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Synthesis, resolution, and chiroptical properties of hemicryptophane cage controlling the chirality of propeller arrangement of a C_3 triamide unit

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Abstract

The five-steps synthesis of a hemicryptophane cage combining a benzene-1,3,5-tricarboxamide unit and a cyclotrimeratrylene (CTV) moiety is described. Chiral high-performance liquid chromatography (HPLC) was used to resolve the racemic mixture. The absolute configuration of the isolated enantiomers was assigned by comparison of the experimental electronic circular dichroism (ECD) spectra with the calculated ones. X-ray molecular structures reveal that the capped benzene-1,3,5-tricarboxamide unit adopts a structurally chiral conformation in solid state: the chirality of CTV moiety controls the Λ or Δ orientation of the three amides.

1 | INTRODUCTION

In 1981, André Collet and co-workers reported the first synthesis of a new class of chiral molecular hosts named cryptophanes, which combined two cyclotrimeratrylene (CTV) units.^{1,2} These hosts were found to display remarkable recognition properties toward neutral molecules like methane,³ atoms like Xe,⁴ anions like triflate,⁵ and metals or organic cations like cesium or choline.^{6,7} The synthesis of enantiopure cryptophanes has been also reported, allowing for the enantioselective recognition of racemic mixture of CHFCIBr or epoxides.^{8,9} In 1982, the same authors published the synthesis of a new class of chiral

molecular hosts, also based on the CTV unit, and named hemicryptophanes, which associate a CTV moiety with another C_3 symmetrical unit.¹⁰ This class of molecular cages was found to have a wide range of applications from molecular receptors to supramolecular catalysts and molecular machines.¹¹

Because of the C_3 -symmetrical CTV unit, hemicryptophanes are chiral molecules that can adopt the P or M configuration.¹² Enantiopure hemicryptophanes can be obtained either by resolution of the racemic mixture or by diastereoselective synthesis.¹³ Besides their use as enantioselective receptors for carbohydrates and neurotransmitters,¹⁴⁻¹⁷ their C_3 symmetry has

allowed to build molecular cages presenting a triple-helical arrangement of the linkers.¹⁸ Indeed, the CTV unit is able to control the chirality of triple helices since the CTV with *P* (respectively *M*) configuration induces a Δ (respectively, Λ) propeller-like arrangement of the linkers. We thus wonder if the chirality of the CTV can control, not only the chirality of the arrangement of the linkers, but also that of the south unit, in particular that of a benzene-1,3,5-tricarboxamide (BTA) moiety ubiquitous in supramolecular chemistry.¹⁹⁻²⁷

Herein, we report the synthesis of the new hemicryptophane cage **1**. The resolution of the racemic mixture was performed by chiral high-performance liquid chromatography (HPLC), and the assignment of the absolute configuration of the two enantiomers was achieved from electronic circular dichroism (ECD) spectra. The X-ray molecular structure of the cage shows that the chirality of the CTV unit is capable of imposing that of the capped benzotriazole (BTA) unit, which constitutes the south part of the hemicryptophane **1**.

2 | MATERIALS AND METHODS

2.1 | Synthesis and materials

2.1.1 | Chemicals and materials

Starting material and solvents were of commercial-grade and were used without further purification. Chromatography was carried out with Merck 60 A (0.040-0.063 mm) silica gel. TLC was performed with Merck silica gel 60 F254 plates. Melting points were determined with a Büchi Melting Point B-545. Infrared (IR) spectra were obtained using a Bruker Alpha Platinum ATR. ¹H nuclear magnetic resonance (NMR) and ¹³C NMR spectra were recorded at 298 K on a Bruker Avance III HD 300, 400, or 500 MHz spectrometer. ¹H NMR and ¹³C NMR chemical shifts δ are reported in ppm referenced to the protonated residual solvent signal. Mass spectra (HRMS) were recorded by the mass spectrometry service at the Spectropôle Aix Marseille Université. Measurements were realized with two internal standards. ECD spectra were recorded on a Jasco J-815 spectrometer in CH₂Cl₂. CTV-Br derivative **3** was prepared according to the common published procedure.²⁸

Compound 4

In a 100-mL round-bottom flask, 1.30 g (1.78 mmol) of **3** are dissolved in 40 mL of anhydrous dimethylformamide (DMF) under argon atmosphere. Then 1.16 g (17.8 mmol) of NaN₃ are added by portions at room temperature. The mixture was stirred at 60°C overnight. After DMF evaporation, the crude product is dissolved in 100 mL of dichloro-

methane and washed three times with water (3 × 100 mL), then with brine (150 mL), and dried over anhydrous Na₂SO₄. A yellowish oil was obtained after evaporation of the solvent under reduced pressure. Diethyl ether (70 mL) was added, and the mixture was stored at 4°C for about 6 hours to give a white solid, which was filtered on a frit and washed with Et₂O to yield **4** (990 mg, 90%).

*R*_f (CH₂Cl₂): 0.23; ¹H NMR (CDCl₃, 300 MHz) δ 6.93 (s, 3H), 6.85 (s, 3H), 4.75 (d, *J* = 13.7 Hz, 3H), 4.14 (t, *J* = 5.2 Hz, 6H), 3.83 (s, 9H), 3.59 to 3.52 (m, 9H); ¹³C NMR (CDCl₃, 75 MHz) δ 149.2, 146.5, 133.9, 131.9, 118.1, 114.2, 69.1, 56.1, 50.3, and 36.4; IR σ = 2931, 2110, 1511, and 1265 cm⁻¹; and HRMS (ESI-TOF) *m/z*: observed 638.2442 [M + Na]⁺ (calculated: 638.2446 for C₃₀H₃₃N₉O₆Na).¹⁴

Compound 5

In a 250-mL round-bottom flask, 490 mg (0.796 mmol) of azide **4** are dissolved in THF (15 mL) and water (0.5 mL) and 3.75 g (14.3 mmol) of PPh₃ are added by portions at 0°C. The mixture is then allowed to warm to room temperature. After 24 hours of stirring at room temperature, solvents are evaporated. Diethyl ether (50 mL) was added to the resulting solid and the mixture was stirred at r.t. for 24 hours. Filtration afforded compound **5** as a white powder (391 mg, 91 %).

*R*_f (CH₂Cl₂/MeOH: 97/3): 0.05; ¹H NMR (CDCl₃, 400 MHz) δ 6.88 (s, 3H), 6.82 (s, 3H), 4.75 (d, *J* = 13.7 Hz, 3H), 4.10 to 3.92 (m, 6H), 3.82 (s, 9H), 3.53 (d, *J* = 13.4 Hz, 3H), 3.05 (t, *J* = 5.2 Hz, 6H); ¹³C NMR (CDCl₃, 100 MHz) δ 148.5, 146.9, 132.6, 131.9, 116.1, 113.8, 72.0, 56.2, 41.6, and 36.5; IR σ = 3430, 2935, 1511, and 1263 cm⁻¹; and HRMS (ESI-TOF) *m/z*: observed 538.2913 [M + H]⁺ (calculated: 538.2912 for C₃₀H₄₀N₃O₆).¹⁴

Hemicryptophane 1

In a 1-L round-bottom flask, CTV-NH₂ derivative **5** (354 mg, 0.658 mmol) was dissolved in anhydrous CH₂Cl₂ (300 mL), then, ET₃N (2.0 mL) was added. A solution of 1,3,5-benzenetricarbonyl trichloride (192 mg, 0.723 mmol) in anhydrous CH₂Cl₂ (220 mL) was slowly added dropwise over 24 hours under stirring at 30°C, and the reaction mixture was stirred at 30°C for 24 hours. The mixture was then filtered and concentrated under reduced pressure. CH₂Cl₂ (60 mL) was added, and the organic layer was washed with aqueous K₂CO₃ (10%, 70 mL) and water (70 mL). Aqueous phases were combined and extracted with CH₂Cl₂ (70 mL). The combined organic layers were dried over MgSO₄, and the organic solvent was removed under reduced pressure to afford a white solid purified by silica gel column chromatography (CHCl₃/MeOH, gradient from 95/5-91/9). Racemic hemicryptophane **1** was obtained as a white solid (132 mg, 29%).

R_f (CHCl₃/MeOH: 93/7): 0.32; m.p. greater than 310°C (decomposition); ¹H NMR (CDCl₃, 500 MHz, 298 K) 7.52 (s, 1H), 6.78 (s, 1H), 6.72 (s, 1H), 6.66 (dd, $J = 7.2, 4.7$ Hz, 1H), 4.80 (td, $J = 11.9, 2.9$ Hz, 1H), 4.43 (d, $J = 13.9$ Hz, 1H), 4.27 (dd, $J = 12.3, 3.0$ Hz, 1H), 4.22 (s, 3H), 4.04 (ddd, $J = 13.8, 7.7, 1.6$ Hz, 1H), 3.43 (ddt, $J = 15.9, 11.6, 4.6$ Hz, 1H), 3.27 (d, $J = 14.0$ Hz, 1H); ¹³C NMR (CDCl₃, 100 MHz, 298 K) δ 164.18, 147.70, 147.26, 132.42, 131.49, 131.41, 126.76, 116.76, 113.79, 77.44, 77.02, 76.60, 66.98, 56.04, 42.17, and 36.73; IR $\sigma = 3383, 2918, 2851, 1663, 1515, 1457, 1258, \text{ and } 1082$ cm⁻¹; and HRMS (ESI-TOF) m/z : observed 694.2758 [$M + H$]⁺ (calculated: 694.2759 for C₃₉H₄₀N₃O₉).

2.2 | Resolution by chiral HPLC

2.2.1 | Methods

The chiral HPLC separations were performed on Agilent 1260 Infinity unit (pump G1311B, autosampler G1329B, DAD G1315D). Analytical (250 × 4.6 mm, 5 μ m) and preparative (250 × 10 mm, 5 μ m) Chiralpak IB from Chiral Technologies Europe (Illkirch, France) are used. Preparative chiral HPLC is performed on Chiralpak IB (250 × 10 mm) column with hexane/ethanol/dichloromethane (50/30/20) as mobile phase. Flow rate was 5 mL/min and ultraviolet (UV) detection was done at 254 nm. About 50 mg of the racemic mixture of **1** are dissolved in 3.2 mL of CH₂Cl₂. Injections were stacked (32 × 100 μ L, every 8 minutes).

2.2.2 | Instrumentation

Optical rotations were measured on a Jasco P-2000 polarimeter with a sodium lamp (589 nm), a halogen lamp (578, 546, 436, 405, and 365 nm), in a 10 cm cell, thermostated at 25°C with a Peltier-controlled cell holder. ECD and UV spectra were measured on a JASCO J-815 spectrometer equipped with a JASCO Peltier cell holder PTC-423 to maintain the temperature at 25.0 ± 0.2°C using a quartz cell of optical pathlength of 1 mm. The ECD spectrometer was purged with nitrogen before recording each spectrum, which was baseline subtracted. The baseline was always measured for the same solvent and in the same cell as the samples. The spectra are presented without smoothing and further data processing.

2.2.3 | Conformational search and simulations of ECD spectra

Conformational search was carried out at the molecular mechanics level using calculations at the MM2 level. Then, the lowest energy structure was selected for DFT optimization with standard parameters and convergence criteria,

which were run using Gaussian16 program at the B3LYP/6-31G(d) level of theory applying PCM for CH₃CN. Finally, ECD calculations were run at TDDFT level for the first 250 excited electronic by using the CAM-B3LYP and B3LYP functionals with singular value decomposition (SVD) basis set in PCM model for CH₃CN. Since they gave very similar results, for the sake of clarity, in the main text are only presented results from CAM-B3LYP functional and SVD basis set (see also Figure S11).

2.2.4 | Resolution

The resolution of the racemic mixture was performed by chiral HPLC using a Chiralpak IB (250 × 10 mm) column with heptane/EtOH/CH₂Cl₂ (50/30/20) as mobile phase to yield the two enantiopure hemicryptophanes (+)-**1** (ee > 99.5%) and (-)-**1** (ee > 97.5%).

M (-): $[\alpha]_D^{25}$ (CH₂Cl₂, $c = 0.16$) = -78; P (+): $[\alpha]_D^{25}$ (CH₂Cl₂, $c = 0.19$) = +79;

3 | RESULTS AND DISCUSSION

3.1 | Synthesis of hemicryptophane **1**

Hemicryptophane **1** was obtained according to the synthetic pathway shown in Scheme 1. Our previously described two-steps procedure provides the CTV derivative **3** as a racemic mixture: vanillyl alcohol **2** first reacts with 1,2-dibromoethane, then Friedel-Crafts reactions catalyzed by scandium triflate in CH₃CN gives the key CTV-**3** with 20% overall yield.²⁸ The CTV-**4** is then synthesized by mixing CTV-**3** with sodium azide in DMF. Addition of triphenyl phosphine to a solution of compound **4** in a THF/H₂O mixture provides the intermediate **5** in 91% yield. Hemicryptophane **1** was obtained by a final macrocyclization reaction step between 1,3,5-benzenetricarbonyl trichloride and CTV-**5** in the presence of triethylamine in dichloromethane (concentration of reactants: 10⁻³ M). Thus, host **1** was synthesized in five steps from vanillyl alcohol in 4.7% overall yield.

3.2 | ¹H NMR Of Hemicryptophane **1**

The ¹H NMR spectrum of hemicryptophane **1** in CDCl₃ is shown in Figure 1 and demonstrates that this molecule displays, on average, a C₃ symmetry in solution. The expected signals of the CTV moiety can be observed: two singlets for the aromatic protons at 6.78 and 6.72 ppm, one singlet for the OMe group at 4.22 ppm, and the characteristic AB system for the diastereotopic protons of the ArCH₂ bridges at 4.43 and 3.27 ppm. The diastereotopic OCH₂CH₂N protons of the linkers give four well-defined signals at 4.80, 4.27,

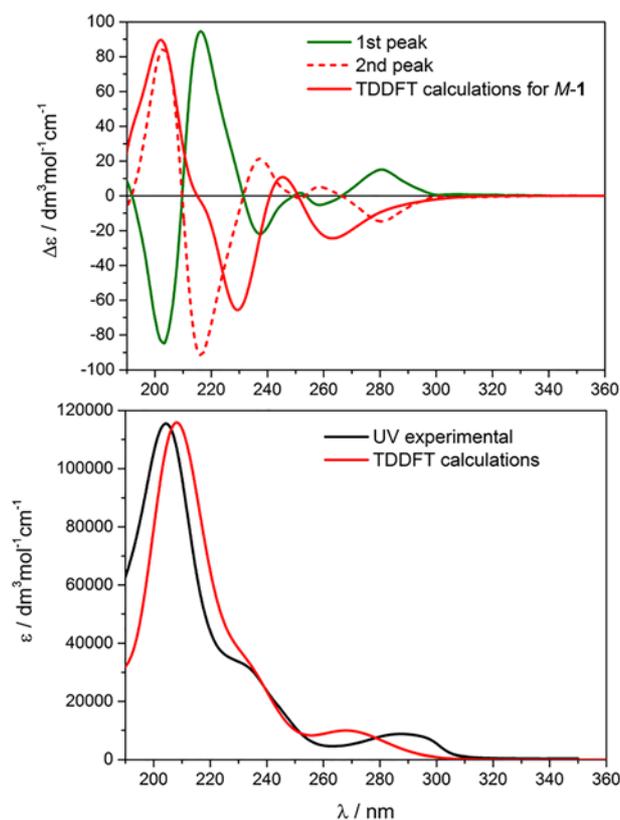


FIGURE 3 Experimental electronic circular dichroism (ECD) spectra of the enantiomers of **1**: the first eluted enantiomer is represented with a green solid line (0.165 mmol. L⁻¹ in CH₃CN) and the second one by a red dotted line (0.166 mmol. L⁻¹ in CH₃CN) together with TDDFT calculations performed for *M*-**1**. Calculations were carried out at the CAM-B3LYP/SVP/PCM (CH₃CN) level of theory; spectrum red shifted by 15 nm, Gaussian bandwidth 0.33 eV. Below the ECD, the calculated and experimental UV spectra of **1** can be found

transitions. (Figure 3). This confirms again the aforementioned stereochemical assignments based on ECD ¹L_a bands, highlighting another time the universal character of experiment correlation found by Collet et al³⁰ for CTV unit.

3.5 | Solid-state structure of hemicryptophane **1**

Crystals suitable for X-ray diffraction were obtained by slow evaporation of a solution of hemicryptophane *rac*-**1** in CHCl₃. The X-ray structure reveals that the hemicryptophane cage crystallizes as a racemate in the space group Pba2 and exhibits a C₃ symmetry, in agreement with ¹H NMR spectrum (Figure 4). Interestingly, *rac*-**1** crystallizes with two independent configurations in the asymmetric unit. The capped BTA unit presents a structurally chiral conformation where the three amides are oriented in similar direction giving rise to a right-

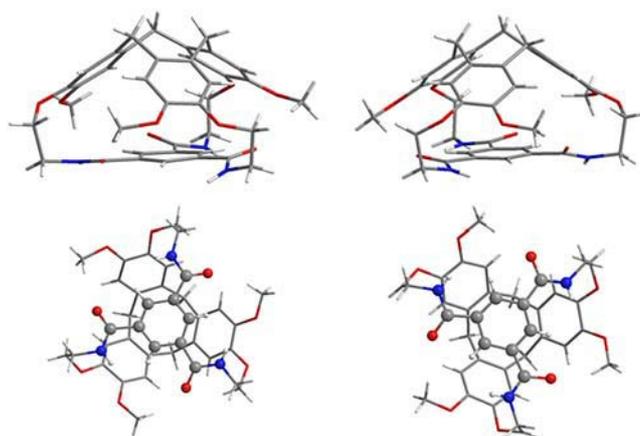


FIGURE 4 X-ray crystal structure of (-)-*M*-**1** (left) and (+)-*P*-**1** (right)

handed or left-handed propeller. Thus, the chirality of the CTV moiety controls the chirality of propeller-like arrangement of the capped BTA unit: the *M* configuration of the CTV imposes a Λ orientation of the amides groups, whereas the *P* one leads to a Δ arrangement of these functions. This highlights the ability of the CTV unit to transfer its chirality to the south part of the cage. This chiral arrangement of the amides is probably retained in solution, since only one set of signal (single diastereomer) is observed on the ¹H NMR spectrum.

4 | CONCLUSION

In conclusion, we have described the synthesis of a new hemicryptophane cage combining a CTV unit with a BTA moiety. The resolution of the racemic mixture was performed by chiral HPLC allowing for the isolation of each enantiomer with good enantiopurity. The assignment of their absolute configuration was achieved using ECD spectroscopy. The X-ray molecular structure shows that, in the solid state, the amide functions of the lower part adopt a chiral orientation, which is controlled by the chirality of the CTV unit. This strong control on the chirality of other chiral-linked units has been already reported for other hemicryptophane cages: for instance with the helical arrangement of the linkers involving intramolecular hydrogen bonding or metal complexation,^{18,33} with the propeller arrangement of atrane units,^{34,35} or with remote chiral *tren* unit.³¹ Thus, this ability of the chirality of the CTV unit to propagate along its linker appears as quite general and efficient even with remote stereogenic units. Taking advantage of this remarkable property, we envisage to build highly functionalized hemicryptophane cages to complex lanthanide metals and to control efficiently the chirality at the metal center with that of the CTV unit in order to provide enantiopure molecular cages for circularly polarized luminescence (CPL) applications.

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