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Supporting Information

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Spontaneous resolution of chiral polyoxometalate-based compounds consisting of 3D chiral inorganic skeletons assembled from different helical units

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Supporting Information

General methods: Chemicals and solvents were either purchased puriss p. A. from commercial suppliers or purified by standards techniques. Catalysts **6** and **7** were prepared according to literature procedures.[1] For thin-layer chromatography (TLC), silica gel plates Merck 60 F254 were used and compounds were visualized by irradiation with UV light and/or by treatment with a solution of phosphomolybdic acid (25 g), $Ce(SO_4)_2$ g H_2O (10 g), conc. H_2SO_4 (60 mL) and H_2O (940 mL) followed by heating or by treatment with a solution of p-anisaldehyde (23 mL), conc. H_2SO_4 (35 mL), acetic acid (10 mL) and ethanol (900mL) followed by heating. Flash chromatography was performed using silica gel Merck 60 (particle size 0.040-0.063 mm), ^{1}H NMR and ^{13}C NMR spectra were recorded on Varian AS 400 or 300. Chemical shifts are given in ! relative to tetramethylsilane (TMS), the coupling constants J are given in Hz. The spectra were recorded in $CDCl_3$ as solvent at room temperature, TMS served as internal standard (! = 0 ppm) for ^{1}H NMR and $CDCl_3$ was used as internal standard (! = 77.16 ppm) for ^{13}C NMR. GC was carried out using a Varian 3800 GC instrument. Chiral GC-column used: CP-Chiralsil-Dex CB 25m x 0.32 mm. HPLC was carried out using a Waters 2690 Millenium with photodiode array detector. Optical rotations were recorded on a Perkin Elemer 241 Polarimeter (d = 589 nm, 1 dm cell). High-resolution mass (ESI) were obtained with a Bruker MicrOTOF spectrometer.

General procedure for the condition screen for the reaction between cinnamic aldehyde and methyl 5-nitro-pentenoate:

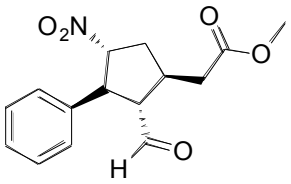
To a stirred solution of the catalyst (20 mol %) in solvent (0.5 mL) was added cinnamic aldehyde **1a** (33 mg, 0.25 mmol), methyl 5-nitro-pentenoate **2a** (48 mg, 0.3 mmol) and additive (0.025 mmol) at room temperature. The resulting reaction mixture was

1. a) M. Marigo, T. C. Wabnitz, D. Fielenbach, K. A. J¿rgensen, Angew. Chem. Int. Ed. **2005**, 44, 794. b) M. Marigo, D. Fielenbach, A. Braunton, A. Kjaersgaard, K. A. J¿rgensen, Angew. Chem. Int. Ed. **2005**, 44, 3703. c) J. FranzŽn, M. Marigo, D. Fielenbach, T. C. Wabnitz, A. Kjaersgaard, K. A. J¿rgensen, J. Am. Chem. Soc. **2005**, 127, 18296. d) Y. Hayashi, H. Gotoh, T. Hayashi, M. Shoji, Angew. Chem. Int. Ed. **2005**, 44, 4212. e) M. Marigo, J. FranzŽn, T. B. Poulsen, W. Zhuang, K. A. J¿rgensen, J. Am. Chem. Soc. **2005**, 127, 6964. g) H. SundŽn, I. Ibrahem, A. C–rdova, Tetrahedron Lett. **2006**, 47, 99. h) I. Ibrahem, A. C–rdova, Chem. Commun. **2006**, 1760.

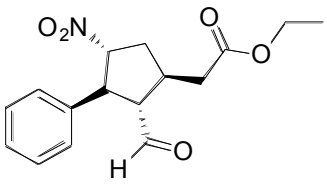
vigorously stirred and monitored by TLC analysis. Then the reaction mixture was washed with water and extracted with CH_2Cl_2. The organic layers were combined, dried over Na_2SO_4 and the solvent was removed under reduced pressure. The residue was purified by silica gel (pentane: ethyl acetate = 6:1) to give the corresponding product **3**.

General procedure for the reaction between different aldehydes and methyl 5-nitro-pentenoate:

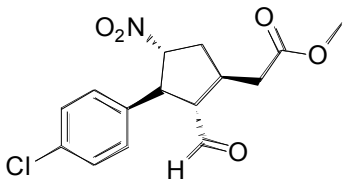
To a stirred solution of the catalyst **6** (20 mol %) in $CHCl_3$ (0.5 mL) was added aldehyde (0.25 mmol), methyl 5-nitro-pentenoate (66 mg, 0.3 mmol) and DABCO (0.025 mmol) at room temperature. Then the reaction was vigorously stirred and monitored by TLC analysis. The reaction mixture was washed with water and extracted with CH_2Cl_2. The organic layer was combined, dried over Na_2SO_4 and the solvent was removed. The residue was purified by silica gel (pentane: ethyl acetate = 6:1-4:1) to give product.



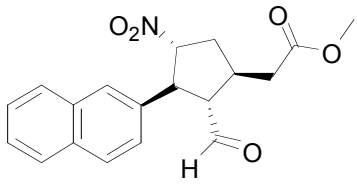
Methyl 2-((1*S*,2*S*,3*R*,4*R*)-2-formyl-4-nitro-3-phenylcyclopentyl)acetate 3a: $[\alpha]_D^{25}$ = -52.1 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.65 (d, J = 2.8 Hz, 1H), 7.37-7.22 (m, 5H), 5.08-5.03 (m, 1H), 4.06 (dd, J = 7.6, 10.4 Hz, 1H), 3.70 (s, 3H), 3.03-2.99 (m, 1H), 2.95-2.89 (m, 1H), 2.75-2.68 (m, 1H), 2.63 (dd, J = 6.0, 16.4 Hz, 1H), 2.54 (dd, J = 6.4, 16.4 Hz, 1H), 2.29-2.21 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.9, 171.9, 137.9, 129.5, 128.4, 127.4, 91.3, 62.6, 52.5, 52.1, 37.5, 37.4, 35.4; The enantiomeric excess was determined by HPLC with an AD column. (n-hexane: i-PrOH = 95:5, # =205 nm), 0.5 mL/min; t_R = major enantiomer 45.6 min, minor enantiomer 62.6 min. HRMS (ESI): calcd. for $[M+Na]^+$ ($C_{15}H_{17}NO_5Na$) requires m/z 314.0999, found 314.1005.



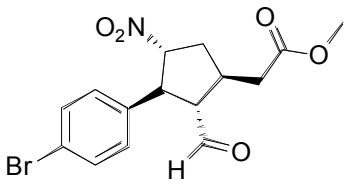
Ethyl 2-((1*S*,2*S*,3*R*,4*R*)-2-formyl-4-nitro-3-phenylcyclopentyl)acetate 3b: $[\alpha]_D^{25}$ = -62.9 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.65 (d, J = 2.4 Hz, 1H), 7.37-7.22 (m, 5H), 5.08-5.03 (m, 1H), 4.14 (q, J = 7.2 Hz, 2H), 4.06 (dd, J = 7.6, 10.4 Hz, 1H), 3.03-3.00 (m, 1H), 2.95-2.89 (m, 1H), 2.75-2.68 (m, 1H), 2.61 (dd, J = 6.0, 16.4 Hz, 1H), 2.52 (dd, J = 7.2, 16.4 Hz, 1H), 2.29-2.21 (m, 1H), 1.27 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.9, 171.9, 137.9, 129.5, 128.4, 127.4, 91.3, 62.6, 52.5, 52.1, 37.5, 37.4, 35.4; The enantiomeric excess was determined by HPLC with an AD column. (iso-hexane: i-PrOH = 97:3, # =210 nm), 0.5 mL/min; t_R = major enantiomer 57.9 min, minor enantiomer 82.2 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{16}H_{19}NO_5Na$) requires m/z 328.1155, found328.1158.



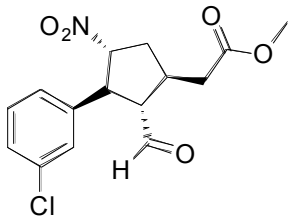
Methyl 2-((1S,2S,3R,4R)-3-(4-chlorophenyl)-2-formyl-4-nitrocyclopentyl)acetate 3c: $[\alpha]_D^{25}$ = - 76.1 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.64 (d, J = 2.4 Hz, 1H), 7.33 (d, J = 8.8 Hz, 2H), 7.18 (d, J = 8.8 Hz, 1H), 5.04-4.99 (m, 1H), 4.03 (dd, J = 8.0, 10.4 Hz, 1H), 3.70 (s, 3H), 3.01-2.88 (m, 2H), 2.75-2.68 (m, 1H), 2.63 (dd, J = 6.0, 16.4 Hz, 1H), 2.55 (dd, J = 6.4, 16.4 Hz, 1H), 2.30-2.21 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.5, 171.9, 136.3, 134.4, 129.7, 128.8, 91.0, 62.4, 52.1, 51.8, 37.4, 37.2, 35.3; The enantiomeric excess was determined by HPLC with an AD column. (n-hexane: i-PrOH = 90:10, # =205 nm), 0.5 mL/min; t_R = major enantiomer 43.4 min, minor enantiomer 55.3 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{15}H_{16}ClNO_5Na$) requires m/z 348.0609,found348.0607.



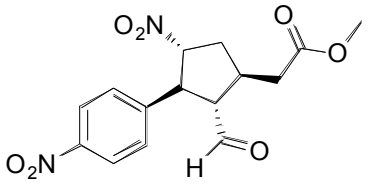
Methyl 2-((1*S*,2*S*,3*R*,4*R*)-2-formyl-3-(naphthalen-2-yl)-4-nitrocyclopentyl)acetate 3d: $[\alpha]_D^{25}$ = - 39.0 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.68 (d, J = 2.17 Hz, 1H), 7.87-7.77 (m, 3H), 7.69 (s, 1H), 7.51-7.47 (m, 2H), 7.34 (dd, J = 1.84, 6.72 Hz, 1H), 5.19-5.12 (m, 1H), 4.23 (dd, J = 7.69, 2.56 Hz, 1H), 3.71 (s, 3H), 3.10-3.01 (m, 1H), 2.80-2.72 (m, 1H), 2.70-2.53 (m, 2H), 2.30 (dt, J = 8.75, 3.03 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.0, 172.0, 135.1, 135.6, 133.2, 129.7, 128.1, 127.9, 127.0, 126.7, 124.7, 91.3, 62.6, 52.9, 52.2, 37.6, 37.5, 35.6; The enantiomeric excess was determined by HPLC with an AD column. (n-hexane: i-PrOH = 95:5, # =254 nm), 1.0 mL/min; t_R = major enantiomer 37.3 min, minor enantiomer 42.2 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{19}H_{19}NO_5Na$) requires m/z 364.1155, found 364.1154.



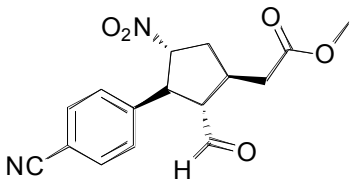
Methyl 2-((1*S*,2*S*,3*R*,4*R*)-3-(4-bromophenyl)-2-formyl-4-nitrocyclopentyl)acetate 3e: $[\alpha]_D^{25}$ = - 68.9 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.63 (d, J = 2.8 Hz, 1H), 7.47 (d, J = 8.8 Hz, 2H), 7.12 (d, J = 8.8 Hz, 1H), 5.04-4.98 (m, 1H), 4.02 (dd, J = 7.6, 10.4 Hz, 1H), 3.73 (s, 3H), 3.00-2.87 (m, 2H), 2.74-2.67 (m, 1H), 2.62 (dd, J = 6.0, 16.8 Hz, 1H), 2.54 (dd, J = 6.4, 16.8 Hz, 1H), 2.29-2.21 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.5, 171.9, 136.9, 132.7, 129.3, 122.5, 91.0, 62.5, 52.2, 51.9, 37.5, 37.3, 35.4; The enantiomeric excess was determined by HPLC with an AD column. (n-hexane: i-PrOH = 90:10, # =205 nm), 0.5 mL/min; t_R = major enantiomer 47.7 min, minor enantiomer 59.8 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{15}H_{16}BrNO_5Na$) requires m/z 392.0104, found 392.0096.



Methyl 2-((1*S*,2*S*,3*R*,4*R*)-3-(3-chlorophenyl)-2-formyl-4-nitrocyclopentyl)acetate 3f: ["]$_D^{25}$ = - 47.9 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.65 (d, J = 2.45 Hz, 1H), 7.31-7.13 (m, 4H), 5.07-5.01 (m, 1H), 4.05 (dd, J = 7.8, 18.34 Hz, 1H), 3.70 (s, 3H), 2.99-2.89 (m, 1H), 2.75-2.67 (m, 2H), 2.63-2.56 (m, 2H), 2.29-2.23 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.5, 172.0, 140.0, 135.4, 131.0, 128.8, 127.7, 126.0, 91.0, 62.6, 52.2, 52.0, 37.5, 37.4, 35.5; The enantiomeric excess was determined by HPLC with an ODH column. (n-hexane: i-PrOH = 95:5, # = 205 nm), 1.0 mL/min; t_R = major enantiomer 68.7 min, minor enantiomer 83.9 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{15}H_{16}ClNO_5Na$) requires m/z 348.0609, found 348.0597.

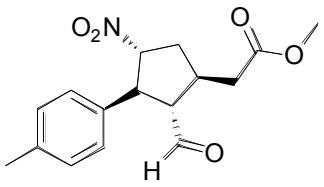


Methyl 2-((1*S*,2*S*,3*R*,4*R*)-2-formyl-4-nitro-3-(4-nitrophenyl)cyclopentyl)acetate 3g: ["]$_D^{25}$ = - 24.0 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.68 (d, J = 2.02 Hz, 1H), 8.22 (d, J = 8.88 Hz, 2H), 7.46 (d, J = 8.70 Hz, 2H), 5.14-5.10 (m, 1H), 4.19 (dd, J = 8.30, 18.70 Hz, 1H), 3.72 (s, 3H), 3.03-2.97 (m, 2H), 2.79-2.73 (m, 1H), 2.64 (t, J = 6.6, 12.8 Hz, 2H), 2.36-2.30 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 199.0, 172.0, 148.0, 145.3, 128.8, 124.7, 90.6, 62.5, 52.3, 51.7, 37.4, 37.1, 35.4; The enantiomeric excess was determined by HPLC with an Ad column. (n-hexane: i-PrOH = 80:20, # =205 nm), 1.0 mL/min; t_R = major enantiomer 38.3 min, minor enantiomer 41.5 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{15}H_{16}N_2O_7Na$) requires m/z 359.0850, found 359.0837.

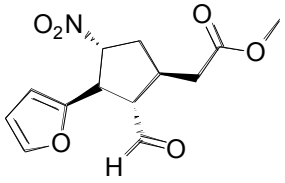


Methyl 2-((1*S*,2*S*,3*R*,4*R*)-3-(4-cyanophenyl)-2-formyl-4-nitrocyclopentyl)acetate 3h: ["]$_D^{25}$ = - 66.5 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.66 (d, J = 1.50 Hz, 1H), 7.66 (d, J = 8.11 Hz, 2H), 7.38 (d, J = 8.18 Hz, 2H), 5.10-5.03 (m, 1H), 4.13 (dd, J = 8.04,

2.40 Hz, 1H), 3.71 (s, 3H), 3.01-2.95 (m, 2H), 2.78-2.70 (m, 1H), 2.62 (dd, J = 5.78, 1.50 Hz, 2H), 2.30 (dt, J = 8.43, 2.20 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 198.8, 171.7, 143.1, 133.1, 128.4, 118.2, 112.3, 90.3, 62.1, 52.1, 51.7, 37.2, 40.0, 35.2; The enantiomeric excess was determined by HPLC with an AD column. (n-hexane: i-PrOH = 80:20, # =254 nm), 1.0 mL/min; t_R = major enantiomer 28.6 min, minor enantiomer 40.4 min; HRMS (ESI): calcd. for $[M+Na]^+$($C_{16}H_{16}N_2O_5Na$) requires m/z 339.0951, found 339.0957.



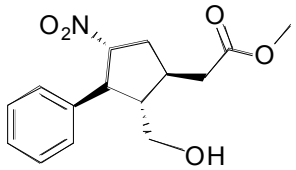
Methyl 2-((1*S*,2*S*,3*R*,4*R*)-2-formyl-4-nitro-3-*p*-tolylcyclopentyl)acetate 3i: ["]$_D^{25}$ = - 53.9 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.64 (d, J = 2.4 Hz, 1H), 7.17-7.10 (m, 4H), 5.05-5.00 (m, 1H), 4.01 (dd, J = 7.6, 10.4 Hz, 1H), 3.69 (s, 3H), 3.03-2.98 (m, 1H), 2.92-2.86 (m, 1H), 2.74-2.67 (m, 1H), 2.62 (dd, J = 5.6, 16.4 Hz, 1H), 2.53 (dd, J = 7.2, 16.4 Hz, 1H), 2.32 (s, 3H), 2.28-2.20 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 200.0, 171.9, 138.2, 134.7, 130.1, 127.3, 91.4, 62.6, 52.3, 52.1, 37.6, 37.3, 35.3, 21.2; The enantiomeric excess was determined by HPLC with an AD column. (iso-hexane: i-PrOH = 90:10, # =210 nm), 0.5 mL/min; t_R = major enantiomer 27.3 min, minor enantiomer 32.5 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{16}H_{19}NO_5Na$) requires m/z 328.1155, found 328.1157.



Methyl 2-((1*S*,2*S*,3*S*,4*R*)-2-formyl-3-(furan-2-yl)-4-nitrocyclopentyl)acetate 3j: ["]$_D^{25}$ = - 68.6 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.74 (d, J = 2.4 Hz, 1H), 7.37-7.36 (m, 1H), 6.32-6.31 (m, 1H), 6.21-6.20 (m, 1H), 5.10-5.06 (m, 1H), 4.01 (dd, J = 6.0, 9.2 Hz, 1H), 3.70 (s, 3H), 3.01-2.89 (m, 2H), 2.71-2.66 (m, 1H), 2.62 (dd, J = 6.4, 16.4 Hz, 1H), 2.53 (dd, J = 7.2, 16.4 Hz, 1H), 2.25-2.17 (m, 1H); ^{13}C NMR (100 MHz,

$CDCl_3$) δ 199.5, 171.8, 150.9, 143.0, 110.8, 107.7, 88.8, 60.5, 52.1, 45.1, 37.9, 37.5, 35.6; The enantiomeric excess was determined by HPLC with an AD column. (n-hexane: i-PrOH = 90:10, # =210 nm), 0.5 mL/min; t_R = major enantiomer 25.5 min, minor enantiomer 32.3 min. HRMS (ESI): calcd. for $[M+Na]^+$($C_{13}H_{15}NO_6Na$) requires m/z 304.0792, found 304.0795.

General procedure for the reduction of product 3 to the corresponding alcohol: Aldehyde **3** (0.1 mmol), dissolved in CH_2Cl_2 (0.5 ml), was diluted with MeOH (2 mL) and $NaBH_4$ (15 mg, 0.4 mmol) was added. After 10 min, NH_4Cl (sat.) was added and the water phase was extracted with CH_2Cl_2. The combined organic layers was dried over Na_2SO_4. The solvent was removed and the residue was purified by flash chromatography (pentane: ethyl acetate = 2:1) to give product **3**.



Methyl 2-((1*S*,2*S*,3*R*,4*R*)-2-(hydroxymethyl)-4-nitro-3-phenylcyclopentyl)acetate 8a: ["]$_D^{25}$ = - 66.8 (c = 1.0, $CHCl_3$); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35-7.31 (m, 2H), 7.28-7.24 (m, 1H), 7.21-7.19 (m, 2H), 5.00-4.95 (m, 1H), 3.70 (s, 3H), 3.67-3.58 (m, 2H), 3.47 (br s, 1H), 2.74-2.61 (m, 3H), 2.48 (dd, J = 6.8, 16.4 Hz, 1H), 2.26 (m, 1H), 2.18-2.10 (m, 1H), 1.95-1.92 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 173.4, 139.2, 129.1, 127.8, 127.7, 91.1, 60.6, 54.3, 53.7, 52.0, 37.8, 37.3, 35.5; HRMS (ESI): calcd. for $[M+Na]^+$($C_{15}H_{19}NO_5Na$) requires m/z 316.1155, found 316.1158

Procedure for the synthesis of ((1*S*,2*R*,3*R*,5*S*)-5-(2-Methoxy-2-oxoethyl)-3-nitro-2-phenylcyclopentyl)methyl 2,4-dichlorobenzoate 9a. To a stirred solution of the aldehyde **3a** (29 mg, 0.1 mmol) in MeOH (2 mL) at 0^{o}C was added $NaBH_4$ (15 mg, 0.4 mmol). After 10 min., saturated NH_4Cl aq. was added and the mixture was extracted with EtOAc (3 * 10 ml). The organic layers were collected and dried over Na_2SO_4. The solvent was removed and the residue was dissolved in CH_2Cl_2 (2 mL). Then 2,4-dichlorobenzoyl chloride (0.1 mmol) and Et_3N (0.1 mmol) was added. After stirring at

NOE of compound 3c: