25-7.21 (m, 2H), 7.19-7.13 (m, 2H), 7.07 (d, J = 9.9 Hz, 1H), 6.62 (d, J = 8.2 Hz, 1H), 4.89 (br t, J = 8.7 Hz, 1H), 4.53 (d, J = 2.2 Hz, 1H), 4.36 (br dt, J = 8.7, 2.4 Hz, 1H), 4.29 (d, J = 2.4 Hz, 1H), 2.04-1.90 (m, 4H), 1.96 (s, 6H), 1.38-1.28 (m, 2H), 1.24-1.15 (m, 2H); $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C) δ 182.2, 174.1, 141.2, 140.3, 139.7, 139.3, 138.9, 131.8 (q, J = 33.6 Hz; two carbons were overlapped), 127.5 (two carbons were overlapped), 127.1 (two carbons were overlapped), 126.4, 125.8, 124.5, 124.3, 123.3 (two carbons were overlapped), 123.2 (q, J = 272.8 Hz; two carbons were overlapped), 117.9 (m), 58.8, 55.4, 50.3, 49.2, 49.1, 45.1 (two carbons were overlapped), 35.9, 26.6, 23.1; IR (KBr, cm$^{-1}$): 3288, 3070, 2952, 2867, 1652, 1538, 1471, 1386, 1278, 1176, 1133, 958, 885, 761, 680. HRMS (FAB$^+$): m/z calcd for C$_{32}$H$_{33}$F$_6$N$_4$OS [M+H]$^+$ 635.2279, found 635.2291.
The synthesis of catalyst C:


To the solution of naphthalene (1.35 g, 10.55 mmol, 5.3 eq) in DME (20 mL) was added small pieces of Na (644 mg, 28 mmol, 14 eq) under argon atmosphere and sonicated at 25 °C for 5 minutes to prepare sodium naphthalenide. A solution of 2 in DME (10 mL) was added dropwise to the solution of sodium naphthalenide at -30 °C and stirred at this temperature for 2 hours. The reaction mixture was poured into the ice water to quench excess amount of Na metal and the product was extracted (Et₂O, 100 mL x 1, 50 mL x 2), washed (brine, 30 mL x 3) and dried (anhyd. Na₂SO₄). The solution was concentrated under reduced pressure and the residue was dissolved in DMF (10 mL) and Fmoc-glycine (714 mg, 2.4 mmol, 1.2 eq) was added. To the solution were subsequently added diethyl cyanophosphonate (DEPC; 0.36 mL, 2.4 mmol, 1.2 eq) and NEt₃ (0.56 mL, 4.0 mmol, 2 eq) at 0 °C and stirred at this temperature for 30 minutes. EtOAc (100 mL) was added to the reaction mixture and the solution was washed (i) satd. NaHCO₃ (20 mL x 2), (ii) brine (20 mL x 5)) and dried (anhyd. Na₂SO₄). After the concentration in vacuo, the residue was purified by column chromatography on silica gel (hexane/EtOAc (7/3 to 5/5)) to yield S5 (937 mg, 1.52 mmol, 76%) as a colorless amorphous solid; [α]D²⁰ +16.6 (c 1.26, CHCl₃); ¹H NMR (CDCl₃, 300 MHz, 50 °C) δ 7.77 (d, J = 7.3 Hz, 2H), 7.57 (dd, J = 7.3, 3.1 Hz, 2H), 7.43-7.23 (m, 8H), 7.17-7.11 (m, 2H), 7.09-7.04 (m, 2H), 5.40 (d, J = 9.0 Hz, 1H), 5.31 (br s, 1H), 4.50 (td, J = 9.0, 2.4 Hz, 1H), 4.34 (d, J = 1.2 Hz, 1H), 4.32 (s, 2H), 4.28-4.12 (br, 1H), 4.27 (d, J = 2.4 Hz, 1H), 4.18 (d, J = 7.1 Hz, 1H), 4.01 (br s, 1H), 3.73 (d, J = 5.3 Hz, 2H), 1.39 (s, 9H); ¹³C NMR (CDCl₃, 75 MHz, 50 °C) δ 168.2, 156.4, 155.2, 143.9, 143.8, 141.4 (two carbons were overlapped), 140.5, 140.3, 139.4, 127.8, 127.1, 127.0, 126.8, 126.7, 126.0, 125.8, 125.10, 125.07, 124.5, 124.2, 120.0, 80.2,
67.5, 51.4, 49.5, 49.4, 49.2, 47.2, 44.7, 28.2 (three carbons were overlapped); IR (KBr, cm⁻¹): 3403, 3325, 3066, 3039, 3018, 2973, 2944, 2931, 2896, 2871, 1712, 1517, 1467, 1450, 1390, 1365, 1243, 1163, 1105, 1047, 759, 740.

HRMS (FAB⁺): m/z calcd for C₃₈H₃₆N₂O₅SNa [M+Na]⁺ 655.2243, found 655.2228.

The preparation of S₆, tert-butyl [(2R,3S)-3-[2-[3,5-bis(trifluoromethyl)phenyl]thioureido]-acetamido|dibenzo[e,h]-bicyclo[2.2.2]octa-5,7-dien-2-ly|carbamate, from S₅.

To the solution of S₅ (145 mg, 0.24 mmol) in CH₂Cl₂ (1 mL) was added diethylamine (50 µL, 0.48 mmol, 2 eq) and stirred at rt for 20 hours. The reaction mixture was acidified with 10% KHSO₄ aq. and the Fmoc-removed amine was extracted with 10% KHSO₄ aq. (10 mL x 3). Aq. layer combined was alkalined with NaHCO₃ and the product was extracted (CH₂Cl₂, 20 mL x 3), washed (brine, 10 mL x 3) and dried (anhyd. Na₂SO₄). The solution was concentrated under reduced pressure and the residue was dissolved in CH₂Cl₂ (2.4 mL), to which was added 3,5-bis(trifluoromethyl)phenyl isothiocyanate (68 µL, 0.36 mmol, 1.5 eq) at 0 °C and stirred at rt for 30 minutes. To the reaction solution was gradually added hexane and the product precipitated, which was collected by filtration to yield S₆ (120 mg, 0.18 mmol, 77%) as a colorless powder; mp 240-241 °C (decomp.); [α]ᵢ₀⁺²⁰ +174.2 (c 1.30, THF); ¹H NMR (DMSO-d₆, 300 MHz, 50 °C) δ 10.44 (br s, 1H), 8.33 (s, 2H), 8.11 (br s, 1H), 7.71 (s, 1H), 7.39-7.34 (m, 4H), 7.22-7.14 (m, 5H), 5.52 (br s, 1H), 4.43 (td, J = 9.5, 2.6 Hz, 1H), 4.33 (d, J = 2.6 Hz, 1H), 4.26 (d, J = 2.6 Hz, 1H), 4.13-4.00 (m, 3H), 1.35 (s, 9H); ¹³C NMR (DMSO-d₆, 100 MHz, 80 °C) δ 181.2, 168.2, 155.5, 142.6, 142.0, 141.8, 140.3, 140.1, 138.0, 130.9 (q, J = 32.9 Hz), 126.9, 126.83, 126.77, 126.6, 126.3, 124.6, 124.5, 123.7 (q, J = 272.9 Hz), 122.1, 116.6, 78.9, 51.7, 49.8, 49.64, 49.58, 47.7, 28.7; IR (KBr, cm⁻¹): 3384, 3299, 3105, 3076, 3047, 2994, 2972, 2925, 1701, 1655, 1599, 1518, 1471, 1458, 1388, 1367, 1346, 1276, 1176, 1137,

To the solution of S6 (100 mg, 0.15 mmol) in CH₂Cl₂ (1.3 mL) was added TFA (0.2 mL) and stirred at rt for 1.5 hour to remove Boc group. The reaction mixture was alkalined by satd. NaHCO₃ aq. and the product was extracted (CH₂Cl₂; 20 mL x 3), washed (brine; 10 mL x 2), dried (anhyd. Na₂SO₄) and concentrated in vacuo to afford deprotected amine as a foam which was used in the next step without further purification. The residue was dissolved in DMF (0.5 mL) and N,N-dimethylglycine (20.8 mg, 0.20 mmol, 1.3 eq) was added. To the solution were subsequently added diethyl cyanophosphonate (DEPC; 30 µL, 0.20 mmol, 1.3 eq) and NEt₃ (45 µL, 0.32 mmol, 2.1 eq) at 0 °C and stirred at this temperature for 1 hour. EtOAc (100 mL) was added to the reaction mixture and the solution was washed (i) satd. NaHCO₃ (20 mL x 2), ii) brine (20 mL x 5)) and dried (anhyd. Na₂SO₄). After the concentration in vacuo, the residue was purified by column chromatography on silica gel (CH₂Cl₂/EtOH 95/5 to 9/1; contains 0.1% of NEt₃) to yield catalyst C (80 mg, 0.13 mmol, 87%) as a colorless amorphous solid; [α]D²² +81.2 (c 1.32, CHCl₃); ¹H NMR (CDCl₃, 300 MHz, 50 °C) δ 9.97 (br s, 1H), 8.12 (s, 2H), 7.93 (br d, J = 4.5 Hz, 1H), 7.54 (s, 1H), 7.37-7.06 (m, 8H), 6.83 (d, J = 9.2 Hz, 1H), 6.13 (MJ) and 6.09 (MN)* (d, J = 8.6 Hz, 1H), 4.54-4.39 (m, 2H), 4.26 (d, J = 2.0 Hz, 1H), 4.21 (d, J = 2.0 Hz, 1H), 4.30-4.09 (m, 2H), 2.97 (MJ) and 2.99 (MN)* (d, J = 16.3 Hz, 1H), 2.67 (MJ) and 2.70 (MN)* (d, J = 16.3 Hz, 1H), 2.14 (MJ) and 2.16 (MN)* (s, 6H) (*: the peaks of rotational isomers; MJ = major isomer, MN = minor isomer);
$^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C) δ 182.21 (MJ) and 182.17 (MN)*, 171.4, 170.3 (MN) and 170.2 (MJ)*, 141.4, 140.25 (MJ) and 140.22 (MN)*, 140.1 (MJ) and 140.0 (MN)*, 139.0, 138.7, 131.5 (q, J = 33.6 Hz), 127.7, 127.5, 127.1, 126.4, 125.7, 124.5, 124.4, 123.4 (q, J = 272.8 Hz), 123.04, 123.01, 117.5 (m), 63.1, 51.0 (MJ) and 50.9 (MN)*, 49.7, 49.60 (MJ) and 49.57 (MN)*, 48.9, 48.2 (MJ) and 48.1 (MN)*, 45.81 (MN) and 45.78 (MJ)* (*: the peaks of rotational isomers; MJ = major isomer, MN = minor isomer); IR (KBr, cm$^{-1}$): 3386, 3301, 3097, 3072, 3047, 3031, 2980, 2950, 2881, 2831, 2786, 1670, 1533, 1471, 1384, 1353, 1278, 1213, 1180, 1133, 1047, 970, 956, 887, 761, 727, 702, 683. HRMS (FAB$^+$): m/z calcd for C$_{31}$H$_{30}$F$_6$N$_5$O$_2$S [M+H]$^+$ 650.2024, found 650.2036.

The preparation of catalyst D, 1-(3,5-Bis(trifluoromethyl)phenyl)-3-[(2S,3R)-3-(dimethylamino)dibenzo[e,h]bicyclo[2.2.2]octa-5,7-dien-2-yl]thiourea, from S3.

To the solution of naphthalene (231 mg, 1.8 mmol, 6 eq) in DME (3 mL) was added small pieces of Na (97 mg, 4.2 mmol, 14 eq) under argon atmosphere and sonicated at 25 °C for 5 minutes to prepare sodium naphthalenide. A solution of S3 (136 mg, 0.3 mmol) in THF (8 mL) was added dropwise to the solution of sodium naphthalenide at -30 °C and stirred at this temperature for 40 minutes. The reaction mixture was poured into the ice water to quench excess amount of Na metal and the product was extracted (Et$_2$O, 40 mL x 3), washed (brine, 20 mL x 3) and dried (anhyd. Na$_2$SO$_4$). The solution was concentrated under reduced pressure and the residue was dissolved in CH$_2$Cl$_2$ (3 mL). 3,5-Bis(trifluoromethyl)phenyl isothiocyanate (70 µL, 0.38 mmol, 1.25 eq) was added to the solution at 0 °C and stirred for 30 minutes. The reaction solution was directly charged into silica gel column chromatography and purified (hexane/EtOAc (8:2)) to obtain catalyst D (119 mg, 0.22 mmol, 74%) as a faint yellowish amorphous solid; [α]$_D^{20}$ +6.6 (c 1.20, CHCl$_3$); $^1$H NMR (DMSO-d$_6$, 300 MHz) δ 10.7 (s, 1H), 8.34 (s, 2H), 7.70 (s, 1H), 7.49 (dd, J = 6.6, 1.5 Hz, 1H),
Bifunctional “roofed” cis-amine-thiourea catalyzed enantioselective Michael addition of nitroolefin and acetylacetone (Table 1 and 2): General procedure

To a solution of trans-β-nitrostyrene (4, 29.8 mg, 0.2 mmol) and “roofed” cis-amine-thiourea organocatalyst (0.02 mmol, 0.1 eq) in toluene or CH₂Cl₂ (0.4 mL) under argon atmosphere was added acetylacetone (3, 41 µL, 0.4 mmol, 2 eq) at 25 °C and stirred at the same temperature. The completion of the reaction was monitored by TLC. The reaction mixture was directly purified by column chromatography on silica gel (hexane/EtOAc (9/1 to 7/3)) to give 3-(2-nitro-1-phenylethyl)pentane-2,4-dione, 5 as a colorless solid; ¹H NMR (600 MHz, CDCl₃): δ 7.34-7.27 (m, 3H), 7.20-7.18 (m, 2H), 4.66 (dd, J = 12.5, 8.0 Hz, 1H), 4.62 (dd, J = 12.5, 4.9 Hz, 1H), 4.37 (d, J = 11.0 Hz, 1H), 4.24 (ddd, J = 11.0, 8.0, 4.9 Hz, 1H), 2.29 (s, 3H), 1.94 (s, 3H); ¹³C NMR (150 MHz, CDCl₃): δ 201.70, 200.94, 135.99, 129.29, 128.50, 127.91, 78.14, 70.68, 42.77, 30.38, 29.52. Spectroscopic data consistent with those previously reported.⁴
(R)-3-(2-nitro-1-phenylethyl)pentane-2,4-dione ((R)-5; Table 1, entry 1; 89% ee):

\[ \alpha \]_D^{29} -184.1 (c 0.35, CHCl_3) (lit. \[ \alpha \]_D^{21} -158.9 (c 1.1, CHCl_3), 93% ee (R)); HPLC analysis: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm): \( t_{\text{major}} = 16.5 \text{ min}, t_{\text{minor}} = 18.5 \text{ min}, 89\% \text{ ee (R)}.

(S)-3-(2-nitro-1-phenylethyl)pentane-2,4-dione ((S)-5; Table 1, entry 8; 89% ee):

\[ \alpha \]_D^{29} +185.9 (c 0.48, CHCl_3); HPLC analysis: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm): \( t_{\text{major}} = 17.4 \text{ min}, t_{\text{minor}} = 15.9 \text{ min}, 89\% \text{ ee (S)}.

(S)-3-(2-nitro-1-p-tolylethyl)pentane-2,4-dione (8a; Table 2, entry 2).

Colorless solid; \[ \alpha \]_D^{22} +197.4 (c 2.58, CHCl_3) (lit. \[ \alpha \]_D^{18} -177.4 (c 0.7, CHCl_3), 93% ee (R)); \(^1\text{H} \) NMR (600 MHz, CDCl_3): \( \delta \) 7.12 (d, \( J = 8.0 \text{ Hz}, 2\text{H} \)), 7.06 (d, \( J = 8.0 \text{ Hz}, 2\text{H} \)), 4.62 (dd, \( J = 12.0, 7.5 \text{ Hz}, 1\text{H} \)), 4.58 (dd, \( J = 12.0, 5.0 \text{ Hz}, 1\text{H} \)), 4.35 (d, \( J = 11.0 \text{ Hz}, 1\text{H} \)), 4.20 (ddd, \( J = 11.0, 7.5, 5.0 \text{ Hz}, 1\text{H} \)), 2.30 (s, 3H), 2.29 (s, 3H), 1.94 (s, 3H); \(^{13}\text{C} \) NMR (150 MHz, CDCl_3): \( \delta \) 201.85, 201.05, 138.35, 132.82, 129.98, 127.77, 78.36, 70.87, 42.47, 30.38, 29.41, 21.05. Spectroscopic data consistent with those previously reported. HPLC analysis: DAICEL CHIRALPAK IC (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm): \( t_{\text{major}} = 13.7 \text{ min}, t_{\text{minor}} = 20.7 \text{ min}, 95\% \text{ ee (S)}.

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(S)-3-(1-(4-methoxyphenyl)-2-nitroethyl)pentane-2,4-dione (8b; Table 2, entry 3).

Colorless solid; [α]_D^{22} +194.1 (c 2.80, CHCl_3) (lit.4 [α]_D^{21} −192.2 (c 1.2, CHCl_3), 94% ee (R)); ¹H NMR (600 MHz, CDCl_3): δ 7.10 (ddd, J = 8.7, 3.0, 2.3 Hz, 2H), 6.84 (ddd, J = 8.7, 3.0, 2.3 Hz, 2H), 4.60 (dd, J = 12.1, 7.2 Hz, 1H), 4.58 (dd, J = 12.1, 5.7 Hz, 1H), 4.33 (d, J = 10.9 Hz, 1H), 4.20 (ddd, J = 10.9, 7.2, 5.7 Hz, 1H), 3.77 (s, 3H), 2.29 (s, 3H), 1.94 (s, 3H); ¹³C NMR (150 MHz, CDCl_3): δ 201.83, 201.10, 159.51, 129.05, 127.65, 114.68, 78.43, 70.94, 55.21, 42.12, 30.34, 29.41. Spectroscopic data consistent with those previously reported.⁴ HPLC analysis: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm) : tₘₜₐₛ₂ = 27.3 min, tₘᵢₙᵢₒᵣ₂ = 25.1 min, 95% ee (S).

(S)-3-(1-(4-fluorophenyl)-2-nitroethyl)pentane-2,4-dione (8c; Table 2, entry 4).

Colorless solid; [α]_D^{22} +175.3 (c 2.58, CHCl_3) (lit.⁵ [α]_D^{25} +12.9 (c 1.0, CHCl_3), 89% ee (S)); ¹H NMR (600 MHz, CDCl_3): δ 7.18 (ddt, J = 8.7, 5.3, 3.0 Hz, 2H), 7.03 (tt, J = 8.7, 3.0 Hz, 2H), 4.62 (dd, J = 12.5, 7.2 Hz, 1H), 4.61 (dd, J = 12.5, 5.3 Hz, 1H), 4.33 (d, J = 10.6 Hz, 1H), 4.24 (ddd, J = 10.6, 7.2, 5.3 Hz, 1H), 2.30 (s, 3H), 1.97 (s, 3H); ¹³C NMR (150 MHz, CDCl_3): δ 201.45, 200.67, 162.50 (d, J = 249.1 Hz), 131.76, 129.67 (d, J = 7.7 Hz), 116.36 (d, J = 21.9 Hz), 78.12, 70.73, 42.05, 30.38, 29.57. Spectroscopic data consistent with those previously reported.⁵有力 HPLC analysis: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm) : tₘₜₐₛ₂ = 14.9 min, tₘᵢₙᵢₒᵣ₂ = 13.4 min, 94% ee (S).
(S)-3-(1-(4-chlorophenyl)-2-nitroethyl)pentane-2,4-dione (8d; Table 2, entry 5).

Colorless solid; [α]$_D^{22}$ +173.0 (c 1.65, CHCl$_3$) (lit. $^4$ [α]$_D^{21}$ +149.1 (c 1.1, CHCl$_3$), 90% ee (R)); $^1$H NMR (600 MHz, CDCl$_3$): δ 7.31 (ddt, $J = 9.1$, 2.7, 1.9 Hz, 2H), 7.14 (ddd, $J = 9.1$, 2.7, 1.9 Hz, 2H), 4.62 (dd, $J = 12.4$, 7.5 Hz, 1H), 4.60 (dd, $J = 12.4$, 5.3 Hz, 1H), 4.33 (d, $J = 11.0$ Hz, 1H), 4.23 (ddd, $J = 11.0$, 7.5, 5.3 Hz, 1H), 2.30 (s, 3H), 1.98 (s, 3H); $^{13}$C NMR (150 MHz, CDCl$_3$): δ 201.34, 200.53, 134.55, 134.52, 129.53, 129.30, 76.79, 70.50, 42.13, 30.40, 29.64. Spectroscopic data consistent with those previously reported.$^4$ HPLC analysis: DAICEL CHIRALPAK AS-H (4.6 x 250 mm, hexane/2-propanol = 7/3, 1.0 mL/min, 210 nm): $t_{major} = 8.9$ min, $t_{minor} = 15.4$ min, 97% ee (S).

(5)-3-(1-(3-chlorophenyl)-2-nitroethyl)pentane-2,4-dione (8e; Table 2, entry 6).

Colorless solid; [α]$_D^{22}$ +167.5 (c 1.05, CHCl$_3$) (lit.$^7$ [α]$_D^{6}$ +124 (c 0.3, CHCl$_3$), 96% ee (S)); $^1$H NMR (600 MHz, CDCl$_3$): δ 7.29-7.26 (m, 2H), 7.21-7.20 (m, 1H), 7.09-7.07 (m, 1H), 4.64 (dd, $J = 12.9$, 7.9 Hz, 1H), 4.62 (dd, $J = 12.9$, 4.9 Hz, 1H), 4.35 (d, $J = 10.6$ Hz, 1H), 4.23 (ddd, $J = 10.6$, 7.9, 4.9 Hz, 1H), 2.30 (s, 3H), 2.00 (s, 3H); $^{13}$C NMR (150 MHz, CDCl$_3$): δ 201.28, 200.41, 138.21, 135.17, 130.56, 128.83, 128.15, 126.11, 77.72, 70.35, 42.34, 30.46, 29.74. Spectroscopic data consistent with those previously reported.$^6$,$^7$ HPLC analysis: DAICEL CHIRALPAK IC (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm): $t_{major} = 10.8$ min, $t_{minor} = 16.3$ min, 94% ee (S).
(S)-3-(1-(2-chlorophenyl)-2-nitroethyl)pentane-2,4-dione (8f; Table 2, entry 8).

Colorless oil; $[\alpha]_D^{22} \pm 248.6$ (c 2.45, CHCl$_3$) (lit.$^7$ $[\alpha]_D^{22} +150$ (c 0.35, CHCl$_3$), >99% ee (S)); $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.44-7.43 (dd, $J = 7.2$, 1.9 Hz, 1H), 7.28-7.23 (m, 2H), 7.16 (dd, $J = 7.2$, 1.9 Hz, 1H), 4.84 (dd, $J = 12.4$, 6.8 Hz, 1H), 4.75 (ddd, $J = 10.2$, 6.8, 4.1 Hz, 1H), 4.66 (dd, $J = 12.4$, 4.1 Hz, 1H), 4.60 (d, $J = 10.2$ Hz, 1H), 2.30 (s, 3H), 2.04 (s, 3H); $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 201.85, 200.80, 133.75, 133.43, 130.64, 129.69, 129.03, 127.64, 76.18, 69.00, 38.85, 30.86, 28.42. Spectroscopic data consistent with those previously reported.$^7$ HPLC analysis: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm) : $t_{\text{major}} = 11.6$ min, $t_{\text{minor}} = 13.4$ min, 96% ee (S).

(S)-3-(2-nitro-1-(o-tolyl)ethyl)pentane-2,4-dione (8g; Table 2, entry 9).

Colorless solid; $[\alpha]_D^{22} \pm 158.5$ (c 2.10, CHCl$_3$) (lit.$^4$ $[\alpha]_D^{20} -122$ (c 1.1, CHCl$_3$), 90% ee (R)); $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.18-7.16 (m, 3H), 7.09-7.07 (m, 1H), 4.65-4.54 (m, 3H), 4.41 (d, $J = 10.2$ Hz, 1H), 2.41 (s, 3H), 2.30 (s, 3H), 1.91 (s, 3H); $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 201.59, 200.92, 136.68, 134.32, 131.59, 128.21, 126.75, 125.97, 77.76, 70.28, 37.69, 30.37, 30.15, 19.50. Spectroscopic data consistent with those previously reported.$^4$ HPLC analysis: DAICEL CHIRALPAK IC (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm) : $t_{\text{major}} = 12.6$ min, $t_{\text{minor}} = 21.4$ min, 97% ee (S).
(R)-3-(1-(furan-2-yl)-2-nitroethyl)pentane-2,4-dione (8h; Table 2, entry 10).

Colorless oil; [α]_D^{22} +152.3 (c 1.47, CHCl_3) (lit. [8] [α]_D^{27} -162.4 (c 1.0, CHCl_3), 97% ee (S)); ^1H NMR (400 MHz, CDCl_3): δ 7.36 (d, J = 1.8 Hz, 1H), 6.30 (dd, J = 3.2, 1.8 Hz, 1H), 6.18 (d, J = 3.2 Hz, 1H), 4.67 (d, J = 6.0 Hz, 2H), 4.41-4.32 (m, 2H), 2.29 (s, 3H), 2.09 (s, 3H); ^13C NMR (150 MHz, CDCl_3): δ 201.41, 200.71, 149.43, 142.87, 110.80, 108.83, 75.80, 67.92, 36.57, 30.59, 29.25. Spectroscopic data consistent with those previously reported. [4,8] HPLC analysis: DAICEL CHIRALPAK AS-H (4.6 x 250 mm, hexane/2-propanol = 7/3, 1.0 mL/min, 210 nm) : t_{major} = 11.2 min, t_{minor} = 14.1 min, 93% ee (R).

(R)-3-(2-nitro-1-(thiophen-2-yl)ethyl)pentane-2,4-dione (8i; Table 2, entry 11).

Colorless solid; [α]_D^{22} +178.1 (c 1.69, CHCl_3) (lit. [4] [α]_D^{18} -155.5 (c 1.2, CHCl_3), 92% ee (S)); ^1H NMR (400 MHz, CDCl_3): δ 7.24 (d, J = 5.0 Hz, 1H), 6.94 (dd, J = 5.0, 3.6 Hz, 1H), 6.89 (d, J = 3.6 Hz, 1H), 4.66 (d, J = 5.9 Hz, 2H), 4.58-4.52 (m, 1H), 4.41 (d, J = 10.5 Hz, 1H), 2.30 (s, 3H), 2.08 (s, 3H); ^13C NMR (150 MHz, CDCl_3): δ 201.41, 200.58, 138.44, 127.35, 126.97, 125.70, 78.48, 71.06, 38.23, 30.51, 29.59. Spectroscopic data consistent with those previously reported. [4] HPLC analysis: DAICEL CHIRALPAK AS-H (4.6 x 250 mm, hexane/2-propanol = 7/3, 1.0 mL/min, 210 nm) : t_{major} = 11.6 min, t_{minor} = 14.9 min, 93% ee (R).
(R)-3-(1-nitropentan-2-yl)pentane-2,4-dione (8j; Table 2, entry 12).

Colorless oil; [α]D20 +141.2 (c 0.78, CHCl3) (lit.7 [α]D f.l. +106 (c 0.22, CH2Cl2), >99% ee (R)); 1H NMR (600 MHz, CDCl3): δ 4.53 (d, J = 12.5, 4.5 Hz, 1H), 4.49 (dd, J = 12.5, 5.3 Hz, 1H), 4.00 (d, J = 8.4 Hz, 1H), 2.89-2.83 (m, 1H), 2.28 (s, 3H), 2.27 (s, 3H), 1.51-1.23 (m, 4H), 0.92 (t, J = 7.2 Hz, 3H); 13C NMR (150 MHz, CDCl3): δ 202.73, 202.31, 75.76, 69.29, 36.73, 31.61, 30.91, 29.83, 19.83, 13.69. Spectroscopic data consistent with those previously reported.7 HPLC analysis: DAICEL CHIRALPAK AD-H (4.6 x 250 mm, hexane/2-propanol = 98/2, 1.0 mL/min, 210 nm) : tmajor = 20.3 min, tminor = 22.5 min, 84% ee (R).

(R)-3-(1-nitro-4-phenylbutan-2-yl)pentane-2,4-dione (8k; Table 2, entry 13).

Colorless oil; [α]D17 +111.5 (c 0.82, CHCl3) (lit.4 [α]D -113 (c 0.9, CHCl3), 83% ee (S)); 1H NMR (600 MHz, CDCl3): δ 7.30 (t, J = 7.2 Hz, 2H), 7.22 (t, J = 7.2 Hz, 1H), 7.14 (d, J = 7.2 Hz, 2H), 4.58 (dd, J = 12.5, 4.5 Hz, 1H), 4.54 (dd, J = 12.5, 4.9 Hz, 1H), 3.97 (d, J = 8.3 Hz, 1H), 2.86-2.79 (m, 2H), 2.60 (ddd, J = 12.0, 9.1, 7.5 Hz, 1H), 2.21 (s, 3H), 2.14 (s, 3H), 1.79-1.73 (m, 1H), 1.63-1.58 (m, 1H); 13C NMR (150 MHz, CDCl3): δ 202.69, 202.23, 140.08, 128.72, 128.30, 126.50, 75.60, 69.27, 36.23, 32.81, 31.06, 30.81, 29.55. Spectroscopic data consistent with those previously reported.4 HPLC analysis: DAICEL CHIRALPAK AD-H (4.6 x 250 mm, hexane/2-propanol = 98/2, 1.0 mL/min, 210 nm) : tmajor = 30.0 min, tminor = 33.3 min, 81% ee (R).
References

S7: $^1$H NMR (CDCl$_3$, 300 MHz)

![H NMR spectrum](image)

S7: $^{13}$C NMR (CDCl$_3$, 75 MHz)

![C NMR spectrum](image)
**S2**: $^1$H NMR (CDCl$_3$, 300 MHz)

**S2**: $^{13}$C NMR (CDCl$_3$, 75 MHz)
2: $^1$H NMR (CDCl$_3$+CD$_2$OD 1 drop, 300 MHz, 50 °C)

2: $^{13}$C NMR (CDCl$_3$, 75 MHz)
S3: $^1$H NMR (CDCl$_3$, 300 MHz)

S3: $^{13}$C NMR (CDCl$_3$, 75 MHz)
**S4a**: $^1$H NMR (CDCl$_3$, 300 MHz)

**S4a**: $^{13}$C NMR (CDCl$_3$, 75 MHz)
**S4b:** $^1$H NMR (CDCl$_3$, 300 MHz)

![H NMR spectrum](image)

**S4b:** $^{13}$C NMR (CDCl$_3$, 75 MHz)

![C NMR spectrum](image)
S4c: $^1$H NMR (CDCl$_3$, 300 MHz)

S4c: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
Catalyst A1: $^1$H NMR (CDCl$_3$, 300 MHz)

Catalyst A1: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
**Catalyst A2:** \(^1\)H NMR (CDCl\(_3\), 300 MHz, 50 °C)

![H NMR spectrum](image)

**Catalyst A2: \(^{13}\)C NMR (CDCl\(_3\), 75 MHz, 50 °C; the peaks of rotational isomers were observed)

![C NMR spectrum](image)
Catalyst A3: $^1$H NMR (CDCl$_3$, 300 MHz, 50 °C)

Catalyst A3: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
6: $^1$H NMR (CDCl$_3$, 300 MHz, 50 °C)

6: $^{13}$C NMR (CDCl$_3$, 100 MHz, 50 °C)
**Catalyst B1: **$^1$H NMR (DMSO-d$_6$, 300 MHz)

![$^1$H NMR spectrum of Catalyst B1](image)

**Catalyst B1: **$^{13}$C NMR (CDCl$_3$, 100 MHz, 50 °C)

![$^{13}$C NMR spectrum of Catalyst B1](image)
Catalyst B2: $^1$H NMR (CDCl$_3$, 300 MHz, 50 °C)

Catalyst B2: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
Catalyst B3: $^1$H NMR (CDCl$_3$, 300 MHz, 50 °C)

Catalyst B3: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
Catalyst B4: $^1$H NMR (DMSO-$d_6$, 300 MHz)

Catalyst B4: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
**S5: $^1$H NMR (CDCl$_3$, 300 MHz, 50 °C)**

**S5: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)**
S6: $^1$H NMR (DMSO-d$_6$, 300 MHz, 50 °C)

S6: $^{13}$C NMR (DMSO-d$_6$, 100 MHz, 80 °C)
Catalyst C: $^1$H NMR (CDCl$_3$, 300 MHz, 50 °C)

Catalyst C: $^{13}$C NMR (CDCl$_3$, 75 MHz, 50 °C)
Catalyst D: $^1$H NMR (DMSO-$d_6$, 300 MHz)

Catalyst D: $^{13}$C NMR (CDCl$_3$, 100 MHz, 50 °C)
5: $^1$H NMR (600 MHz, CDCl$_3$)

5: $^{13}$C NMR (150 MHz, CDCl$_3$)
8a: $^1$H NMR (600 MHz, CDCl$_3$)

8a: $^{13}$C NMR (150 MHz, CDCl$_3$)
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8b: $^{13}$C NMR (150 MHz, CDCl$_3$)
8c: $^1$H NMR (600 MHz, CDCl$_3$)

8c: $^{13}$C NMR (150 MHz, CDCl$_3$)
8d: $^1$H NMR (600 MHz, CDCl$_3$)

8d: $^{13}$C NMR (150 MHz, CDCl$_3$)
8e: $^1$H NMR (600 MHz, CDCl$_3$)

8e: $^{13}$C NMR (150 MHz, CDCl$_3$)
8f. $^{1}$H NMR (600 MHz, CDCl$_3$)

8f. $^{13}$C NMR (150 MHz, CDCl$_3$)
8g. $^1$H NMR (600 MHz, CDCl$_3$)

8g. $^{13}$C NMR (150 MHz, CDCl$_3$)
8h: $^1$H NMR (400 MHz, CDCl$_3$)

8h: $^{13}$C NMR (150 MHz, CDCl$_3$)
8i: $^1$H NMR (400 MHz, CDCl$_3$)

8i: $^{13}$C NMR (150 MHz, CDCl$_3$)
8j. $^1$H NMR (600 MHz, CDCl$_3$)

8j. $^{13}$C NMR (150 MHz, CDCl$_3$)
8k: $^1$H NMR (600 MHz, CDCl$_3$)

8k: $^{13}$C NMR (150 MHz, CDCl$_3$)
HPLC Spectrum

5: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)

(Prepared in the presence of A1 (10 mol%) at 25°C for 48 h (Table 1, entry 1).)

(Prepared in the presence of B3 (2.5 mol%) at 25°C for 30 min (Table 1, entry 12).)

(Prepared in the presence of B3 (0.5 mol%) at -30°C for 24 h (Table 1, entry 22; Table 2, entry 1).)

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Series S
8a: DAICEL CHIRALPAK IC (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)

8b: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)
8c: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)

8d: DAICEL CHIRALPAK AS-H (4.6 x 250 mm, hexane/2-propanol = 7/3, 1.0 mL/min, 210 nm)
8e: DAICEL CHIRALPAK IC (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)

\[\text{Cl} \quad \text{(for 48 h)}\]

<table>
<thead>
<tr>
<th>Peak #</th>
<th>Retention Time</th>
<th>Area ((\mu)g/min)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.9</td>
<td>126900.4</td>
<td>51.56%</td>
</tr>
<tr>
<td>2</td>
<td>16.3</td>
<td>119191.2</td>
<td>48.43%</td>
</tr>
</tbody>
</table>

8f: DAICEL CHIRALPAK IE (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)

\[\text{Cl}\]

<table>
<thead>
<tr>
<th>Peak #</th>
<th>Retention Time</th>
<th>Area ((\mu)g/min)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.8</td>
<td>156247.5</td>
<td>97.51%</td>
</tr>
<tr>
<td>2</td>
<td>16.2</td>
<td>4239.3</td>
<td>2.48%</td>
</tr>
</tbody>
</table>
8g: DAICEL CHIRALPAK IC (4.6 x 250 mm, hexane/2-propanol = 85/15, 1.0 mL/min, 210 nm)

8h: DAICEL CHIRALPAK AS-H (4.6 x 250 mm, hexane/2-propanol = 7/3, 1.0 mL/min, 210 nm)
**8i**: DAICEL CHIRALPAK AS-H (4.6 x 250 mm, hexane/2-propanol = 7/3, 1.0 mL/min, 210 nm)

<table>
<thead>
<tr>
<th>Peak #</th>
<th>Retention Time</th>
<th>Area (µL/min)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>11.6</td>
<td>4493.8</td>
<td>50.671</td>
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<tr>
<td>2</td>
<td>14.9</td>
<td>4569.3</td>
<td>48.329</td>
</tr>
</tbody>
</table>

**8j**: DAICEL CHIRALPAK AD-H (4.6 x 250 mm, hexane/2-propanol = 98/2, 1.0 mL/min, 210 nm)

<table>
<thead>
<tr>
<th>Peak #</th>
<th>Retention Time</th>
<th>Area (µL/min)</th>
<th>Area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20.4</td>
<td>12978.4</td>
<td>49.941</td>
</tr>
<tr>
<td>2</td>
<td>22.4</td>
<td>12902.5</td>
<td>50.059</td>
</tr>
</tbody>
</table>
8k: DAICEL CHIRALPAK AD-H (4.6 x 250 mm, hexane/2-propanol = 98/2, 1.0 mL/min, 210 nm)