Angewandte Chemie
Eine Zeitschrift der Gesellschaft Deutscher Chemiker

Supporting Information

69451 Weinheim, Germany

Lanthanitin; A chiral nano-ball encapsulating 18 lanthanum ions through ferritin-like assembly

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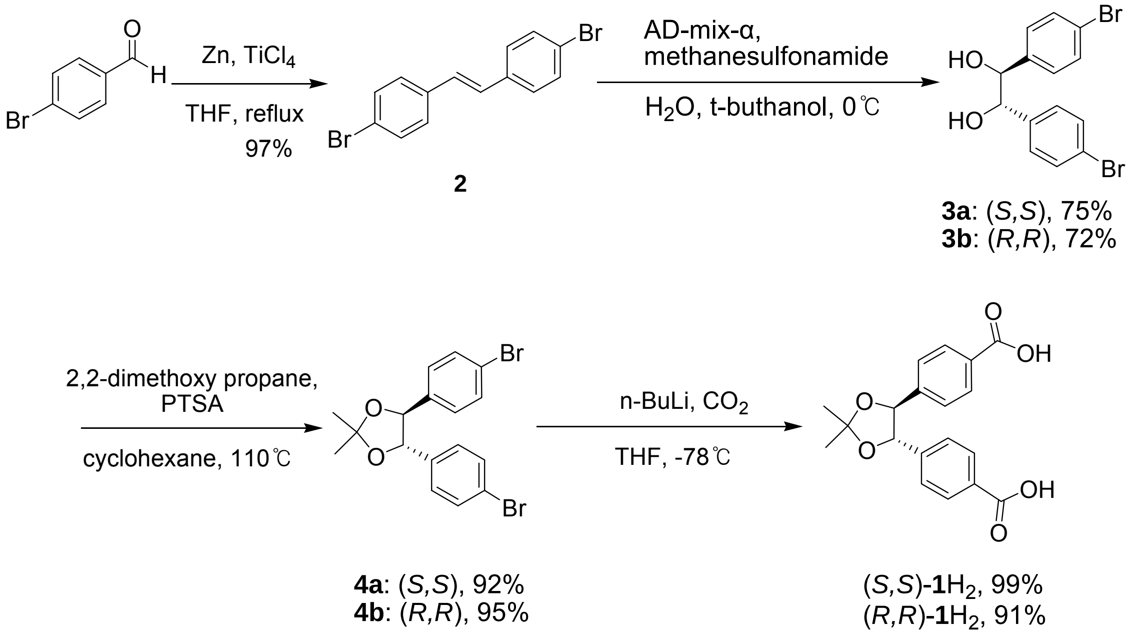
1. Synthesis of (*S*,*S*)-1H_2 and (*R*,*R*)-1H_2

1.1. General consideration for the synthesis

Unless otherwise noted, all materials were obtained from commercial suppliers Aldrich and TCI, and used without further purification. Tetrahydrofuran(THF) was freshly distilled from sodium benzophenone ketyl prior to use. Toluene was distilled from calcium hydride and stored over 4Å molecular sieve. Evaporation of organic solvents was conducted using a Büchi rotary evaporator with a desktop vacuum pump. Thin layer chromatography plates (Silica gel 60 F_{254}, Merck) were visualized by ultraviolet light and/or treatment with acidic *p*-anisaldehyde stain followed by gentle heating. Chromatographic purification of products were accomplished by flash chromatography by using Merck silica gel 60(230~400mesh) with a mixture of hexane and ethyl acetate as eluent. ^{1}H NMR spectra were recorded on Varian Gemini 75 MHz spectrometer with complete proton decoupling. Chemical shifts are reported in ppm relative to the methyl peak of TMS. High performance liquid chromatography (HPLC) was conducted using a Waters model 600 pumping system with a Waters model 2487 ultraviolet detector at 254nm. Infrared (IR) spectra were recorded on a Bomem 102 FT-IR spectrometer. Optical retations were measured at the 589nm sodium D-Line with RUDOLPH AUTOPOL automatic polarimeter. Low- and High-resolution FAB mass spectra were obtained by JEOL JMS-AX505WA mass spectrometer. Melting points were measured with capillary melting point apparatus of Thomas Hoover and are uncorrected.

1.2. Scheme for the preparation of (*S*,*S*)-**1**H_2 and (*R*,*R*)-**1**H_2

The synthesis was carried out by the following scheme.



Scheme 1.

1.3. Experimental Procedures for the synthesis of ligands.

Trans-4,4’-Dibromostilbene (2)

To a stirred suspension of zinc powder (19.90 g, 302 mmol) in dry THF (300 ml), $TiCl_4$ (16.50 ml, 151 mmol) was added dropwise at -10^{0}C. After the completion of the addition, a solution of 4-bromobenzaldehyde (10.00 g, 54 mmol) in dry THF (250 ml) was added dropwise while the mixture was refluxed and stirred for 5h. The solution was quenched with saturated aqueous $NaHCO_3$ solution and extracted with ethyl acetate (3 x). The combined organic layer was washed with brine, dried on $MgSO_4$, and concentrated in vacuo. The resultant white precipitate was washed with hexane to leave a white solid (8.84 g, 97 %). m.p. 183-185 ^{o}C; TLC (Hex:EA, 5:1 v/v): R_F = 0.62; ^{1}H-NMR (300 MHz, $CDCl_3$, 25 ^{o}C, TMS): δ 7.01 p.p.m. (s, 2H), 7.37 (d, J = 8.7 Hz, 4H), 7.49 (d, J = 8.7 Hz, 4H); ^{13}C-NMR (75 MHz, $CDCl_3$): δ 121.6, 128.0, 128.1, 131.8, 135.9; IR (KBr): 3,055 cm^{-1}; analysis(% calcd, % found for $C_{14}H_{10}Br_2$): C (49.74, 49.33), H (2.98, 2.94).

(*S*,*S*)-1,2-Bis(4-bromophenyl)-ethane-1,2-diol (3a)

AD-mix-α (50 g, 1.4 g per mmol) was stirred in two phases of *t*-butyl alcohol (180 ml) and water (180 ml) at r.t. After the two phases were clearly formed, $CH_3SO_2NH_2$ (3.38g, 35.50 mmol) was added to the AD-mix-α solution at 0^{o}C. *trans*-4,4’-Dibromostilbene (12.00 g, 35.50 mmol) was added to the reaction mixture in one portion at 0^{o}C. The resultant reaction mixture was stirred at 0^{o}C for 6 h. After completion of the reaction, the mixture was quenched with a saturated aqueous Na_2CO_3 solution and extracted with ethyl acetate (x3). The combined extract was washed with brine, dried on anhydrous $MgSO_4$ and filtered. The filtrate was concentrated under reduced pressure to give a pale yellow precipitate. The crude product was purified by column chromatography (SiO_2) with an eluent of Hex/EA=1:1. A white solids (9.00 g, 26.63 mmol) was obtained in 75 % yield.

m.p. 183-185 ^{o}C; TLC (Hex:EA, 1:1 v/v): R_F = 0.45; $[\alpha]_D^{18}$ (deg cm^{3} g^{-1} dm^{-1}) = -1434 (c = 0.005 g cm^{-3} in $CHCl_3$); ^{1}H-NMR (300 MHz, $CDCl_3$, 25 ^{o}C, TMS): δ 7.34 p.p.m. (d, J = 8.4 Hz, 4H), 6.90 (d, J = 8.4 Hz, 4H), 4.48 (s, 2H), 3.27 (s, 2H); ^{13}C-NMR (75 MHz, $CDCl_3$): δ 78.4, 122.0, 128.6, 131.3, 138.4; IR (KBr): 3379, 3055, 2933 cm^{-1}; analysis(% calcd, % found for $C_{14}H_{12}Br_2O_2$): C (45.20, 45.14), H (3.25, 3.23): HPLC (Daicel Chiralpak AD-H, n-Hex/IPA = 9 : 1, flow 0.5 ml/min, detection at 254 nm): τ_R = 20.25 min. 99.9 % ee.

(*R*,*R*)-1,2-Bis(4-bromophenyl)-ethane-1,2-diol (3b)

Same procedure as above, but using AD-mix-β instead of AD-mix-α, was applied to obtain **3b.** 8.2g (22.0 mmol, 72% yield) of **3b** was obtained from 10.3 g (30.6 mmol) of **2**. HPLC: τ_R = 18.43 min, 99.8 % ee; $[\alpha]_D^{18}$ (deg cm^{3} g^{-1} dm^{-1})= -1418 (c = 0.0052 g cm^{-3} in $CHCl_3$).

(*S*,*S*)-4,5-bis-(4-bromo phenyl)-2,2-dimethyl-[1,3]dioxolane (4a)

A reaction mixture of (S,S)-1,2-bis(4-bromophenyl)-ethane-1,2-diol (15.60 g, 42 mmol), *p*-TsOH·H_2O (319 mg, 1.68 mmol, 4 mol%), 2,2-dimethoxypropane (7.70 ml, 62.90 mmol), cyclohexane (600ml, 0.07M) equipped with a Dean-Stark trap was stirred at reflux. After 3h, the reaction mixture was concentrated in vacuo to give crude product as a dark oil. This was purified by column chromatograpy (SiO_2, eluent: Hex : EA = 5 : 1) to afford a white solid (16.00 g, 92 %). m.p. 130 ^{o}C; TLC (Hex:EA, 5:1 v/v): R_F = 0.65; $[\alpha]_D^{20}$ (deg cm^{3} g^{-1} dm^{-1}) = -1329 (c = 0.043 g cm^{-3} in $CHCl_3$); ^{1}H NMR (300 MHz, $CDCl_3$, 25 ^{o}C, TMS): δ 1.66 p.p.m. (s, 6H), 4.62 (s, 2H), 7.08 (d, J = 8.4 Hz, 4H), 7.46 (d, J = 8.4 Hz, 4H); ^{13}C NMR (75 MHz,

$CDCl_3$): δ 27.1, 84.8, 109.8, 122.3, 128.2, 131.6, 135.4; IR (KBr): 2996, 2884, 1911, 1601 cm^{-1}; analysis(% calcd, % found for $C_{16}H_{16}Br_2O_2$): C (49.54, 49.53), H (3.91, 3.90).

(*R,R*)-4,5-bis-(4-bromo phenyl)-2,2-dimethyl-[1,3]dioxolane (4b)

Same procedure as above employing of 3.00 g (8.06 mmol) of (R,R)-1,2-Bis(4-bromophenyl)-ethane-1,2-diol **(3b)** provided 3.16 g (7.66 mmol, 95%) of (R,R)-4,5-bis-(4-bromo phenyl)-2,2-dimethyl-[1,3]dioxolane **(4b)** as a white solid. Spectral data of **4b** are identical with those of **4a** except for $[\alpha]_D^{20}$ (deg cm^3 g^{-1} dm^{-1}) = +1330 (c = 0.051 g cm^{-3} in $CHCl_3$).

(*S,S*)- 4,5-Di(4-carboxy-phenyl)-2,2-dimethyl-[1,3]dioxolane ((*S,S*)-1H$_2$)

A solution of n-butyllithium (4.4 ml of 1.6 M solution in hexane, 7.1mmol) was added slowly to a solution of (S,S)-4,5-bis-(4-bromo phenyl)-2,2-dimethyl-[1,3]dioxolane (1.32 g, 3.20mmol) in distilled THF (32 ml) at –78℃ under argon atmosphere. After stirring for 30 min at –78℃, the fresh dry ice was added to a reaction mixture and was allowed to warm to room temperature. The reaction mixture was quenched with an H_2O and NaOH(1N 100ml) extracted with ethyl acetate. The crude aqueous solution was treated with an aqueous HCl solution (1 N, 100 mL) to make *p*H of the solution to 1 and the organic compounds were extracted with ethyl acetate. The organic extracts were combined and washed with brine, dried over anhydrous $MgSO_4$ and filtered. The filtrate was then concentrated under reduced pressure to give a solid crude product. The residue was purified by recrystallization to afford white solid (1.08g, 3.15mmol, 99%). m.p. 237-238 °C; TLC (CH_2Cl_2:MeOH, 10:1 v/v): R_F = 0.42; $[\alpha]_D^{18}$ (deg cm^3 g^{-1} dm^{-1}) = -1899 (c = 0.0015 g cm^{-3} in DMF); ^{1}H NMR (300 MHz, [D$_6$]DMSO, 25 °C, TMS): δ 1.59 p.p.m. (s, 6H), 4.82 (s, 2H), 7.32 (d, *J* = 7.4 Hz, 4H); 7.92 (d, *J* = 7.7 Hz, 4H); 13.0 (br, 2H); ^{13}C NMR (75 MHz, [D$_6$]DMSO): δ 27.6, 84.6, 110.1, 127.7, 130.2, 131.5, 141.8, 167.7; IR (KBr): 3027, 1693 cm^{-1}; HRMS (*m/z*): $[M+Na]^+$ calcd for $C_{19}H_{18}NaO_6$, 365.1000; found, 365.1001.

(*R,R*)- 4,5-Di(4-carboxyphenyl)-2,2-dimethyl-[1,3]dioxolane ((*R,R*)-1H$_2$)

Same procedure as above employing of with 2.50 g (6.07 mmol) of (*R,R*)-4,5-bis-(4-bromophenyl)-2,2-dimethyl-[1,3]dioxolane **(4b)** provided 1.90 g (5.52 mmol, 91%) of (*R,R*)-4,5-Di(4-carboxyphenyl)-2,2-dimethyl-[1,3]dioxolane **((*R,R*)-1H$_2$)** as a white solid. Spectral data of **(*R,R*)-1H$_2$** are identical with those of **(*S,S*)-1H$_2$** except for $[\alpha]_D^{20}$ (deg cm^3 g^{-1} dm^{-1}) = +1905 (c = 0.0015 g cm^{-3} in DMF).

2. Preparation and characterization of (*S*) and (*R*) lanthanitins

2.1. Crystallization

When $LaCl_3 \cdot 6H_2O$ (0.010 g, 0.10 mmol) and **1**H$_2$, an acid form of **1** (0.010 g, 0.10 mmol) was heated at 60 ºC for two weeks in the mixed solution of *N,N'*-diethylformaimde (DEF) (3.0 mL) and H_2O (3.0 mL), colorless prismatic crystals were obtained with the yield of ~30% based on the used ligand. The crystals were slightly soluble in water, but not soluble in common organic solvents. IR (KBr, cm^{-1}): ν_{CO} 1667(s), 1460(s). Anal. Calcd. for $[La_{18}(CO_3)_2(C_{19}H_{16}O_6)_{24}(H_2O)_{32}](CO_3) \cdot (H_2O)_{20.5}(DEF)_{1.5} = C_{466.5}H_{505.5}N_{1.5}O_{207}La_{18}$: C, 46.90; H, 4.27; N, 0.18. Found: C, 46.90; H, 4.11; N, 0.15.

2.2. Single crystal X-ray diffraction studies of (*S*)-lanthanitin

A prismatic colorless crystal with a suitable size (0.50 mm x 0.30 mm x 0.30 mm) was attached on a glass capillary, which was positioned in a $N_2(g)$ stream at 243(2)K upon mounting on a Bruker SMART CCD diffractometer equipped with a normal focus and graphite monochromated Mo-target X-ray tube ($\lambda = 0.71073$ Å) operated at 2,000 W power (50 kV, 40 mA). Total 1,315 frames were collected with varying ω with an exposure time of 5 s/frame. The last 50 frames were collected over the same Ewald sphere as those of the first 50 frames in order to detect possible crystal decay. The frames were integrated with the SAINT software package with a narrow frame algorithm[1]. The final cell constants were based on the *xyz* centroids of 9,543 reflections. Analysis of the data showed negligible decay during collection. An absorption correction was applied using SADABS[2]. The structure was solved by direct methods and subsequent difference Fourier syntheses and refined with the SHELX-TL software package[3]. A total of 211,188 reflections were collected in the range $1.05° < \theta < 20.84°$ of which 32,002 were independent and 22,331 were observed ($I > 2\sigma(I)$). All stages of weighted full-matrix least-squares refinement were conducted using F_o^2 data and converged to give $R1 = 0.0835$ ($I > 2\sigma(I)$), $wR2 = 0.2268$ (all data) and GOF = 1.029. The diffuse electron density due to the disordered and unidentified moieties was treated with the SQUEEZE routine within the PLATON software package[4]. Statistics prior to treatment of data with SQUEEZE were $R1 = 0.1057$ ($I > 2\sigma(I)$), $wR2 = 0.3132$ (all data) and GOF = 1.042. The crystal belongs to the tetragonal space group $P4_122$ (No. 91) with Z = 4. As the crystallographic 2-fold axis passed Lanthanitin, the asymmetric unit is composed of a half of the whole molecule. All the non-hydrogen atoms were refined anisotropically with restraints on the thermal parameters of six atoms due to the non-positive definite problems; EADP instructions have been applied to O(14W), O(15W), C(9E), C(7K), O(4L), and C(16J) by using the thermal parameters of the neighboring or adjacent atoms. Bond distance restraints (SADI) were applied to La(9)…O(14W) and La(9)…O(15W) pairs because of the rather short distance between La(9) and O(15W). In addition, the 12 ligands have been restrained to have same structures by using SAME instructions. Hydrogen atoms were generated with the ideal geometry. The suitable positions for the included solvent molecules could not be determined from diffuse electron density residuals with the current x-ray data. As the total solvent accessible volume was 19,714 Å^3 per unit cell volume 60,864 Å^3 (32.4%), which was calculated by SOLV in the PLATON program package, 4,928 Å^3 per one lanthanitin was presumed as available room for the unidentified disordered solvent molecules. Lanthanitins are packed in a similar way of a body-centered cubic array which produced large octahedral hydrophilic cavities, on which water molecules attached by binding to the exposed lanthanium ion to surface. The crystal formula was used from a reasonable estimate with the aid of both elemental microanalysis (EA) and the size of the available volume in the unit cell. The absolute configuration was confirmed by the Flack's x parameter, 0.060(19). Although a tendency of disorder near La(7) produced a large residual peak near the atom, it was difficult to resolve it clearly with the current x-ray data and to find one missing coordinated water molecule around La(7).

1. Saint Plus, v.6.01, Bruker Analytical X-ray, Madison, WI, 1999.
2. Sheldirck, G. M. SADABS. Program for Empirical Absorption Correction of Area Detector

Data,University of Gottigen: Gottingen, Germany, 1996.
3. Sheldrick, G. M. SHELX-TL, v.6.14; Bruker Analytical X-ray, Madison, WI, 2000.
4. Spek, A. L. PLATON, The University of Utrecht, Utrecht, The Netherlands, 1999

Table S1. Crystal data and structure refinement for (*S*)-Lanthanitin.

Empirical formula	$C_{466.5} H_{505.5} N_{1.5} O_{207} La_{18}$	
Formula weight	11945.60	
Temperature	243(2) K	
Wavelength	0.71073 Å	
Crystal system	Tetragonal	
Space group	$P4_122$ (No. 91)	
Unit cell dimensions	a = 27.5037(10) Å	α= 90°.
	b = 27.5037(10) Å	β= 90°.
	c = 80.460(3) Å	γ = 90°.
Volume	60864(4) $Å^3$	
Z	4	
Density (calculated)	1.304 Mg/m^3	
Absorption coefficient	1.312 mm^{-1}	
F(000)	23988	
Crystal size	0.50 x 0.30 x 0.30 mm^3	
Theta range for data collection	1.05 to 20.84°.	
Index ranges	$-27 \le h \le 27, -27 \le k \le 27, -57 \le l \le 80$	
Reflections collected	211188	
Independent reflections	32002 [R_{int} = 0.1348]	
Completeness to theta = 20.84°	99.9 %	
Absorption correction	SADABS	
Max. and min. transmission	0.6943 and 0.5599	
Refinement method	Full-matrix-block least-squares on F^2	
Data / restraints / parameters	32002 / 6391 / 2893	
Goodness-of-fit on F^2	1.029	
Final R indices [I>2sigma(I)]	R1 = 0.0835, wR2 = 0.2086	
R indices (all data)	R1 = 0.1125, wR2 = 0.2268	
Absolute structure parameter	0.060(19)	
Largest diff. peak and hole	2.581 and -0.983 e.$Å^{-3}$	

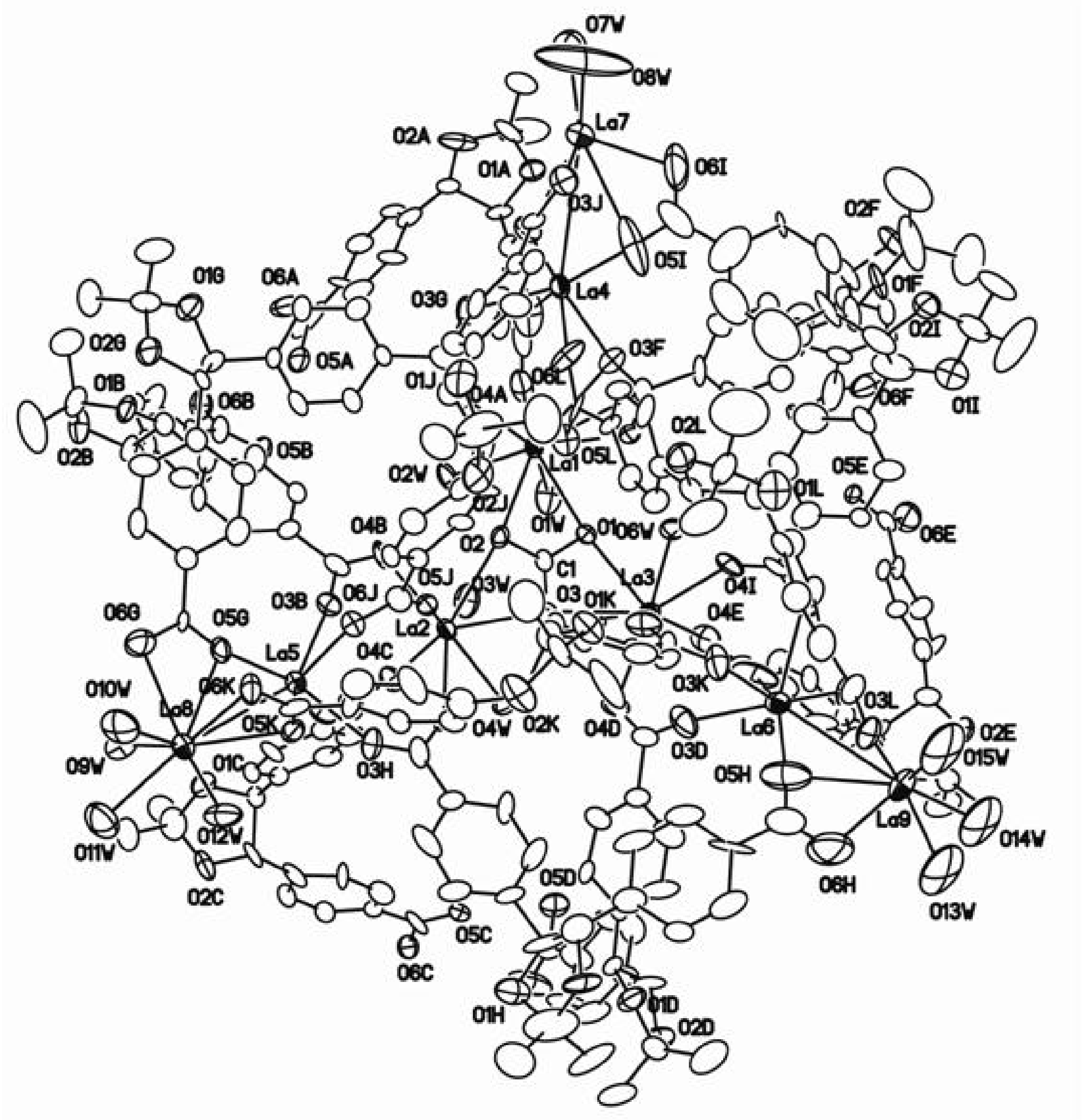


Figure S1. ORTEP drawing of the asymmetric unit of (*S*)-lanthanitin with selected atomic labels.

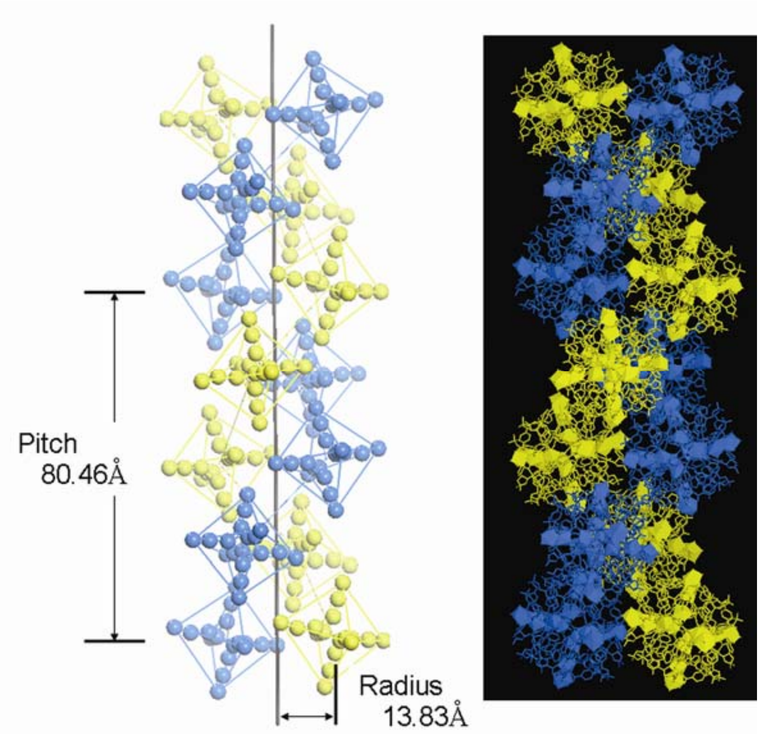


Figure S2. The pitch and radius of lanthanitin double helix. La(III) ions are drawn as balls in the left figure, and polyhedra in the right.

2.3. Single crystal X-ray diffraction studies of (*R*)-lanthanitin

A prismatic colorless crystal with a suitable size (0.35 mm x 0.30 mm x 0.25 mm) was attached on a glass capillary, which was positioned in a $N_2(g)$ stream at 130(2)K upon mounting on a Bruker SMART APEX2 CCD diffractometer equipped with a normal focus and graphite monochromated Mo-target X-ray tube (λ = 0.71073 Å) operated at 2,000 W power (50 kV, 40 mA). Total 2,160 frames were collected with varying ω with an exposure time of 10 s/frame. The frames were integrated with the SAINT software package with a narrow frame algorithm[1]. The final cell constants were based on the *xyz* centroids of 1,260 reflections. Analysis of the data showed negligible decay during collection. An absorption correction was applied using SADABS[2]. The structure was solved by direct methods and subsequent difference Fourier syntheses and refined with the SHELX-TL software package[3]. A total of 416,135 reflections were collected in the range $0.75° < \theta < 20.82°$ of which 23,290 were independent and 17,552 were observed ($I > 2\sigma(I)$). All stages of weighted full-matrix least-squares refinement were conducted using F_o^2 data and converged to give $R1 = 0.0921$ ($I > 2\sigma(I)$), $wR2 = 0.2341$ (all data) and GOF = 1.076. The diffuse electron density due to the disordered and unidentified moieties was treated with the SQUEEZE routine within the PLATON software package[4]. Statistics prior to treatment of data with SQUEEZE were $R1 = 0.1266$ ($I > 2\sigma(I)$), $wR2 = 0.3985$ (all data) and GOF = 1.196. The crystal belongs to the tetragonal space group $P4_322$ (No. 95) with Z = 4. As the crystallographic 2-fold axis passed Lanthanitin, the asymmetric unit is composed of a half of the whole molecule. All the carbon atoms of the 12 organic ligands were refined anisotropically due to the non-positive definite problems. EADP instructions have been applied to O(2), O(4B), O(6J), and O(13W) by using the thermal parameters of the neighboring or adjacent atoms. In addition, the 12 ligands have been restrained to have same structures by using SAME instructions. Hydrogen atoms were generated with the ideal geometry. The absolute configuration was confirmed by the Flack's x parameter, 0.013(3).

Table S2. Crystal data and structure refinement for (*R*)-lanthanitin.

Empirical formula	$C_{466.5}$ $H_{505.5}$ $N_{1.5}$ O_{207} La_{18}	
Formula weight	11945.60	
Temperature	130(2) K	
Wavelength	0.71073 Å	
Crystal system	Tetragonal	
Space group	$P4_322$ (No. 95)	
Unit cell dimensions	a = 27.2922(6) Å	α= 90°.
	b = 27.2922(6) Å	β= 90°.
	c = 79.728(3) Å	γ = 90°.
Volume	59386(3) $Å^3$	
Z	4	
Density (calculated)	1.336 Mg/m^3	
Absorption coefficient	1.345 mm^{-1}	
F(000)	23988	
Crystal size	0.35 x 0.30 x 0.25 mm^3	
Theta range for data collection	0.75 to 20.82°.	
Index ranges	$-19 \leq h \leq 19$, $-19 \leq k \leq 19$, $-79 \leq l \leq 79$	
Reflections collected	416135	
Independent reflections	23290 [R_{int} = 0.2179]	
Completeness to theta = 20.82°	75.8 %	
Absorption correction	SADABS	
Max. and min. transmission	0.7298 and 0.6504	
Refinement method	Full-matrix-block least-squares on F^2	
Data / restraints / parameters	23290 / 18 / 1366	
Goodness-of-fit on F^2	1.076	
Final R indices [I>2sigma(I)]	R1 = 0.0921, wR2 = 0.2177	
R indices (all data)	R1 = 0.1213, wR2 = 0.2341	
Absolute structure parameter	0.13(3)	
Largest diff. peak and hole	1.229 and -0.654 e.$Å^{-3}$	

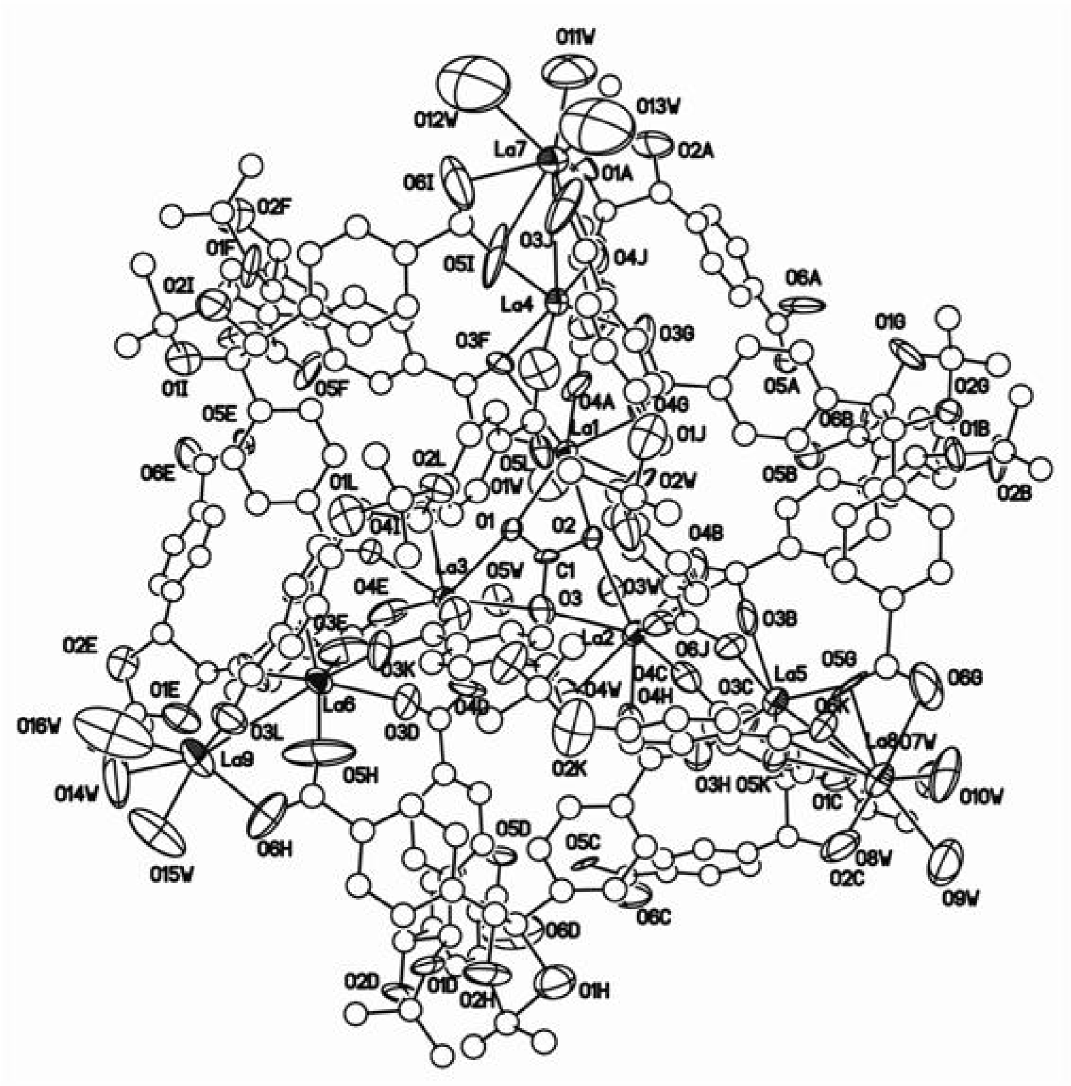


Figure S3. ORTEP drawing of the asymmetric unit of (*R*)-lanthanitin with selected atomic labels.

3. Circular dichroism (CD)[1] measurement of lanthanitins

UV-VIS absorption spectra of various solutions were measured between 800 and 200 nm with a Jasco UVIDEC 650 spectrophotometer. CD spectra were recorded using a Jasco J-810 spectropolarimeter. The DRCD spectra were obtained by inserting a diffused reflectance sphere in the optical path of the instrument. This J-810 was specifically modified to allow simultaneous detection of LD (linear dichroism) as a simple way to verify one of potential artifacts.

1. Kuroda, R. & Honma, T. CD spectra of solid-state samples. *Chirality* **12**, 269-277 (2000).