New developments in porphyrin-like macrocyclic chemistry: a novel family of dibenzotetraaza[14]annulene-based cofacial dimers

- SUPPORTING INFORMATION

K. M. Zwoliński and J. Eilmes*

List of contents:

1. General information

All solvents and reagents were commercially available and used as received unless otherwise stated. N,N-dimethylformamide was dried under 4 Å molecular sieves for at least 4 days before use. Dichloromethane (CH_2Cl_2, 99.8%, POCH, Gliwice, Poland) was distilled over calcium hydride. Deutero-chloroform $CDCl_3$ used in association constant determination experiment was deacidified by storage over potassium carbonate.

All starting materials were purchased from commercial sources (Sigma-Aldrich, Fluka, Lancaster) and used as-received. Melting points were measured with the use of a Boethius apparatus and were uncorrected. Samples of DABCO and zinc(II) cofacial dimer used for the association constant (K_a) determination were weighted on a microbalance Sartorius Pro11 AG Göttingen Germany (ISO9001, accuracy ± 0.001 mg).

Macrocyclic ligand **1** (7,16-bis(2-hydroxybenzoyl)-5,14-dihydrodibenzo[b,i][1,4,8,11]tetraazacyclotetradecine) was prepared by the procedures described elsewhere.[1] Other derivatives of the parent macrocycle: **2** (7,16-bis[2-(3-bromopropoxy)benzoyl]-5,14-dihydro-dibenzo[b,i][1,4,8,11]tetraazacyclotetradecine) and **3** (7,16-bis[2-(4-bromo-butoxy)benzoyl]-5,14-dihydro-dibenzo[b,i][1,4,8,11]tetraazacyclotetradecine) were synthesized according to the literature procedures[2] and stored at room temperature in a desiccator until needed.

Compound **1a** (7,16-bis(3-hydroxypropyl)-5,14-dihydrodibenzo[b,i][1,4,8,11]tetraazacyclotetradecine) and its Ni complex (**Ni-1a**) were synthesized according to a literature procedure[3]. Compound **4** (7,16-bis(3-bromopropyl)-5,14-dihydrodibenzo[b,i][1,4,8,11]-tetraazacyclotetradecine) was synthesized according to the literature procedure[4].

2. Methods

Nuclear magnetic resonance experiments

The NMR spectra were recorded using Bruker AMX (500 MHz) and a Mercury Varian (300 MHz) spectrometers at ambient temperature in DMSO-d_6 or $CDCl_3$ solvents. The chemical shifts are reported in parts per million (ppm) and the coupling constants *J* are given in hertz (Hz). Data are reported as follows: chemical shift, multiplicity (s-singlet, br.s –broad singlet, d – doublet, dd- doublet of doublets), coupling constant and integration. The residual signal of DMSO-d_6 solvent was used as an internal reference standard (δ_H = 2.500 ppm and δ_C = 39.50 ppm).

Mass spectrometry

The mass spectrometry experiments were performed on a ESI-ITD mass spectrometer Esquire 3000 (Bruker-Daltonics, Bremen, Germany). The heated capillary temperature was set to 250^{o}C. About 1 mg of sample was dissolved in 1 ml of $CHCl_3$ and the spray solution was prepared by adding 1 ml of CH_3OH (final ratio 1:1, v/v). After mixing, sample was injected by continuous infusion at a flow rate of 3 microliters/minute. Mass range applied was over the range from 300 to 1500 m/z. Scans were acquisited for at least one minute for MS as well as MS/MS spectra.

In case of heat sensitive samples temperature was set down to 150-160^{o}C or to easily observed abnormalities in ion formation. About 1 mg of sample was dissolved in $CHCl_3$ and CH_3OH mixture (1:1 v/v). The spray solution was prepared by adding 1 mg of sample to 10 ml of the solvent mixture solution (final concentration 0.1 mg/ml). After mixing, sample was injected by continuous infusion at a flow rate of 3 microliters/minute into the ion source.

---

[1] I. Sigg, G. Haas, T. Winkler, *Helv. Chim. Acta*., 1982, **65**, 275-279.
[2] (a) D. Pawlica, M. Radic-Stojkovic, Ł. Dudek, I. Piantanida, L. Sieroń, J. Eilmes, *Tetrahedron*, 2009, **65**, 3980-3989; (b) Ł. Dudek, J. Grolik, A. Kaźmierska, E. Szneler, A. Eilmes, K. Stadnicka, J. Eilmes, *Tetrahedron Lett*., 2011, **52**, 3597-3601.
[3] R. Hanke, E. Breitmaier, *Chem. Ber*., 1982, **115**, 1657-1661.
[4] D. Pawlica, M. Radic-Stojkovic, L. Sieroń, I. Piantanida, J. Eilmes, *Tetrahedron*, 2006, **62**, 9156-9165.

IR spectroscopy

Fourier transform infrared (FT-IR) spectra were measured at room temperature in a transmission mode in the range of 4000-400 cm^{-1} with a FTIR Bruker Equinox55 spectrometer. Both spectra in hexachlorobutadiene (HCB) and KBr pellets were recorded. The pellets were prepared by adding 0.8 mg of a sample powder to 200 mg of dry KBr. The powders were mixed homogeneously and compressed at a pressure of 10 KPa to form transparent pellets.

Fourier transform infrared FT-IR ATR (Attenuated total reflection) spectra were recorded at room temperature with a FT-IR Thermo Fisher Nicolet IR200 spectrometer equipped with a diamond and operating in a single-reflection mode.

UV-vis spectroscopy

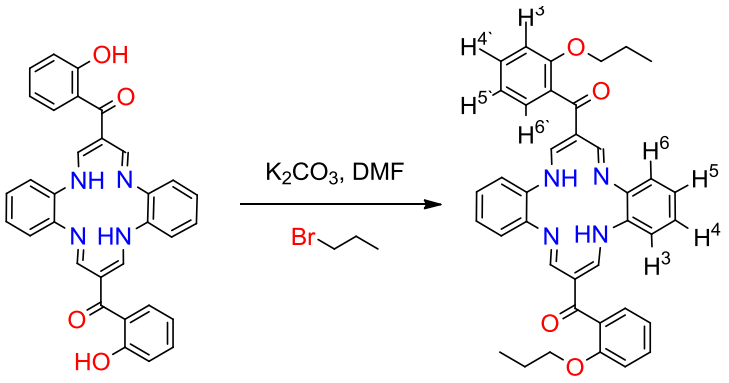
Electronic absorption spectra were obtained in chloroform or dichloromethane solutions using matched 1 cm quartz cuvettes and were recorded with a Hitachi U-3900H spectrophotometer.

Elemental analyses

Elemental analyses were conducted using an Euro-EA (EuroVector) and a VarioMicroCube microanalyzers. Samples were analysed with standard parameters in a CHN mode.

3. Synthetic procedures and spectroscopic characterization of the new compounds:

a) 7,16-bis[(2-propoxy)benzoyl]-5,14-dihydrodibenzo[b,i][1,4,8,11] tetraazacyclotetradecine (DBTAA-Mon-n-Pr)



1 **DBTAA-Mon-n-Pr**

Starting ligand **1** (400 mg, 0.76 mmol) was added in a single amount to a suspension of anhydrous K_2CO_3 (626 mg, 4.53 mmol) in 20 ml of dry N,N-dimethylformamide. The resulting mixture was stirred at room temperature for 30 minutes. Then, 1-bromopropane (0.3 ml, 3.3 mmol) was added in a single amount to a clear red solution and the resulting mixture was stirred at room temperature for five days. Orange precipitate was filtered off, washed with cold methanol and dried under vacuum. The residue was recrystallized from $CHCl_3$/n-hexane to give orange needles (300 mg, 65%).

m.p.: 145-146 °C

FTIR-ATR, ν (cm^{-1}): 3070 (=C-H), 2956 (C-H, CH_3), 2920 (C-H), 2860 (C-H, CH_3), 1649 (C=O), 1590 oraz 1558 (C=N oraz C=C macrocycle), 1450 (C=C), 1237 (Ar-O-C), 743.

^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ_H 0.89 (6 H, t, *J* = 7.4 Hz, CH_3), 1.69 (4 H, m, *J* = 7.4, 6.5 Hz, CH_2), 3.96 (4 H, t, *J* = 6.5 Hz, OCH_2), 6.99 (2H, dd, J = 0.5, 8.3 Hz, H-3`), 7.05 (2 H, dd, J =1.0, 7.5 Hz, H-5`), 7.06-7.20 (8 H, m, H-3-6), 7.38 (2 H, dd, *J* = 1.5Hz, 7.5 Hz, H-6`), 7.43 (2 H, ddd, *J* = 1.8Hz, 7.4, 8.3 Hz, H-4`), 8.60 (4 H, d, J = 6.6 Hz, -N=CH), 14.40 (2 H, t, ^{3}J = 6.6 Hz, NH).

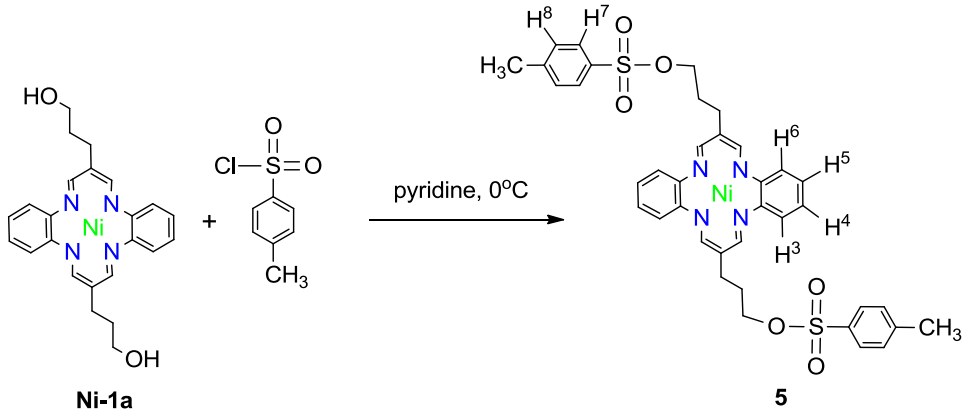
UV-vis λ (CH_2Cl_2): 345 nm (ε= $6.8 \cdot 10^4$ $dm^3 \cdot mol^{-1} \cdot cm^{-1}$), 354 nm (ε= $6.7 \cdot 10^4$ $dm^3 \cdot mol^{-1} \cdot cm^{-1}$), 386 nm (ε= $3.2 \cdot 10^4$ $dm^3 \cdot mol^{-1} \cdot cm^{-1}$).

MS (ESI+, m/z): Mass calcd for $C_{38}H_{37}N_4O_4$ $[M+H]^+$ 613.3 Da, found: 613.4 Da $[M+H]^+$ (100%).

Elemental analysis: Anal. calcd. for. $C_{38}H_{36}N_4O_4 \cdot 0.25H_2O$: C, 73.95; H, 5.96; N, 9.08; Found: C, 73.80; H, 5.91; N, 9.13.

b) Ni(II) complex of bis(tosylpropyl)DBTAA (5)

{7,16-bis[3-(4-metylobenzenesulfonate)propyl]-5,14-dihydrodibenzo[b,i][1,4,8,11]tetra-azacyclotetradecinato(2-)}Ni(II);



Ni-1a **5**

4-Toluenesulfonyl chloride (495 mg, 2.6 mmol) was added in a single amount to a cold solution of the starting complex **Ni-1a** (200 mg, 0.43 mmol) in 150 ml of dry pyridine and left in a refrigerator at 0 °C for 48 h. Then, the reaction mixture was poured into $CHCl_3$ (50 ml) and washed rapidly with cold distilled water (4x200 ml) to remove excess pyridine. The organic phase was separated and dried over anhydrous $MgSO_4$. Excess of pyridine was removed using a short column of silica, eluting with $CHCl_3$:acetone (v:v, 49:3). First, the fast-moving band was collected and precipitated by adding an equal volume of diethyl ether. The solid residue was filtered off and dried under vacuum. The crude residue was taken up in $CHCl_3$ and chromatographed on silica gel with $CHCl_3$:acetone (v:v, 30:1) as an eluent. Second, the main red fraction was collected and concentrated in a rotary evaporator. An equal volume of n-hexane was added to the concentrated solution and the solution left for 12 h. The resulting precipitate was filtered off, washed repeatedly with n-hexane (10 ml) and dried under vacuum. Brown powder (148 mg, 44.3%).

m.p.: > 260 °C

FTIR (ATR) ν (cm^{-1}): 3072, 3026, 2963, 2931, 2900, 2851, 1601, 1579, 1451, 1360, 1330, 1295, 1238, 1170, 1096, 1045, 1001, 928, 830, 810, 753, 731, 664.

^{1}H NMR (300 MHz, 0.036 M, $CDCl_3$, TMS) δ_H 1.83 (4 H, m, $CH_2C\mathbf{H}_2CH_2O$), 2.38 (10 H, s, br.s, $C\mathbf{H}_2CH_2CH_2O$, CH_3), 4.06 (4 H, t, *J* = 5.9 Hz, $CH_2CH_2C\mathbf{H}_2O$), 6.83 (4 H, br.m, H-4,5), 7.23 (4 H, br.m, H-3,6), 7.28 (4 H, d, *J* = 8 Hz, H-8), 7.44 (4 H, s, N=CH), 7.78 (4 H, d, *J* = 8.3 Hz, H-7).

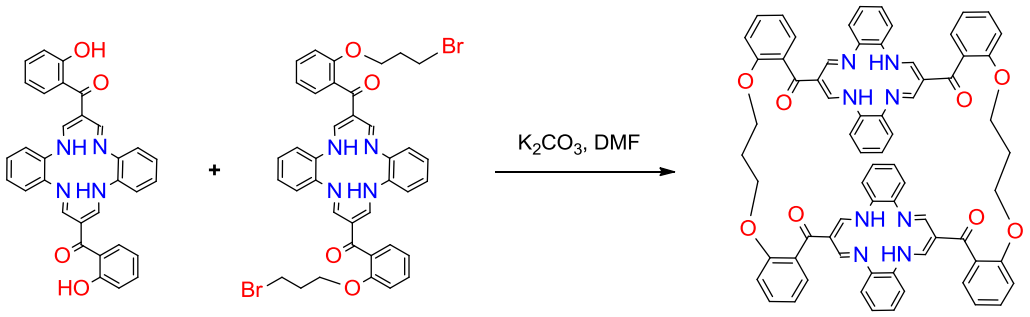
^{1}H NMR (300 MHz, DMSO-d_6, TMS) δ_H 1.77 (4 H, m, $CH_2C\mathbf{H}_2CH_2O$), 2.27 (6 H, s, CH_3), 2.35 (4 H, t, *J* = 7.4 Hz, $C\mathbf{H}_2CH_2CH_2O$), 3.98 (4 H, t, *J* = 6.3 Hz, CH_2O), 6.80 (4 H, m, J = 3.3, 6.8 Hz, H-4,5), 7.34 (4 H, d, *J* = 7.9 Hz, H-8), 7.53 (4 H, m, J=3.5, 6.3 Hz, H-3,6), 7.71 (4 H, d, *J* = 8.3 Hz, H-7), 7.74 (4 H, s, N=CH).

^{13}C NMR (75 MHz, 0.036 M, $CDCl_3$, TMS) δ_C 21.60, 27.99, 32.05, 69.19, 113.10, 123.74, 127.84, 129.87, 132.98, 144.45(br.), 144.77, 145.03.

MS (ESI+, m/z): Mass calcd. for $C_{38}H_{39}N_4O_6S_2Ni$ $[M+H]^+$ 769.2 Da, found: 769.4 Da $[M+H]^+$ (100%).

Elemental analysis: Anal. calcd. for. $C_{38}H_{38}N_4O_6S_2Ni$: C, 59.31; H, 4.98; N, 7.28; Found: C, 58.95; H, 4.95; N, 7.31.

c) Cofacial dimer 6 (DBTAA-dim-3)



1 2 **6: DBTAA-Dim-3**

Starting ligand **1** (100 mg, 0.189 mmol) and its corresponding bis(3-bromopropyl) derivative **2** (145 mg, 0.189 mmol) were added in a single amount to a suspension of anhydrous K_2CO_3 (215 mg, 1.52 mmol) in 120 ml of dry N,N-dimethylformamide. The resulting mixture was stirred at room temperature for a week. Orange precipitate was filtered off and suspended in distilled water (100 ml). After stirring for 10 minutes the solid residue was filtered off, dried under vacuum and crystallized at 0 °C from $CHCl_3$/n-hexane (v:v, 3:1) to give orange crystals (73 mg, 34%).

m.p.: > 260 °C

IR ν (cm^{-1}): 3065, 2991, 2958, 2884, 1646, 1586, 1556, 1487, 1446, 1412, 1209, 1285, 1231, 1140, 1099, 1047, 1005, 957, 906, 822, 737, 659.

^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ_H 2.07 (4 H, quin, *J* = 6.4 Hz, CH_2), 4.09 (8 H, t, *J* = 6.5 Hz, OCH_2), 6.98-7.10 (24 H, m, H3-6, H-5`, H-3`), 7.32 (4 H, dd, *J* = 1.7, 7.5 Hz, H-6`), 7.41, (4 H, ddd, J = 1.8, 7.5, 8.3 Hz, H-4`), 8.52 (8 H, br.s, N=CH), 14.30 (4 H, br.s, NH).

^{13}C NMR (75 MHz, $CDCl_3$, TMS) δ_C 28.9, 65.8, 110.4, 112.7, 115.4, 121.1, 126.4, 129.0, 129.4, 131.2, 137.0, 152.9, 155.4, 192.8.

UV-vis λ ($CHCl_3$): λ 342nm (ε= $5.49 \cdot 10^4$ $dm^3 \cdot mol^{-1} \cdot cm^{-1}$), 387nm (ε= $2.22 \cdot 10^4$ $dm^3 \cdot mol^{-1} \cdot cm^{-1}$).

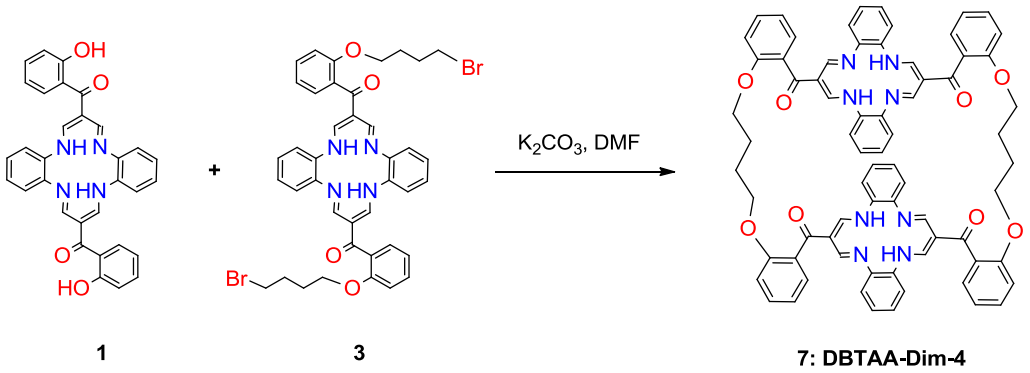
MS (ESI+, m/z): Mass calcd. for $C_{70}H_{57}N_8O_8$ $[M+H]^+$ 1137.4 Da, found: 1137.6 Da $[M+H]^+$ (100%).

MS/MS (ESI+, m/z=1137.3 Da): m/z 1019.3 Da (100%).

MS/MS (ESI+, m/z=1019.3 Da): m/z 901.3 (100%) and 819.4 Da (80%).

Elemental analysis: Anal. calcd. for. $C_{70}H_{56}N_8O_8 \cdot 0.5CHCl_3$: C, 70.74; H, 4.76; N, 9.36; Found: C, 70.54; H, 5.06; N, 9.01.

d) Cofacial dimer 7 (DBTAA-dim-4)



1 3 **7: DBTAA-Dim-4**

Table 1. Optimization of the synthesis of the cofacial dimer DBTAA-dim-4 (7) under various conditions. All reactions were performed in DMF in the presence of K_2CO_3.

No.	Concentration [mM]	Reaction conditions	Yield[a] [%]
1	1.57	RT, 48 h	23%
2	3.15	RT, 7 days	44%
3	7.14	60°C, 6 h	37%

[a]Yield of pure dimer after post-synthetic workout

Method A (RT, 7days)

Starting ligand **1** (100 mg, 0.189 mmol) and its corresponding bis(4-bromobutyl) derivative **3** (151 mg, 0.189 mmol) were added in a single amount to a suspension of anhydrous K_2CO_3 (215 mg, 1.52 mmol) in 60 ml of dry N,N-dimethylformamide. The resulting mixture was stirred at room temperature for a week. Orange precipitate was filtered off and suspended in distilled water (100 ml). After stirring for 15 minutes the solid residue was filtered off and dried under vacuum. Orange powder (97 mg, 44%).

Method B (60°C, 6h)

Starting ligand **1** (263 mg, 0.50mmol) and its corresponding bis(4-bromobutyl) derivative **3** (400 mg, 0.50 mmol) were dissolved in 70 ml of dry N,N-dimethylformamide at 60 °C. Anhydrous K_2CO_3 (275 mg, 1.94 mmol) was added in a single amount to the resulting solution, and the mixture was heated at 60°C under stirring for 6 h. The mixture was then slowly cooled down and left at room temperature for 12 h. Orange precipitate was filtered off, suspended in dichloromethane (50 ml) and shaken in a separatory funnel with a concentrated HCl solution (20%, 100 ml). The organic phase was then separated and washed with distilled water and a saturated solution of $NaHCO_3$ until neutral pH was reached. Dichloromethane solution was separated, evaporated to dryness in a rotary evaporator and dried under vacuum. Orange powder (215 mg, 36.8%).

Method C (high dilution conditions)

A solution of starting ligand **1** (100 mg, 0.189 mmol) and its corresponding bis(4-bromobutyl) derivative **3** (151 mg, 0.189 mmol) in 120 ml of dry N,N-dimethylformamide was injected at a rate of 3 ml/h with a micro-feeder into a vigorously stirred (1000 rpm) suspension of anhydrous K_2CO_3 (275 mg, 1.94 mmol) in 30 ml of dry N,N-dimethylformamide. After the addition was completed, the mixture was further stirred for 48 h at room

temperature. Orange precipitate was filtered off, washed with cold $CHCl_3$ (2x10ml) and suspended in distilled water (80 ml). After stirring for 1 h the solid residue was filtered off and dried under vacuum. Orange powder (52 mg, 23%).

The product can be additionally recrystallized from hot $CHCl_3$ or CH_2Cl_2 if analytically pure sample is desired.

Orange powder. m.p.: > 260 °C

IR (HCB) ν (cm^{-1}): 3075, 2934, 2879.

IR (KBr) ν (cm^{-1}): 3071, 2926, 2876, 2855, 1652, 1614, 1596, 1562, 1486, 1448, 1417, 1322, 1288, 1256, 1142, 1096, 1046, 1012, 965, 910, 830, 749.

^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ_H 1.69 (8 H, m, CH_2), 3.84 (8 H, t, *J* = 5.6 Hz, OCH_2), 6.78-6.82 (4 H, br.m., H-5`), 7.06-7.13 (20 H, m, H-3-6, H-3`), 7.32-7.41 (8 H, m, H-4`, H-6`), 8.51 (8 H, d, *J* = 6.2 Hz, N=CH), 14.33 (4 H, t, J = 6.2 Hz, NH).

Crystalline powder is poorly soluble in $CDCl_3$ at room temperature, therefore longer accumulation time is required for adequate signal-to-noise (S/N) ratio. To improve S/N ratio and to obtain a satisfactory ^{1}H NMR spectrum, it is also recommended to heat up the sample suspension in $CDCl_3$ immediately before ^{1}H NMR data acquisition.

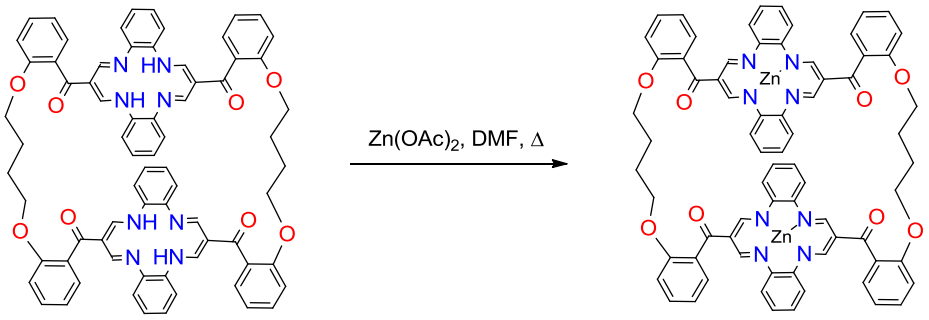
UV-vis λ ($CHCl_3$): λ 343 oraz 385(sh) nm.

MS (ESI+, m/z): Mass calcd. for $C_{72}H_{61}N_8O_8$ $[M+H]^+$ 1165.5 Da, found: 1165.6 Da $[M+H]^+$ (100%).

MS/MS (ESI+, m/z=1165.4 Da): m/z 901.4 Da (100%).

Elemental analysis: Anal. calcd. for.: $C_{72}H_{60}N_8O_8 \cdot 0.6CH_2Cl_2$: C, 71.69; H, 5.07; N, 9.21; Found: C, 71.62; H, 5.05; N, 9.13.

e) Dinuclear Zn(II) complex of the cofacial dimer 7 (Zn_2-DBTAA-dim-4) (8)



7: DBTAA-Dim-4 **8: Zn_2-DBTAA-Dim-4**

A suspension of **7** (DBTAA-Dim-4) (97 mg, 0.083 mmol) in a solution of anhydrous zinc acetate (218.3 mg, 1.19 mmol) in 30 ml of dry N,N-dimethylformamide was heated at 90 °C with stirring until suspension disappeared and a clear deep-red solution was obtained (ca. 2-3 h). The clear solution was further heated at 90 °C for the next 2 h and slowly cooled to room temperature. Then the reaction mixture was poured into $CHCl_3$ (30 ml), washed repeatedly with water (2x200 ml), dried over anhydrous $MgSO_4$ and passed through a short column of silica gel with acetone as an eluent. The deep-red solution was evaporated to dryness and redissolved in $CHCl_3$ (15 ml). Zinc(II) complex **8** (Zn_2-DBTAA-Dim-4) was precipitated from the $CHCl_3$ solution with an excess of diethyl ether. A solid product was filtered off and dried under vacuum. Red powder (72 mg, 67%).

m.p.: > 260 °C

IR ν (cm^{-1}): 3063, 3027, 2933, 2871, 1622 (C=O), 1596, 1574, 1514, 1473, 1445, 1389, 1307, 1209, 1141, 1099, 1041, 919, 740, 598.

^{1}H NMR (300 MHz, DMSO-d_6, TMS) δ_H 1.40 (8 H, br.s, CH_2), 3.66 (8 H, br.s, OCH_2), 6.87 (4 H, d, *J* = 8.5 Hz, H-3`), 6.97-7.10 (20 H, br.m, H-3-6, H-5`), 7.24 (4 H, dd, *J* = 1.7, 7.5Hz, H-6`) 7.37 (4 H, dt, *J* = 1.7, 8.4 Hz, H-4`), 8.43 (8 H, br.s, N=CH).

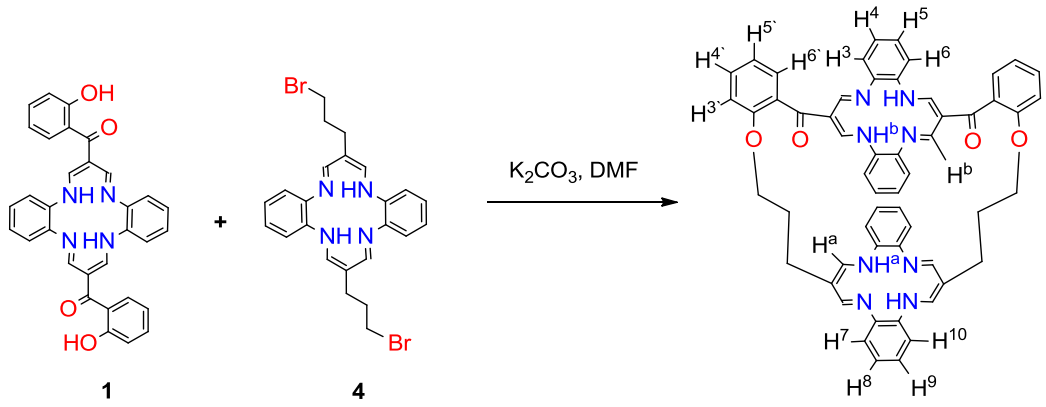
^{13}C NMR (75 MHz, DMSO-d_6) δ_C 24.64, 66.45, 109.83, 112.08, 114.67, 120.66, 125.79, 128.73, 130.41, 130.47, 140.56, 154.50, 155.04, 192.39.

UV-vis λ ($CHCl_3$): λ 359, 298 nm.

MS (ESI+, m/z): Mass calcd. for $C_{72}H_{57}N_8O_8Zn_2$ $[M+H]^+$ 1289.3 Da, found: 1289.1 Da $[M+H]^+$ (100%).

Elemental analysis: Anal. calcd. for.: $C_{72}H_{56}N_8O_8Zn_2 \cdot 3H_2O$: C, 64.24; H, 4.64; N, 8.32; Found: C, 64.44; H, 4.48; N, 8.21.

f) Cofacial dimer with unsymmetrical bridges 9 (DBTAA-dim-3asym)



Starting ligand **1** (100 mg, 0.19 mmol) was added to a suspension of K_2CO_3 (521 mg, 3.82 mmol) in 70 ml of dry N,N-dimethylformamide and vigorously stirred until a clear deep-red solution was obtained. Then γ,γ`–bis(3-bromopropyl)-DBTAA **4** (100 mg, 0.19 mmol) was added in a single amount and the resulting mixture was heated at 70 °C until starting materials were totally consumed (ca. 5-7 h) as indicated by TLC ($CHCl_3$:aceton, v:v, 6:1, Rf_{LBr}= 0.8). Then the solvent was evaporated to dryness under reduced pressure in a rotary evaporator and the crude residue was taken up in 10 ml of $CHCl_3$, filtered through a fluted filter and chromatographed on basic Al_2O_3 with pure $CHCl_3$ until the first two fractions were separated. Then $CHCl_3$ was replaced by a $CHCl_3$:acetone (v:v, 49:3) mixture and a deep-red fraction was collected and evaporated to leave the dimer as a brown powder (63 mg, 37.3%)

Brown powder. m.p.: 197-200 °C.

IR (KBr) ν (cm^{-1}): 3062 (C=C), 2920 (C-H), 1644 (C=O i C=N), 1593 (C=N), 1560 (C=C i C=N), 1500, 1486, 1446, 1420, 1288 (C-O-C), 1255, 909, 740.

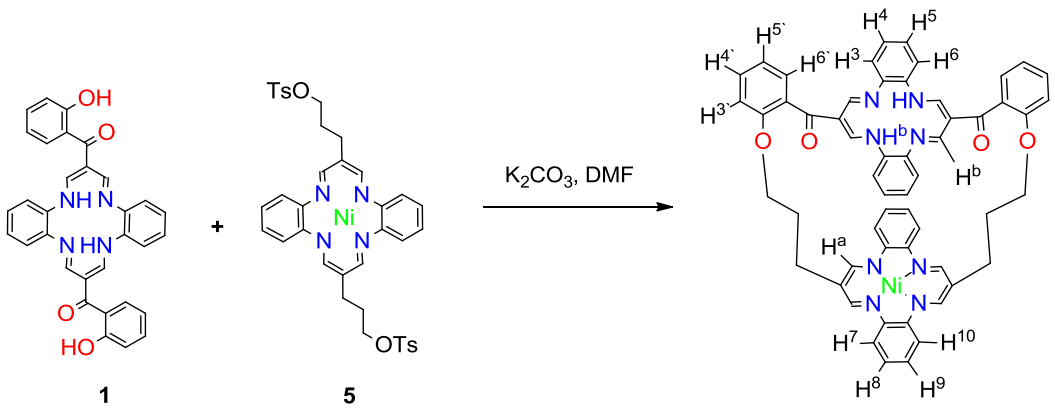
^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ_H 1.92 (4 H, p, *J* = 6.4 Hz, CH_2), 2.27 (4 H, t, *J* = 7.0 Hz, CH_2), 4.15 (4 H, t, *J* = 6.0 Hz, OCH_2), 6.70 (4 H, dd, *J* = 3.4, 6.0 Hz, H-7, H-10), 6.80 (4 H, dd, *J* =3.4, 6.0 Hz, H-8, H-9), 6.91 (8H, br.s, H-3-6), 7.00-7.05 (4H, m., H-3`, H-5`), 7.32 (2H, dd, *J* = 1.8, 7.7 Hz, H-6`), 7.37 (4 H, d, *J* = 5.8 Hz, N=$CH^a$), 7.43 (2 H, ddd, *J* = 1.8, 7.4, 8.4 Hz, H-4`), 8.43 (4 H, d, *J* = 6.5 Hz, N=CH^b), 13.34 (2 H, t, *J* = 5.9 Hz, NH^a), 14.28 (2H, t, *J* = 6.6 Hz, NH^b).

^{1}H NMR (300 MHz, DMSO-d_6, TMS) δ_H 1.82 (4 H, m, CH_2), 2.21 (4 H, t, *J* = 6.9 Hz, CH_2), 4.15 (4 H, t, J = 6.0 Hz, OCH_2), 6.68 (4 H, dd, *J* = 3.3, 6.0 Hz, H-7, H-10), 6.91-6.94 (8+4 H, s, dd, *J* = 3.4, 6.0 Hz, H-8, H-9, H-3-6), 7.04 (2 H, dt, *J* = 0.7, 7.4 Hz, H-5`), 7.20 (2 H, d, *J* = 8.4 Hz, H-3`), 7.28 (2 H, dd, *J* = 1.7, 7.5 Hz, H-6`), 7.47 (2+4 H, d, *J* = 6.0 Hz, N=$CH^a$, m, H-4`), 8.32 (4 H, d, *J* = 6.6 Hz, N=CH^b), 13.22 (2 H, t, J = 5.9 Hz, NH^a), 14.13 (2 H, t, *J* = 6.7Hz, NH^b).

MS (ESI+, m/z): Mass calcd. for $C_{56}H_{48}N_8O_4$ $[M]^+$ 896.7 Da, found: 896.4 Da $[M+H]^+$ (100%).

Elemental analysis: Anal. calcd. for.: $C_{56}H_{48}N_8O_4 \cdot CHCl_3$: C, 67.36; H, 4.86; N, 11.02; Found: C, 67.28; H, 4.92; N, 11.02.

g) Mononuclear Ni(II) complex of the cofacial dimer with unsymmetrical bridges (Ni-DBTAA-dim-3asym) 10

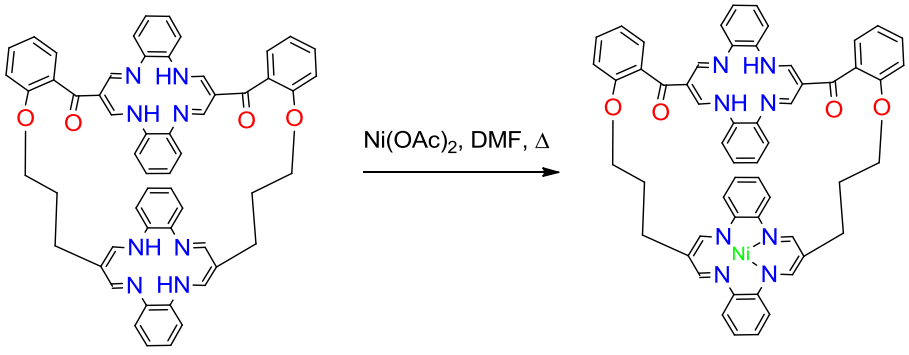


1 5 **10: DBTAA-Dim-3asym-Ni**

Path A

A mixture of the starting ligand **1** (55 mg, 0.1 mmol), Ni(II) complex of bis-tosylate **5** (80 mg, 0.1 mmol) and anhydrous K_2CO_3 (116 mg, 0.85 mmol) in a 70 ml of dry N,N-dimethylformamide was heated at 70°C for 7 h. Then the solvent was evaporated to dryness under reduced pressure in a rotary evaporator and the crude residue was dissolved in 10 ml of $CHCl_3$, filtered through a fluted filter and chromatographed on silica gel with $CHCl_3$:acetone (v:v, 49:3) as an eluent. After separation of a first undesirable fraction, a more polar mixture of $CHCl_3$:acetone (v:v, 10:1) was used to separate the main deep-red fraction, which was concentrated with a rotary evaporator and left at room temperature overnight. A brown precipitate was filtered off and dried under vacuum. Brown powder (42 mg, 42.2%).

Path B



9: DBTAA-Dim-3asym **10: DBTAA-Dim-3asym-Ni**

A mixture of 9 (DBTAA-dim-3asym) (25 mg, 0.045 mmol) and $Ni(OAc)_2 \cdot 4H_2O$ (65 mg, 0.26 mmol) in anhydrous N,N-dimethylformamide (40 ml) was heated at 70°C for 7 h. Then the solution was slowly cooled to room temperature and poured into water (150 ml). A solid precipitate was filtered off, dissolved in dichloromethane (80 ml), dried over anhydrous $MgSO_4$, evaporated to dryness on a rotary evaporator and finally dried under vacuum. Brown powder (16 mg, 60%).

Brown powder. m.p.: > 260°C

IR (ATR) ν (cm^{-1}): 3061 (C=C), 2910 (C-H), 2842 (C-H), 1642 (C=O), 1604, 1587 (C=N), 1559 (C=C), 1454 (C=N···Ni), 1438, 1334 (C=C···Ni), 1280 (C-O-C), 1250, 1215, 1099, 1048, 1010, 940, 905, 805, 726.

^{1}H NMR (300 MHz, $CDCl_3$, TMS) δ_H 2.01 (4 H, m, CH_2), 2.39 (4 H, t, *J* = 7.0 Hz, CH_2), 4.18 (4 H, t, *J* = 5.1 Hz, OCH_2), 6.51 (4 H, dd, *J* = 3.3, 6.1 Hz, H-7, H-10), 6.84-7.04 (16 H, m, H-8, H-9, H-3`, H-3-6), 7.28 (2 H, dd, *J* = 1.6 Hz, H-6` partially overlap with residual $CDCl_3$ solvent signal), 7.31 (4 H, s, N=CH[a]), 7.41 (2 H, ddd, *J* = 1.7, 7.4, 8.4 Hz, H-4`), 8.40 (4 H, d, *J* = 5.2 Hz, N=CH[b]), 14.24 (2 H, t, *J* = 5.6 Hz, NH[b]).

MS (ESI+, m/z): Mass calcd. for $C_{56}H_{46}N_8O_4NiNa$ $[M+Na]^+$ 975.3 Da, found: 975.4 Da $[M+Na]^+$ (100%).

Elemental analysis: Anal. calcd. for.: $C_{56}H_{46}N_8O_4Ni{\cdot}0.5H_2O$: C, 69.86; H, 4.92; N, 11.64; Found: C, 69.96; H, 4.93; N, 11.41.

4. Molecular models of cofacial dimers and bidentate ligands DABCO and 4,4'-bipyridine

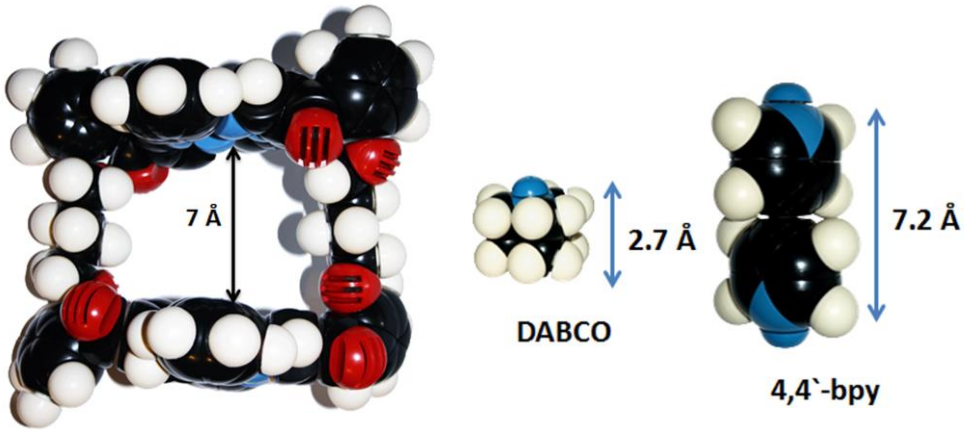


Figure S1. Corey-Pauling-Koltun space filling model of: a) cofacial dimer **8** (Zn_2-DBTAA-dim-4), b) bidentate ligands: 1,4-diazabicyclo[2.2.2]octane (DABCO) and 4,4'-bipyridine (4,4'-bpy). The cross-cavity N···N distance is estimated for extended dimer conformation.

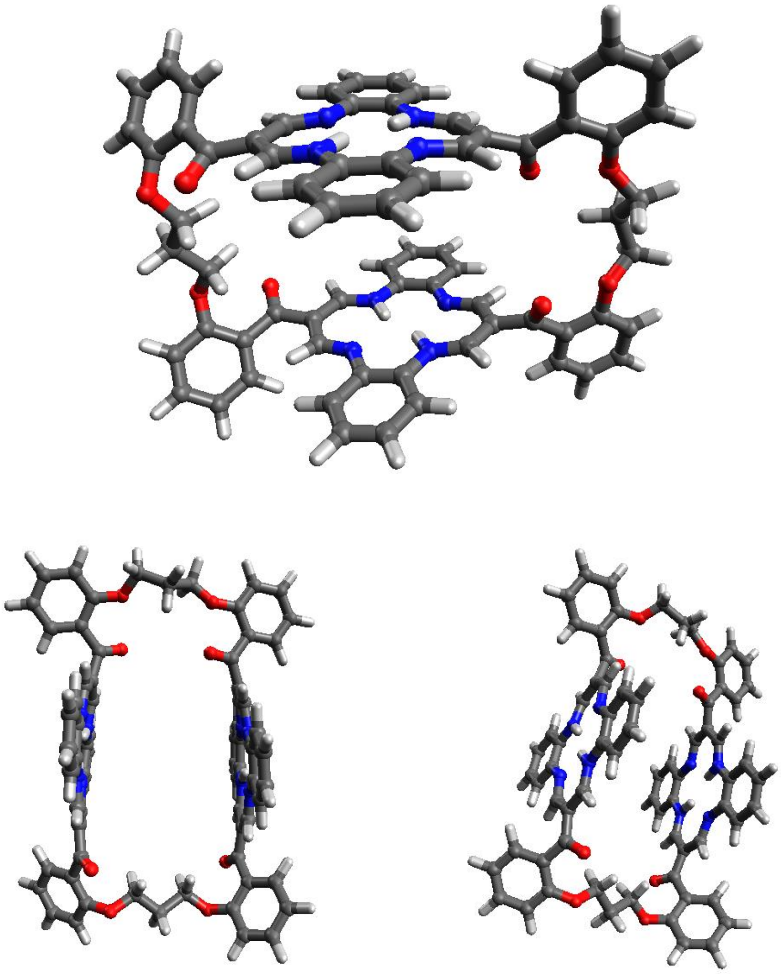


Figure S2. Stick models of the cofacial dimer **6** (DBTAA-dim-3).

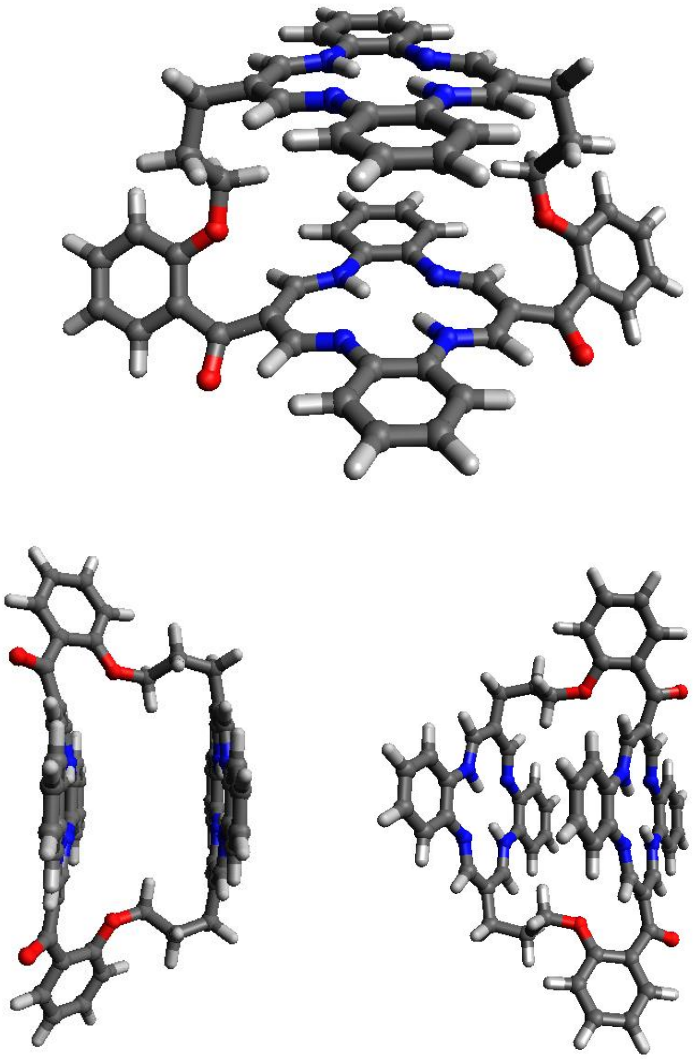


Figure S3. Stick models of the cofacial dimer **9.**

5. Determination of the association constant K_a for the inclusion complex of 8 (Zn_2-DBTAA-dim-4) with DABCO by the single-point method

Solutions for NMR spectroscopic analysis were prepared as follows. Appropriate amounts of carefully weighted amounts of zinc (II) cofacial dimer **8** (Zn_2-DBTAA-dim-4) (2.02 mg, $1.55 \cdot 10^{-3}$ mmol) and DABCO (0.69 mg, $6.19 \cdot 10^{-3}$ mmol) were added to a small vial. Next, 0.7 ml of deacidified $CDCl_3$ was added to yield the desired total concentrations of the two components. After careful mixing, the resulting solution was transferred to a NMR tube and analyzed immediately.

As a result of strong binding, chemical exchange is slow on the NMR timescale and two distinct resonances for both complexed and uncomplexed DABCO are observed at 3.07 and 2.77 ppm respectively (see Fig. S1 below). The association constant was calculated by single-point method[5] by integration of signals belonging to complexed and uncomplexed DABCO species.

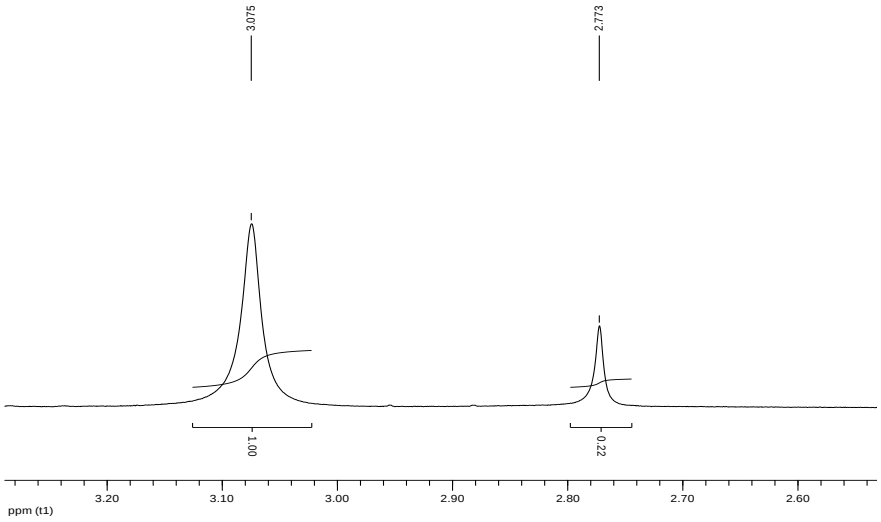


Figure S4. Upfield region of the ^{1}H NMR spectrum of a mixture of **8** (Zn_2-DBTAA-Dim-4) and DABCO, recorded at 298K in deacidified $CDCl_3$, showing signals of -NCH_2- protons of the complexed and uncomplexed DABCO.

Initial (total) concentrations of DABCO and zinc (II) cofacial dimer **8** (Zn_2-DBTAA-dim-4):

$C^0_{DABCO} = 8.84 \cdot 10^{-3}$ mol/dm^3

$C^0_{Zn2\text{-}Dim2m} = 2.21 \cdot 10^{-3}$ mol/dm^3

Equilibrium concentrations of DABCO, zinc (II) cofacial dimer **8** (Zn_2-DBTAA-dim-4) and their inclusion complex:

$C_{[Zn2\text{-}dim2m(DABCO)]} = [(1/(1+0{,}22)] \cdot 8.84 \cdot 10^{-3}$ mol/dm$^3 = 7.25 \cdot 10^{-3}$ mol/dm^3

$C_{DABCO} = 8.84 \cdot 10^{-3}$ mol/dm$^3 - 7.25 \cdot 10^{-3}$ mol/dm$^3 = 1.59 \cdot 10^{-3}$ mol/dm^3

$C_{Zn2\text{-}dim2m} = 2.21 \cdot 10^{-3}$ mol/dm$^3 - 1.59 \cdot 10^{-3}$ mol/dm$^3 = 0.62 \cdot 10^{-3}$ mol/dm^3

$K_a = 7.25 \cdot 10^{-3}$ mol/dm^3/($1.59 \cdot 10^{-3}$ mol/dm$^3 \cdot 0.62 \cdot 10^{-3}$ mol/dm^3)

$K_a = 7400$ (mol/dm^3)$^{-1}$

[5] (a) J. C. Jr., Adrian, C. S. Wilcox, *J. Am. Chem. Soc*., 1991, **113**, 678–680; (b) D. A. Stauffer, R. E. Barrans, D. A. Dougherty, *J. Org. Chem*., 1990, **55**, 2762–2767; (c) M. A. Petti, T. J. Shepodd, R. E. Barans, D. A. Dougherty, *J. Am. Chem. Soc*., 1998, **110**, 6825–6840.

6. Electrospray tandem mass spectrometry experiments (ESI-MS/MS)

A typical positive ion-mode ESI-MS spectrum, with the protonated pseudo-molecular ion $[M+H]^+$ as the base peak, is shown for the cyclic dimer **7** (Fig.S2(a)). In electrospray tandem mass spectrometry (ESI-MS/MS) experiments the pseudo-molecular ions $[M+H]^+$ of both dimers **6** and **7** efficiently lose $C_7H_5N_2$ fragments upon collision-induced dissociation (CID). The suggested mechanism involves protonation of the macrocyclic amine group initiating the loss of neutral benzimidazole units while positive charge remains probably at the 'benzoyl' fragment where it gains extra stabilization arising from beneficial interaction with the carbonyl group. This type of heterocyclic fragmentation pattern is considered to be highly diagnostic for DBTAA-cyclic dimers.

a) b)

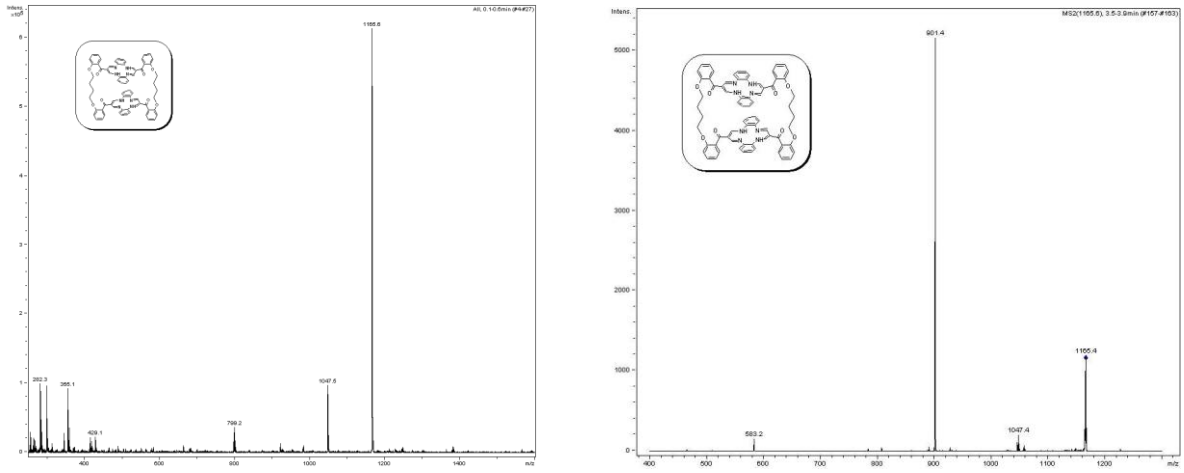


Figure S5. Electrospray spectra in a positive mode of: a) cofacial dimer DBTAA-dim-4 (**7**) and b) tandem mass spectrometry experiment (ESI-MS/MS) using a single-charge precursor ion $[M+H]^+$ (m/z 1165.6 Da).

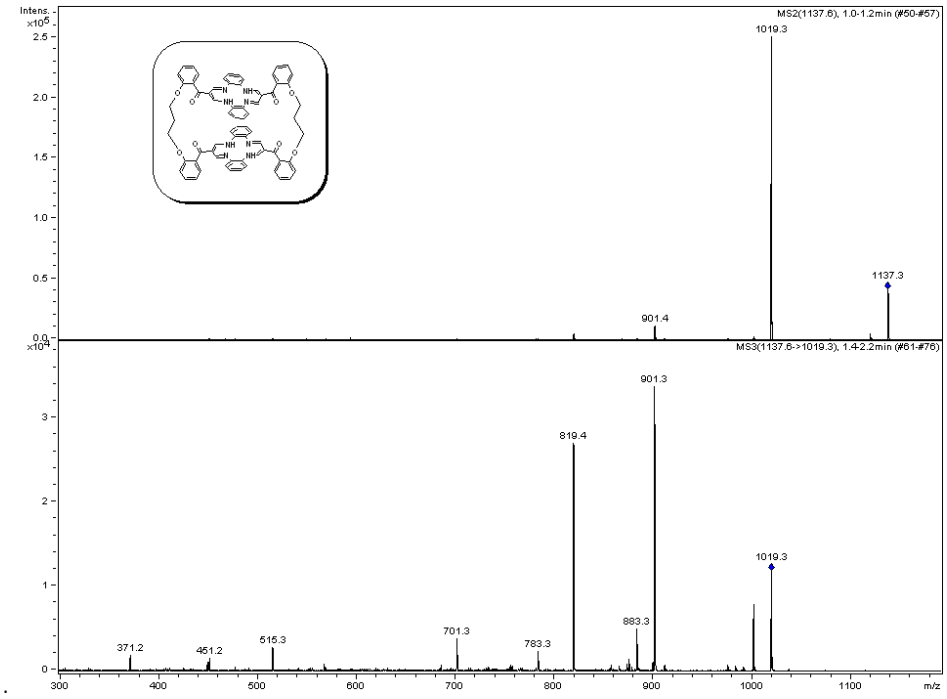


Figure S6. Electrospray tandem mass spectrometry experiments (ESI-MS/MS) with the cofacial dimer DBTAA-dim-3 (**6**): a) single-charge precursor ion $[M+H]^+$ (m/z 1137.3 Da) (upper spectrum) and b) daughter ion (m/z 1019.3 Da) (bottom spectrum).

7. Selected spectra:

a) Spectra of-7,16-bis[2-(propoxy)benzoyl]-5,14-dihydrodibenzo[b,i][1,4,8,11]tetra-azacyclotetradecine

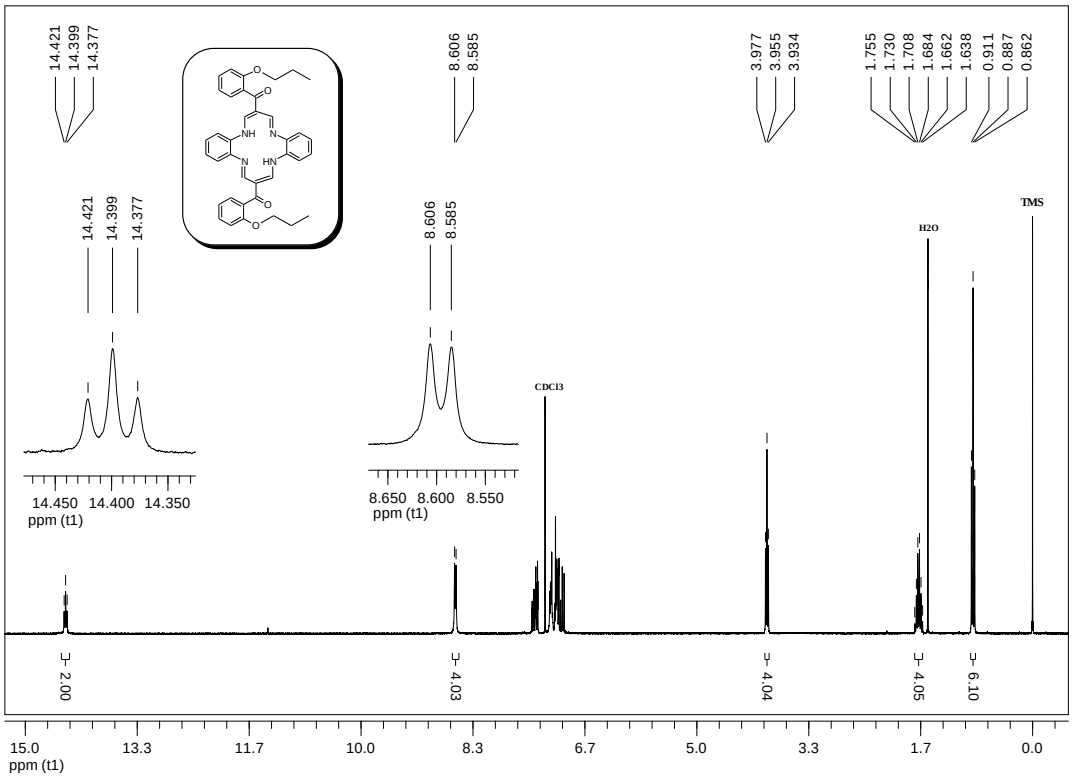


Figure S7. ^{1}H NMR spectrum of the monomeric DBTAA-mon-n-Pr, recorded in $CDCl_3$.

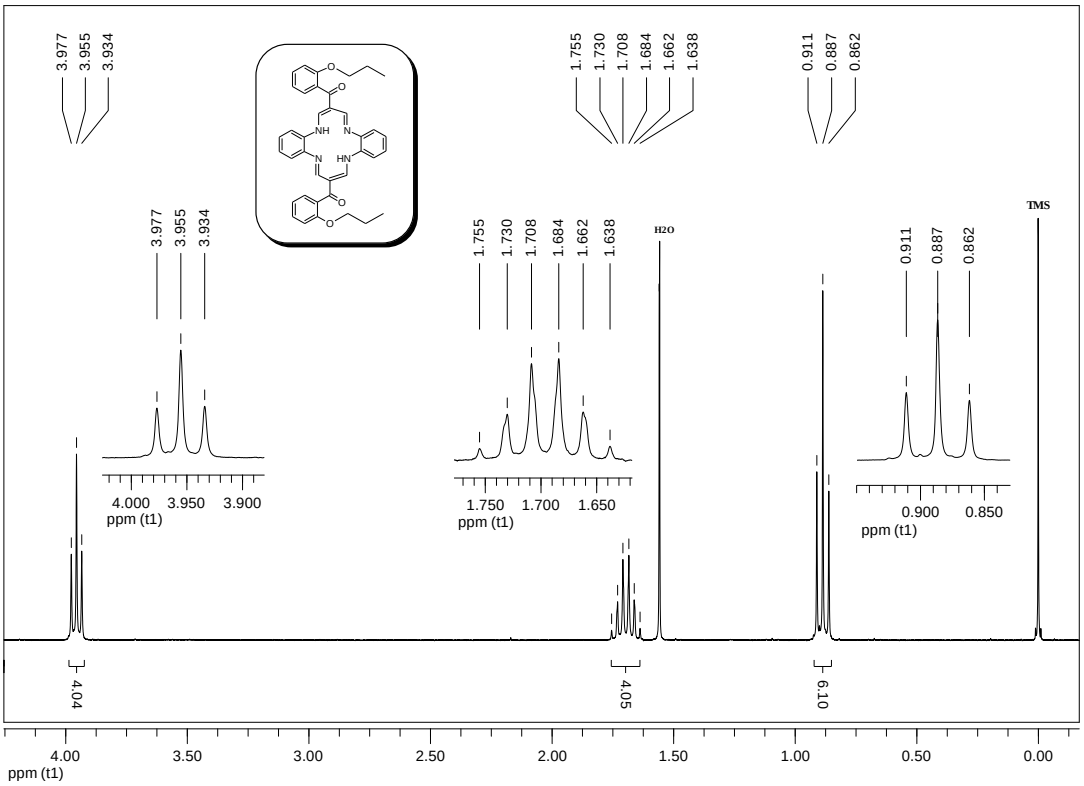


Figure S8. Upfield region of the ^{1}H NMR spectrum of the monomeric DBTAA-Mon-n-Pr, recorded in $CDCl_3$.

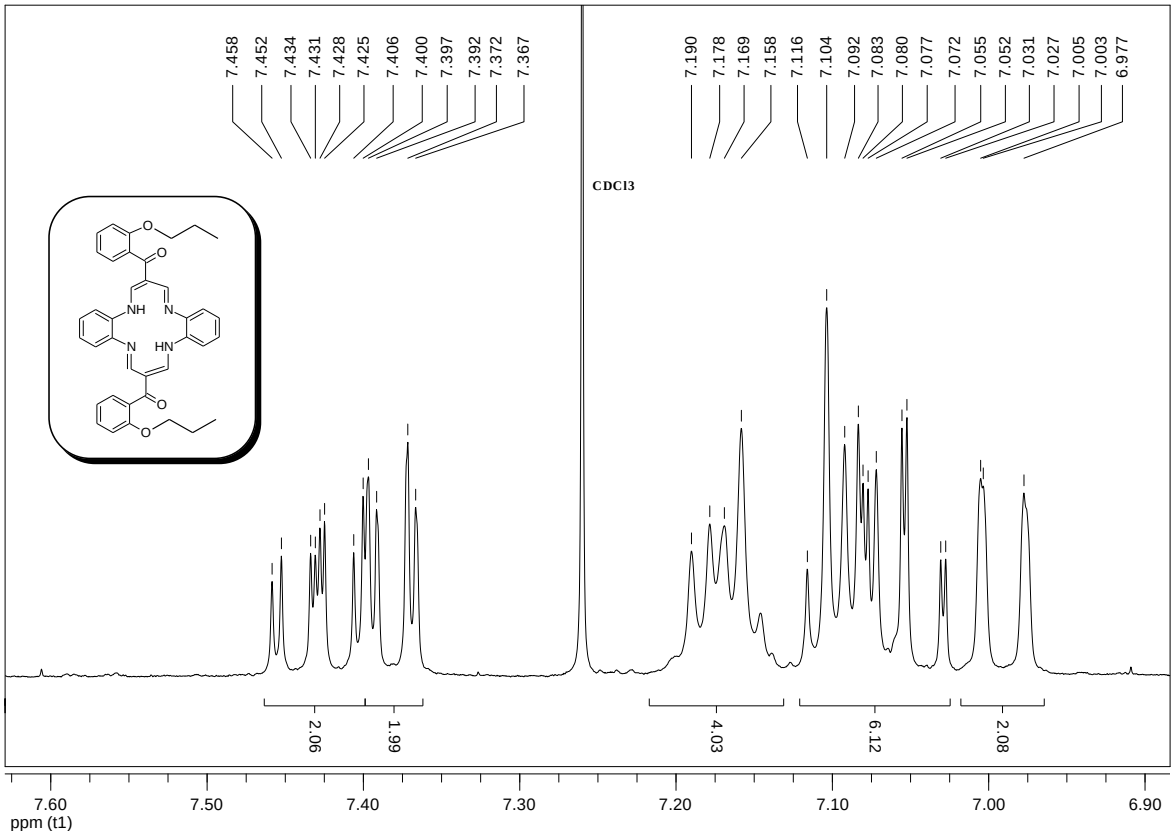


Figure S9. Aromatic region of the ^{1}H NMR spectrum of the monomeric DBTAA-mon-n-Pr, recorded in $CDCl_3$.

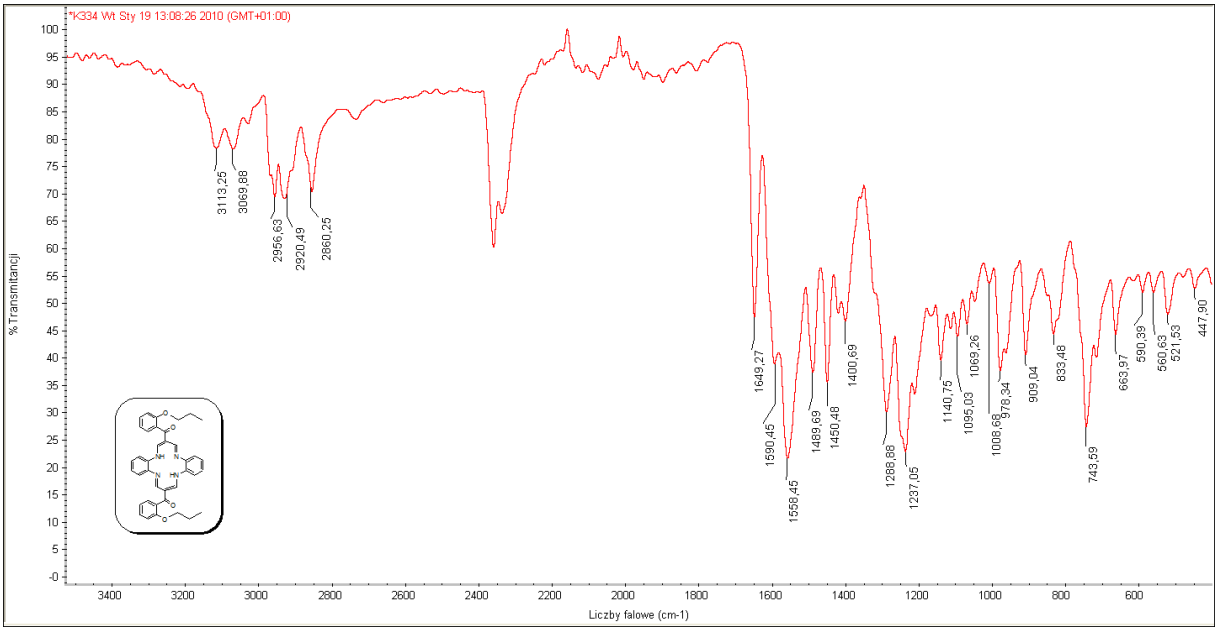


Figure S10. IR spectrum of the monomeric DBTAA-Mon-n-Pr in a range 440-3500 cm^{-1}

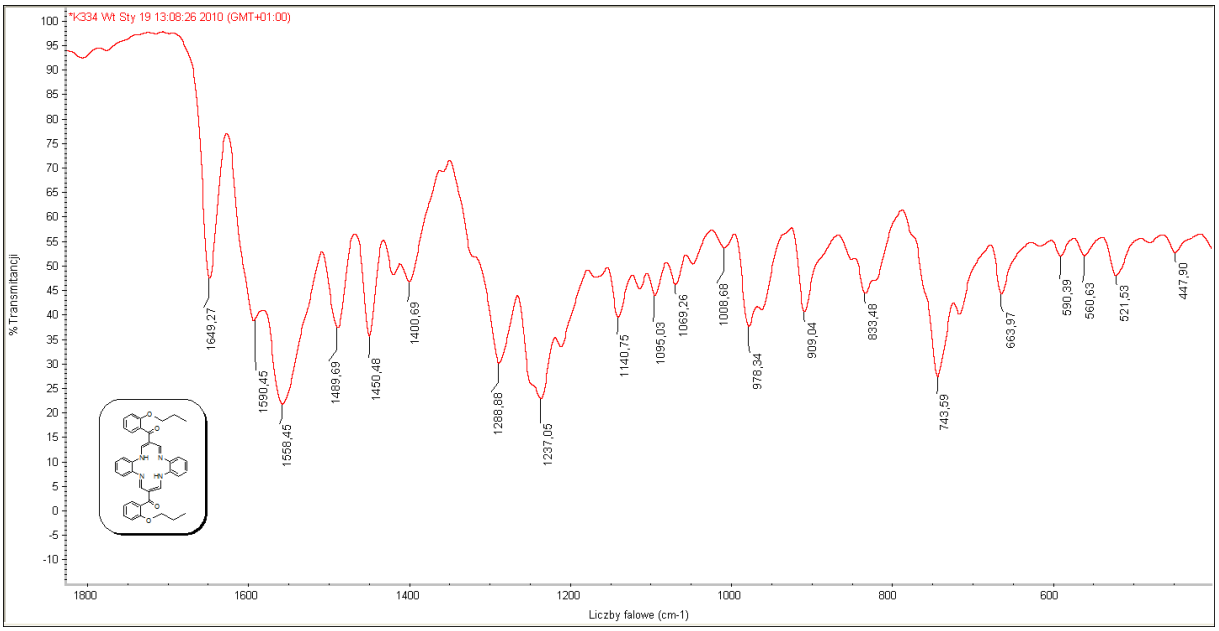


Figure S11. IR spectrum of the monomeric DBTAA-Mon-n-Pr in a range 440-1800 cm^{-1}

(a) (b)

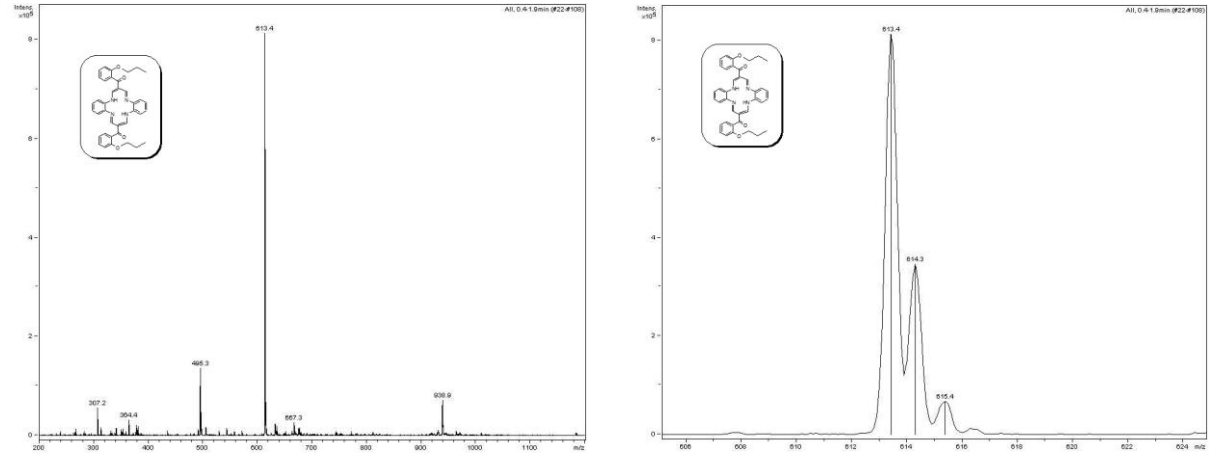


Figure S12. Electrospray mass spectrum of the monomeric DBTAA-mon-n-Pr, recorded in a positive mode (a) and observed isotopic distributions for the pseudomolecular ion $[M+1]^+$ (b).

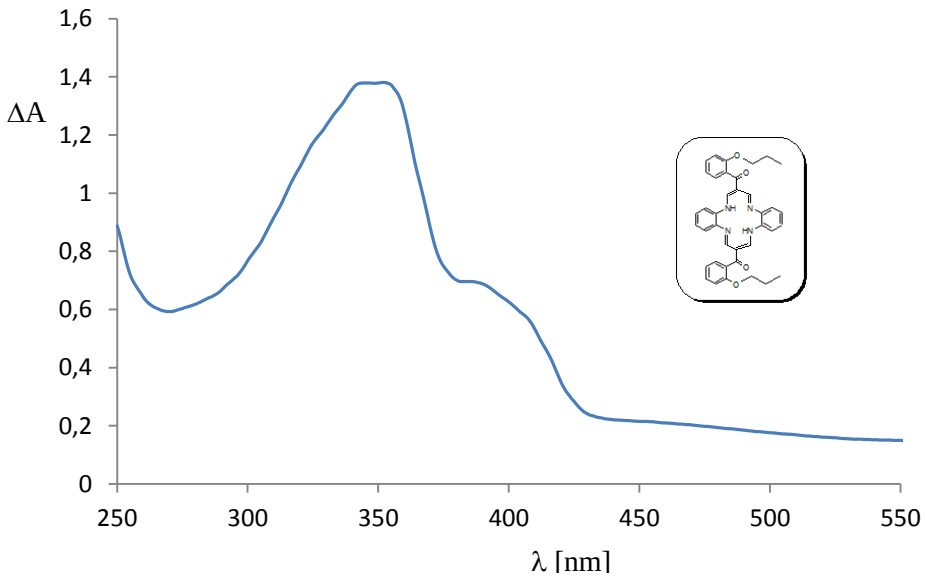


Figure S13. UV-vis absorption spectrum of the monomeric DBTAA-mon-n-Pr in dichloromethane.

b) Spectra of the cofacial dimer 6 (DBTAA-dim-3)

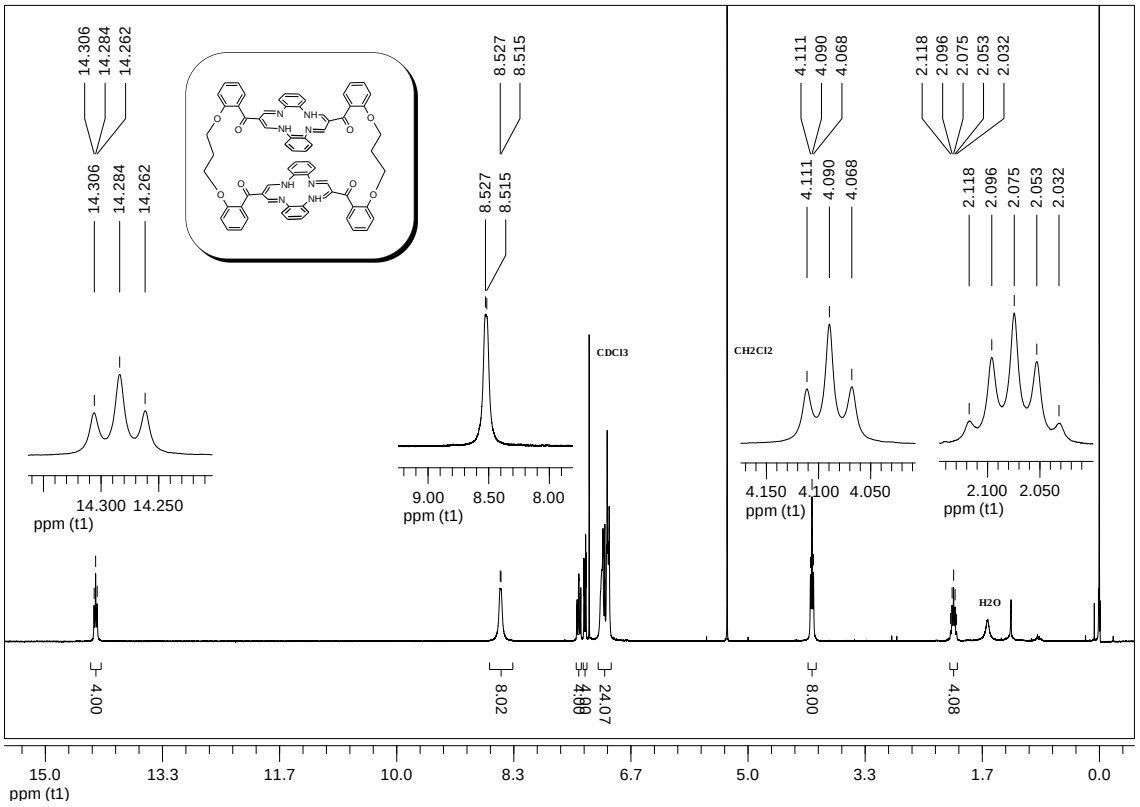


Figure S14. ^{1}H NMR spectrum of the cofacial dimer **6** (DBTAA-dim-3), recorded in $CDCl_3$.

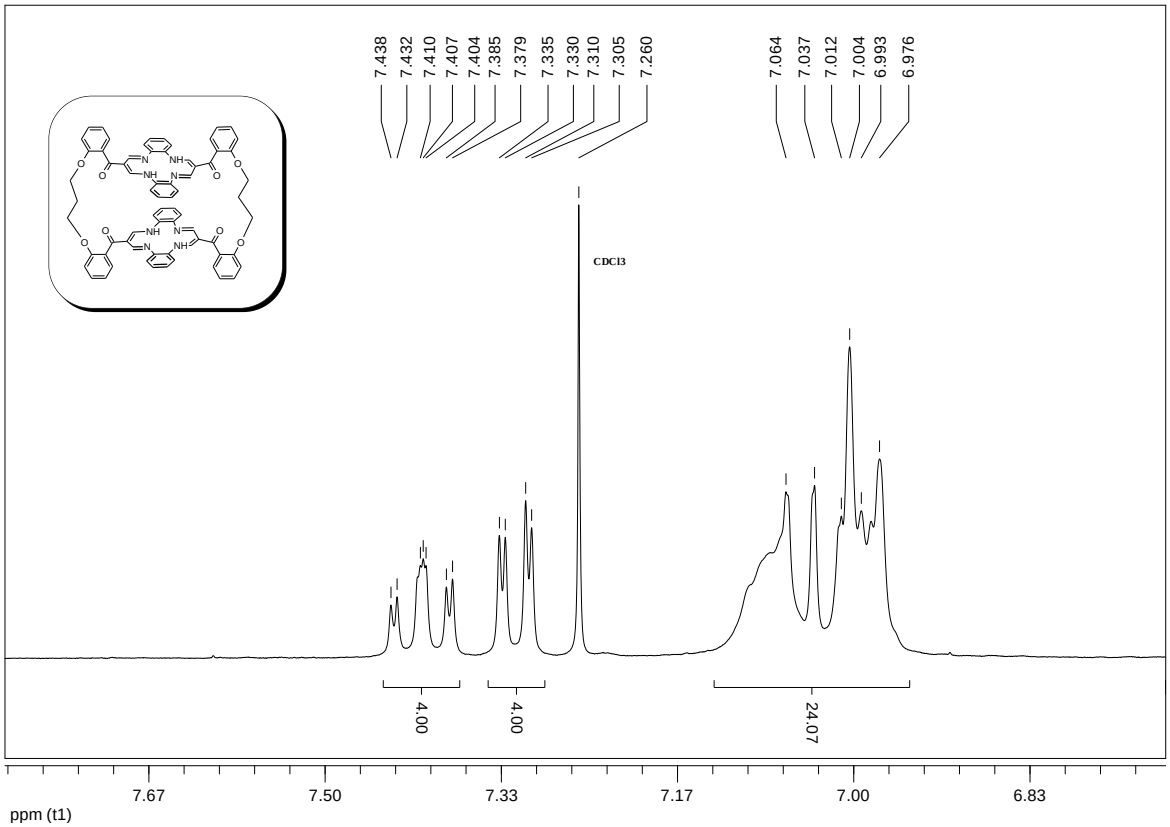


Figure S15. Aromatic region of the ^{1}H NMR spectrum of the cofacial dimer **6** (DBTAA-dim-3), recorded in $CDCl_3$.

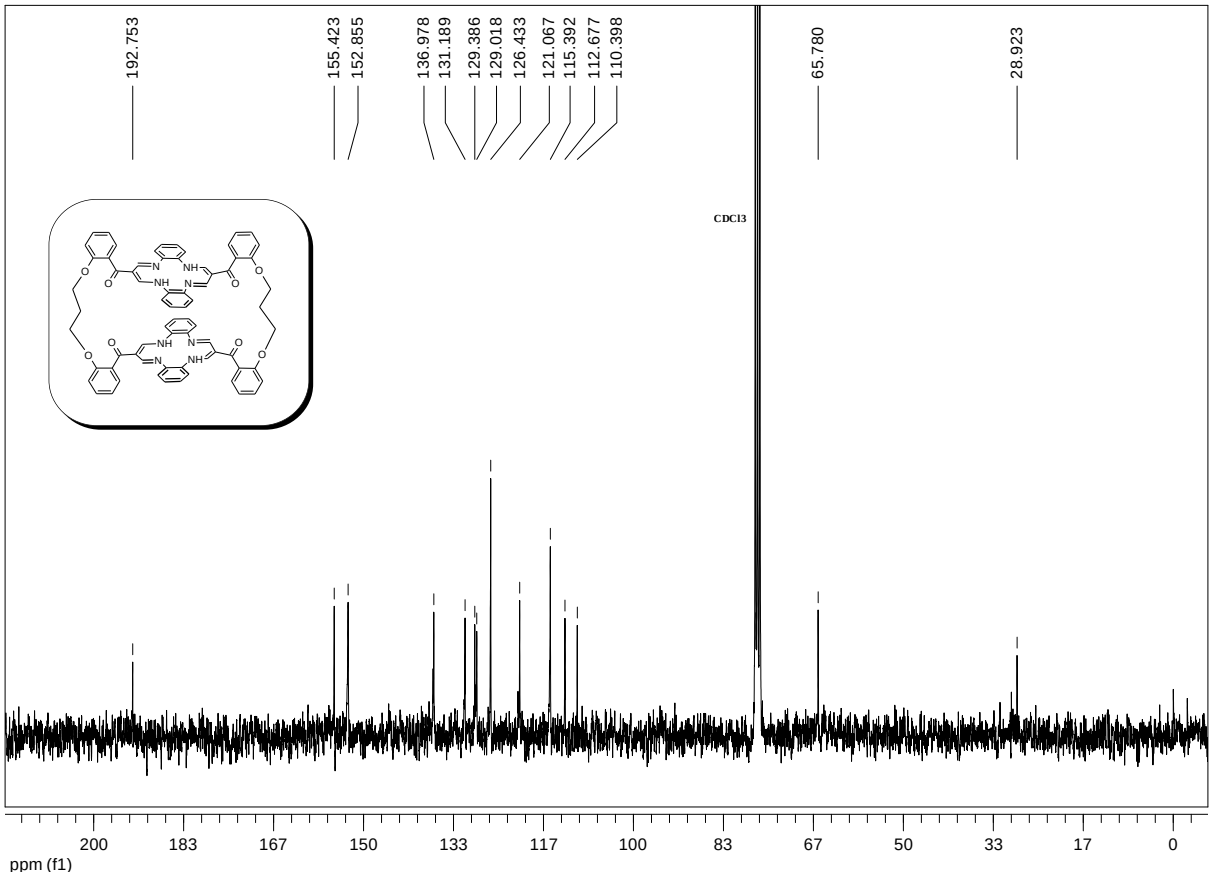


Figure S16. ^{13}C NMR spectrum of the cofacial dimer **6** (DBTAA-dim-3), recorded in $CDCl_3$.

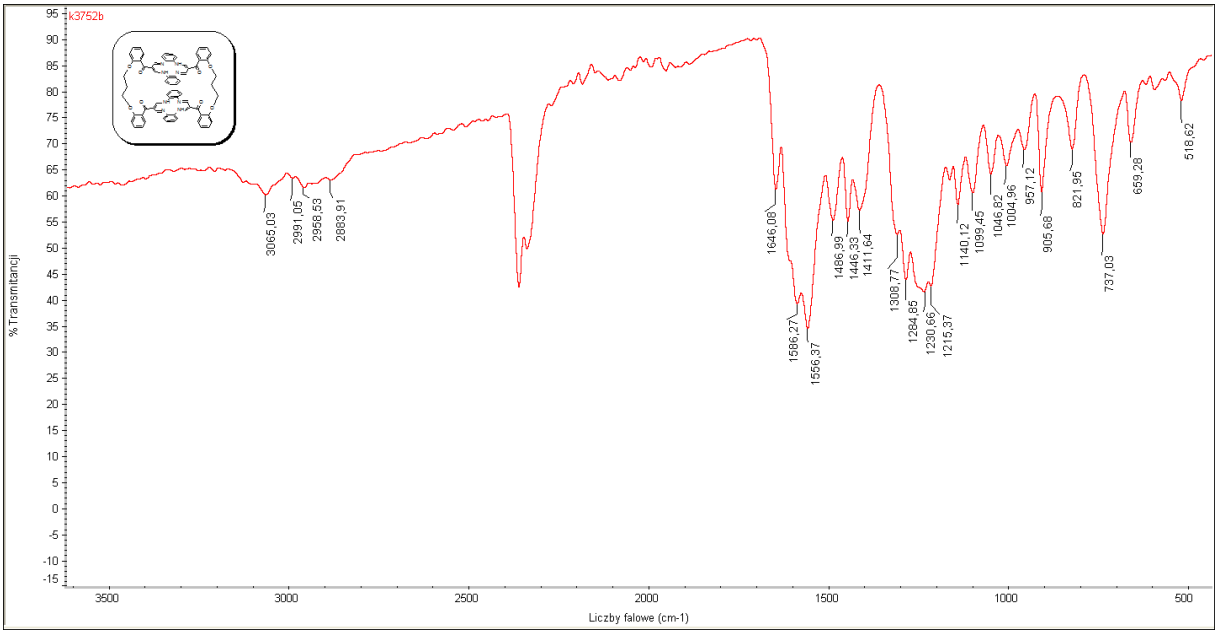


Figure S17. IR spectrum of the cofacial dimer **6** (DBTAA-dim-3) in a range 500-3500 cm^{-1}

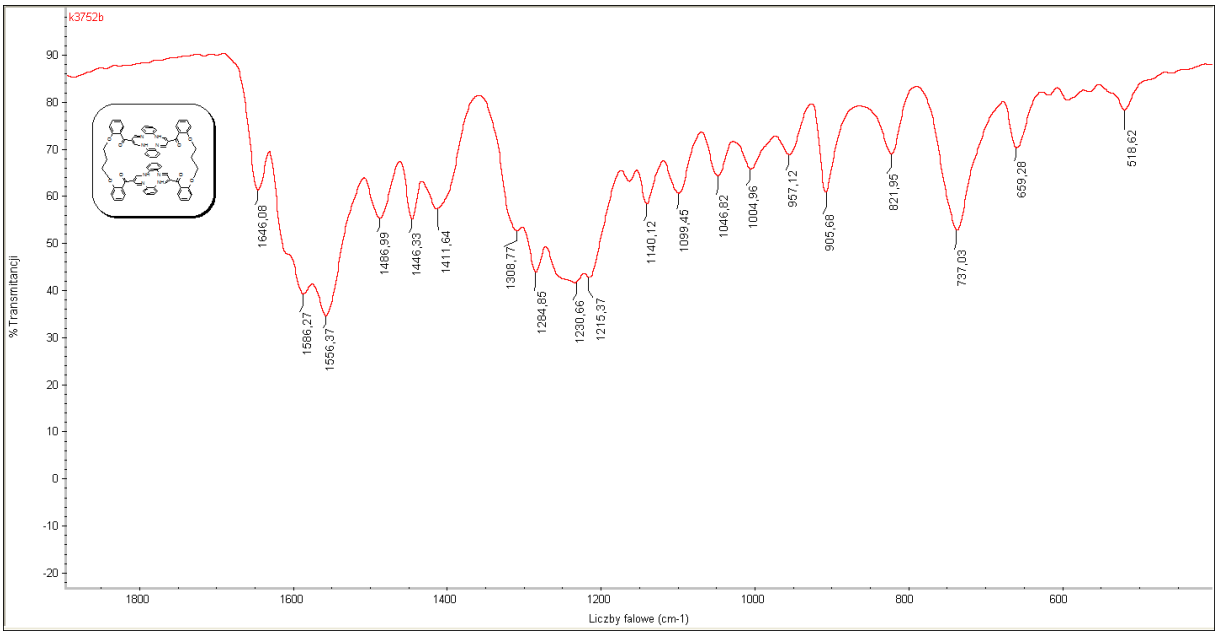


Figure S18. IR spectrum of the cofacial dimer **6** (DBTAA-dim-3) in a range 400-1900 cm^{-1}

a) b)

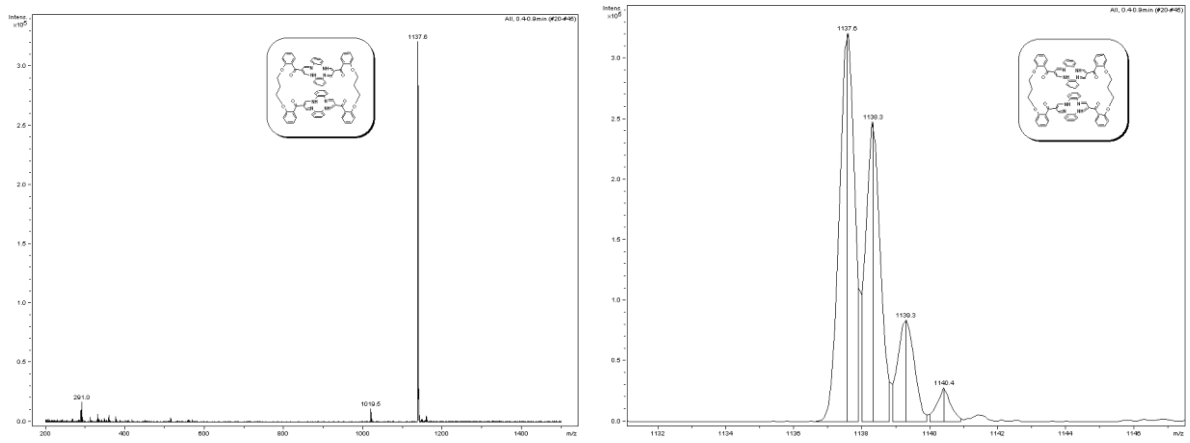


Figure S19. Electrospray mass spectrum of the cofacial dimer **6** (DBTAA-dim-3), recorded in a positive mode (a) and observed isotopic distributions for the pseudomolecular ion $[M+1]^+$ (b).

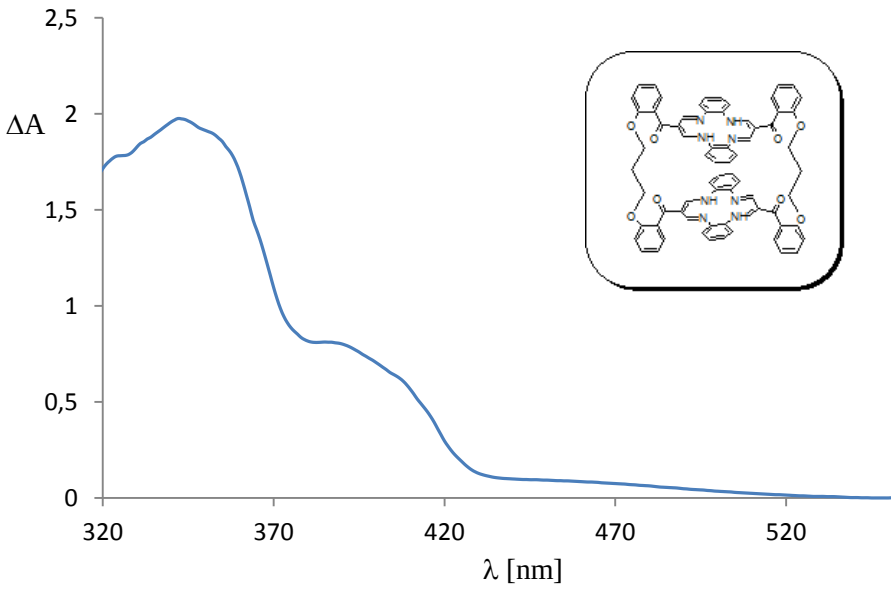


Figure S20. UV-vis absorption spectrum of the cofacial dimer **6** (DBTAA-Dim-3) in chloroform.

c) Spectra of the dinuclear zinc(II) complex **8** (Zn_2-DBTAA-dim-4)

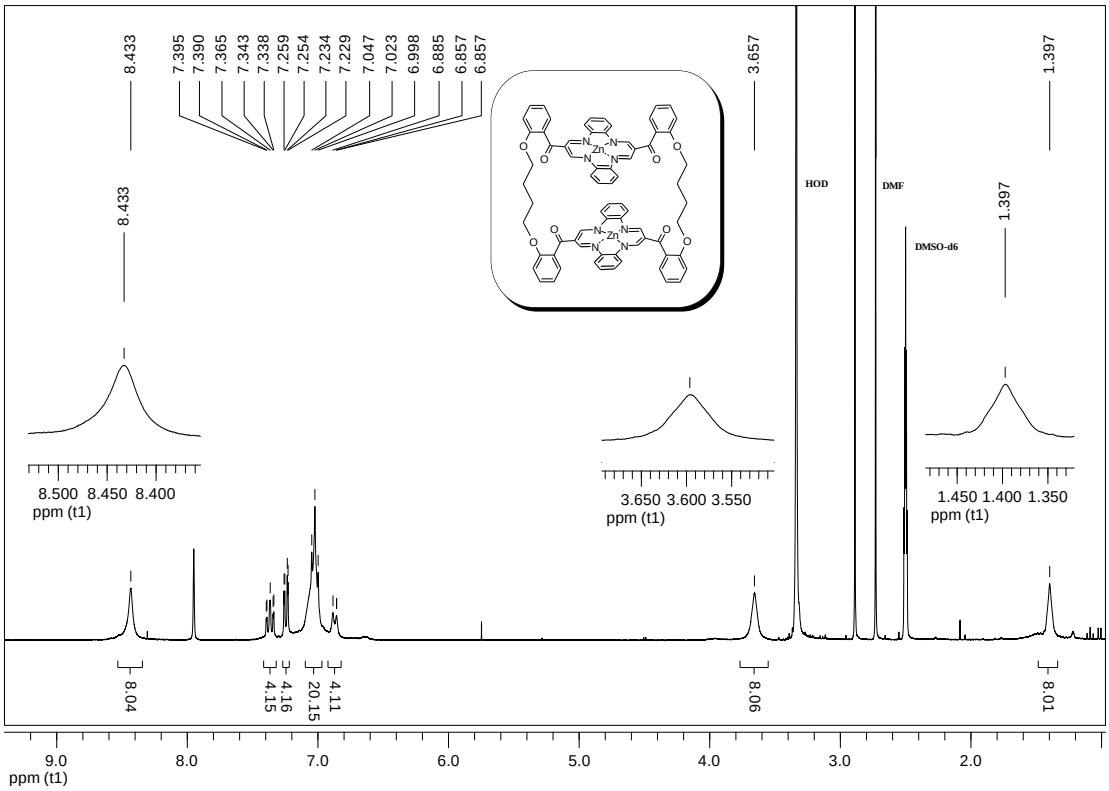


Figure S21. ^{1}H NMR spectrum of dinuclear zinc(II) complex **8** (Zn_2-DBTAA-dim-4), recorded in DMSO-d_6. The sample contains DMF.

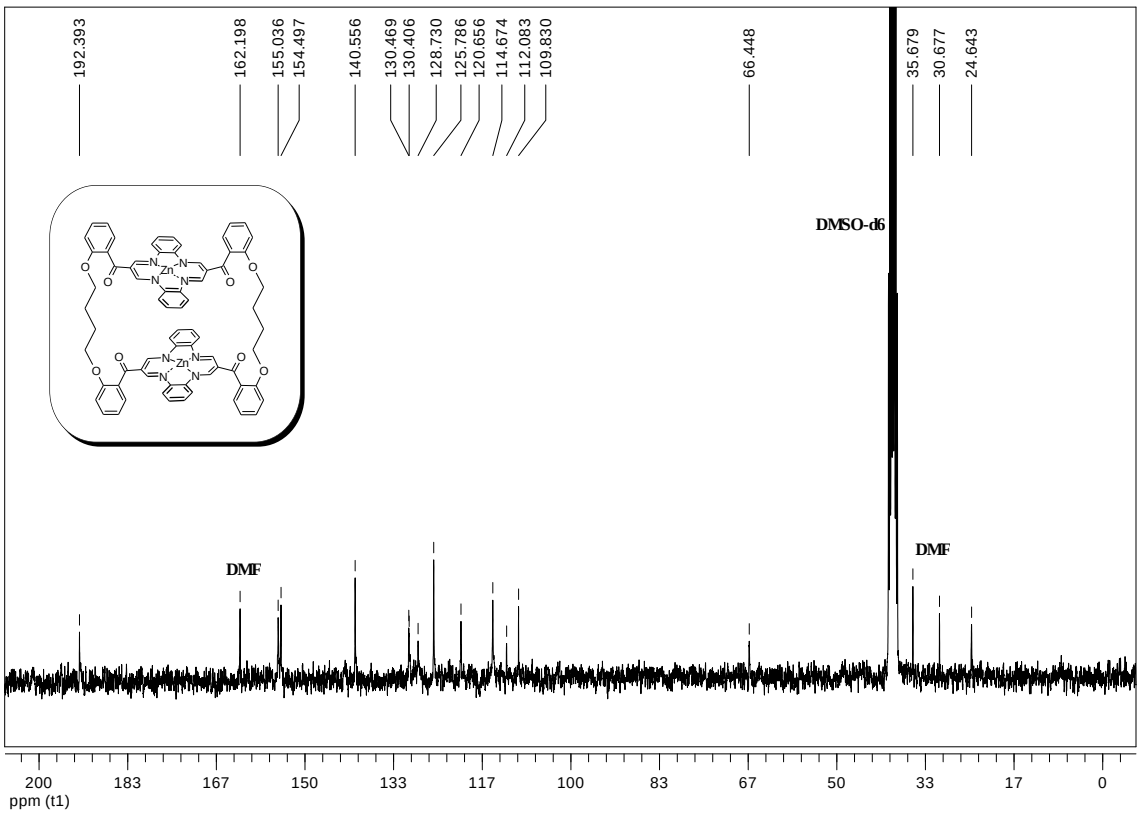


Figure S22. ^{13}C NMR spectrum of dinuclear zinc(II) complex **8** (Zn_2-DBTAA-Dim-4), recorded in DMSO-d_6. The sample contains DMF.

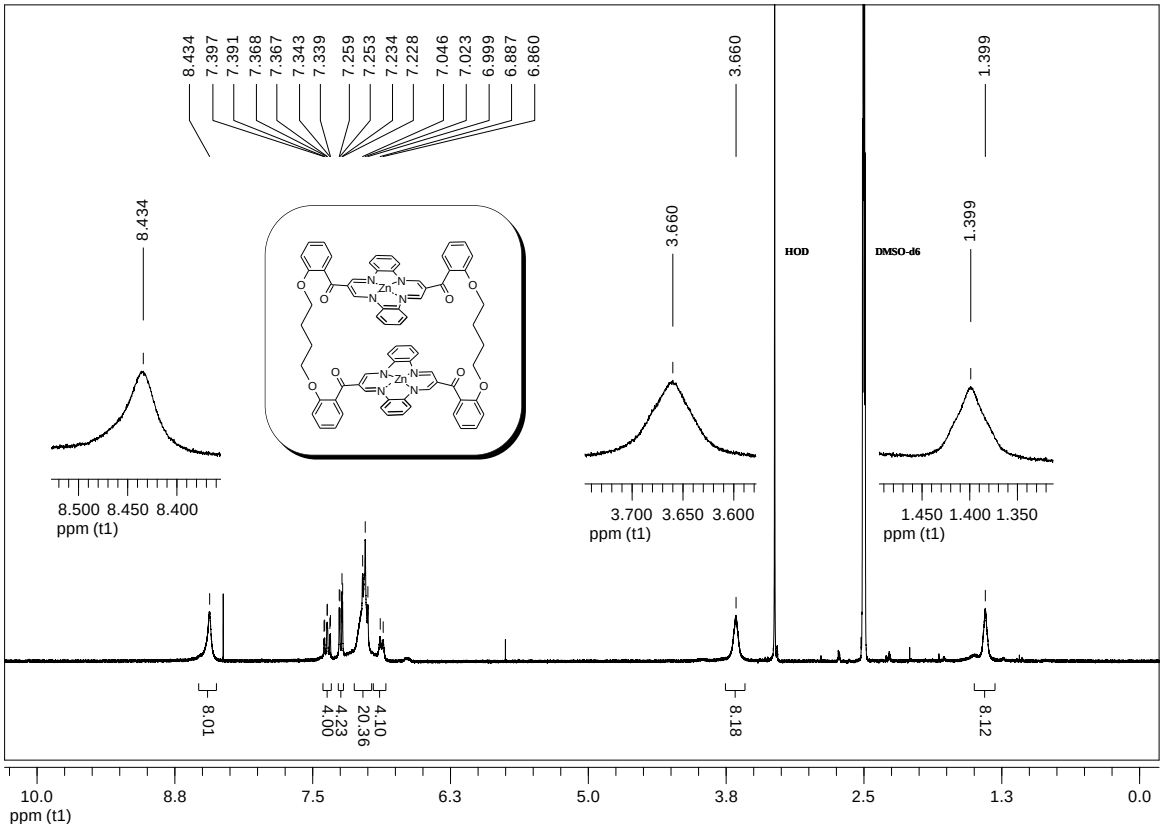


Figure S23. ^{1}H NMR spectrum of dinuclear zinc(II) complex **8** (Zn_2-DBTAA-dim-4), recorded in DMSO-d_6.

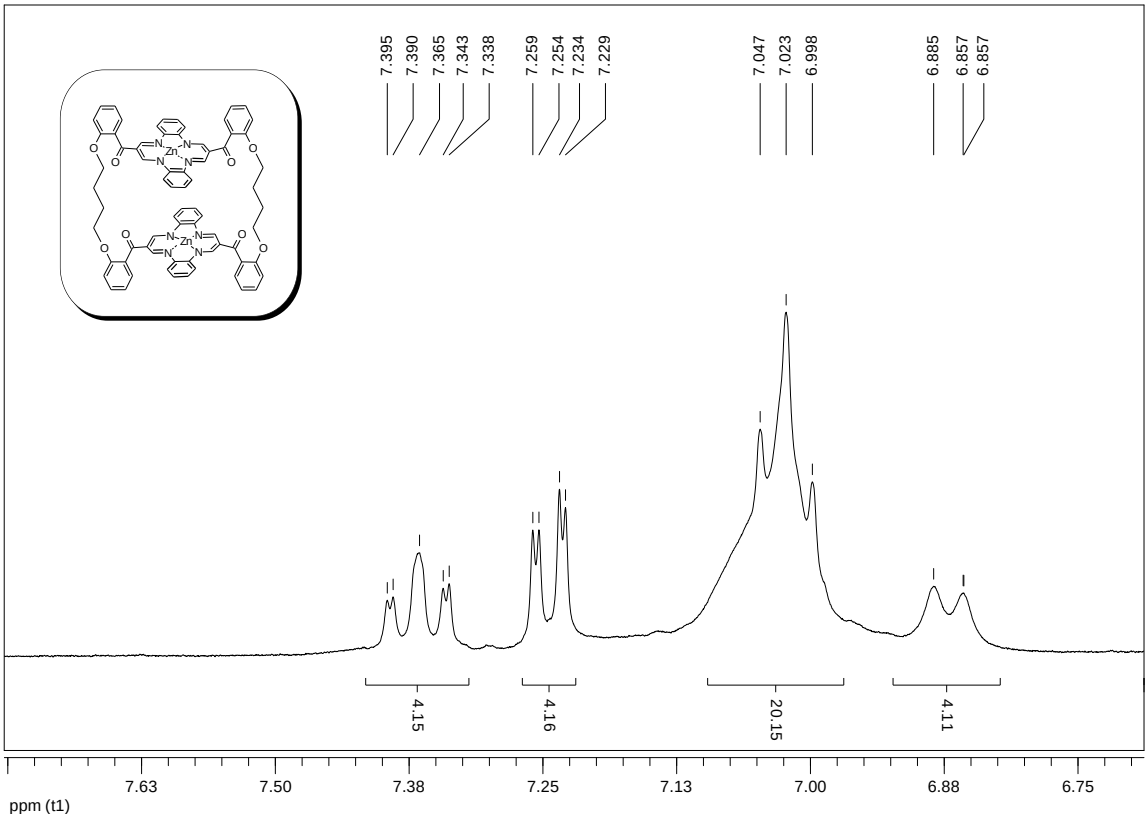


Figure S24. Aromatic region of the ^{1}H NMR spectrum of dinuclear zinc(II) complex **8** (Zn_2-DBTAA-dim-4) recorded in DMSO-d_6.

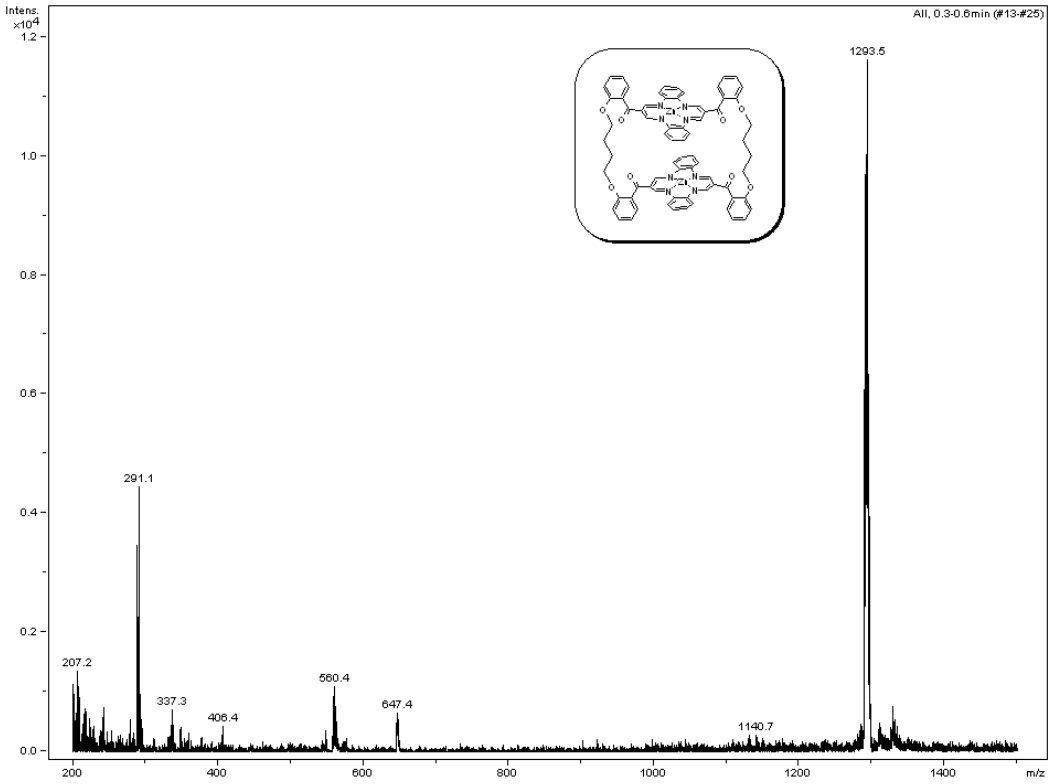


Figure S25. Electrospray mass spectrum of **8** (Zn_2-DBTAA-dim-4), recorded in a positive mode.

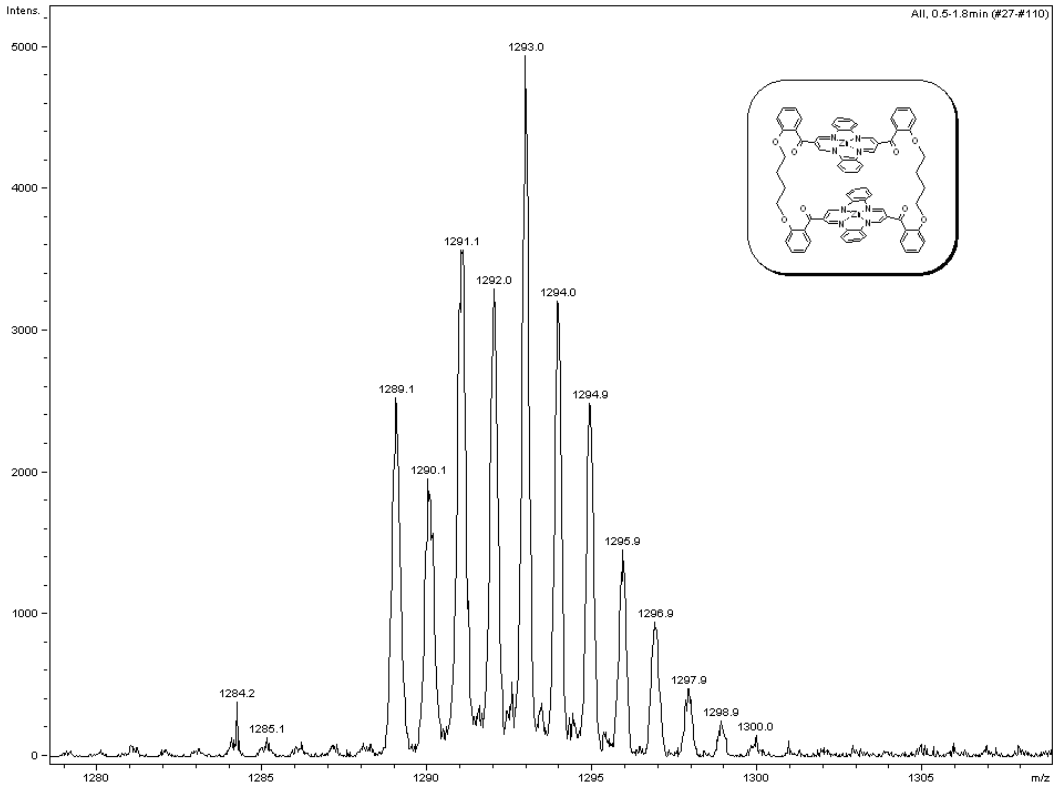


Figure S26. Experimentally observed isotopic distributions for the pseudomolecular ion $[M+1]^+$ of Zn_2-DBTAA-dim-4 (**8**).

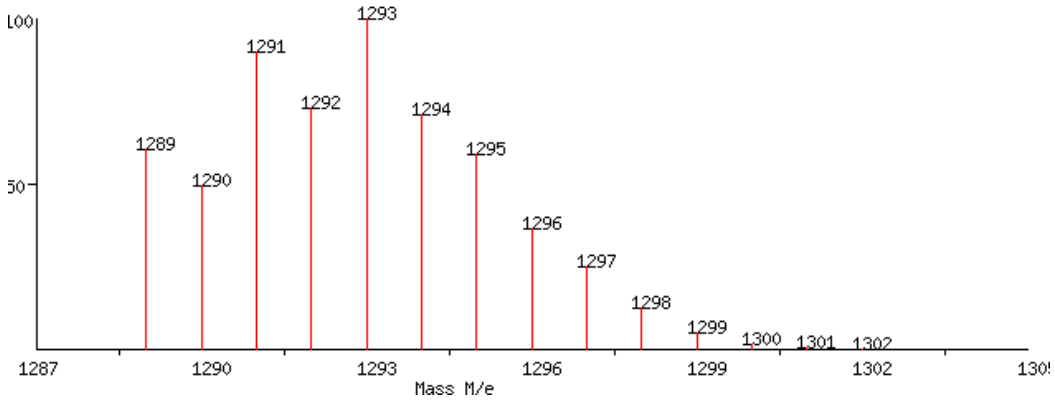


Figure S27. Theoretical isotope distribution for the pseudomolecular ion of (**8**) (Zn_2-DBTAA-dim-4) (calculated for $C_{72}H_{57}N_8O_8Zn_2$ ($M+H^+$)).

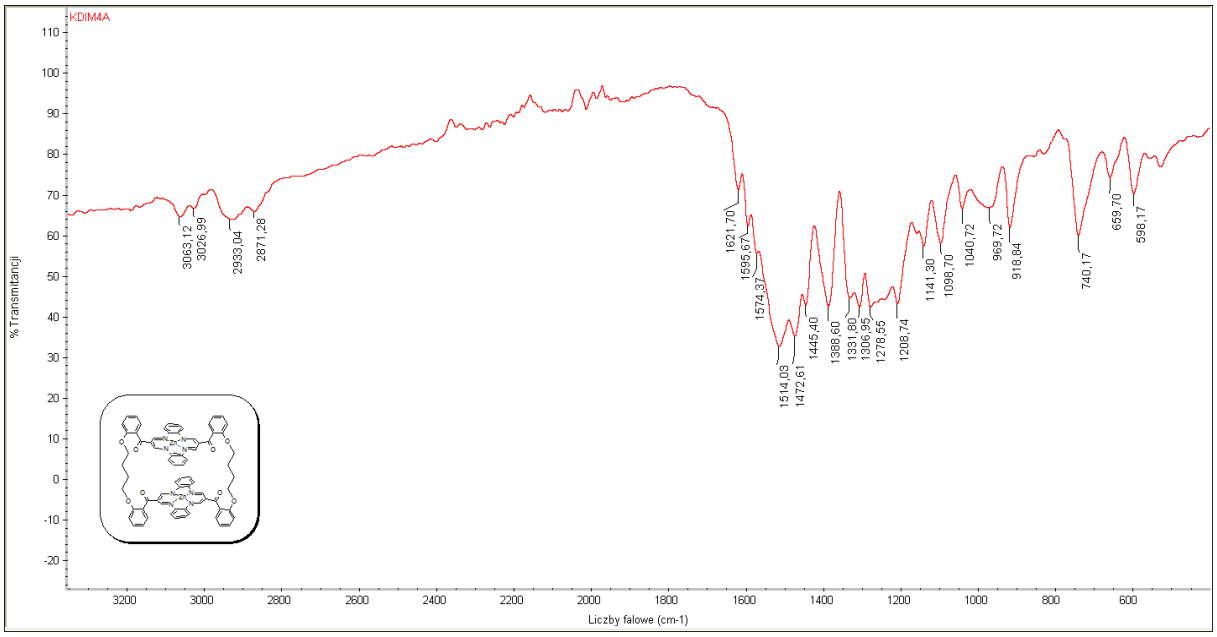


Figure S28. IR spectrum of the zinc(II) complex **8** (Zn_2-DBTAA-dim-4) in a range 3300-400 cm^{-1}

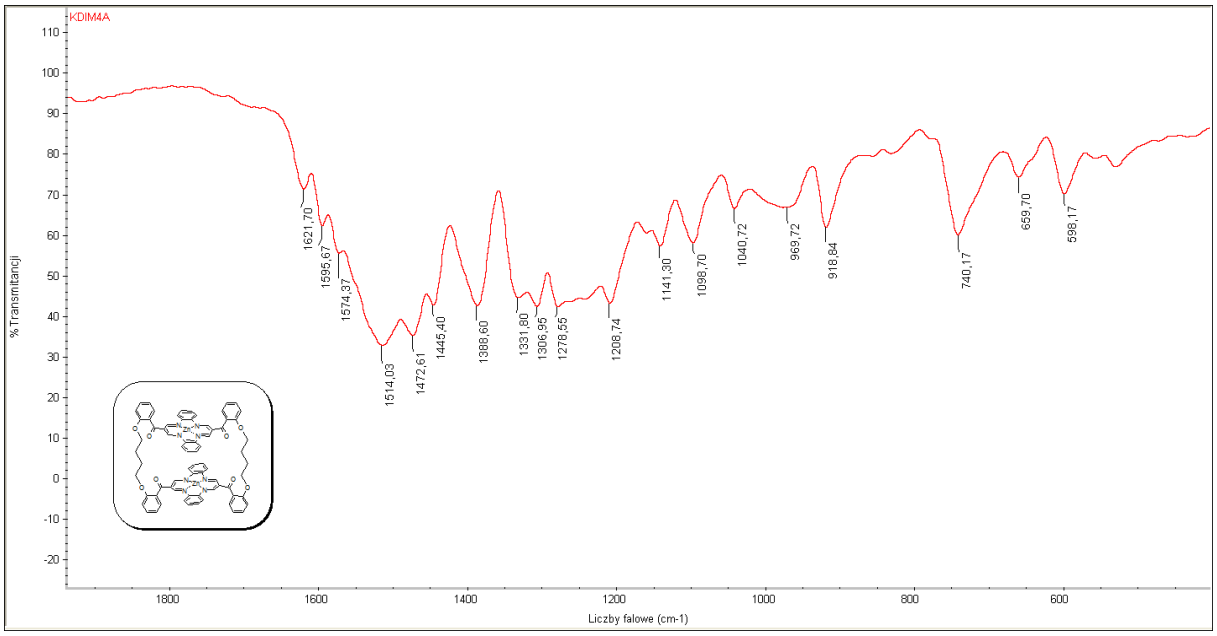


Figure S29. IR spectrum of the zinc(II) complex **8** (Zn_2-DBTAA-dim-4), in a range 1950-400 cm^{-1}

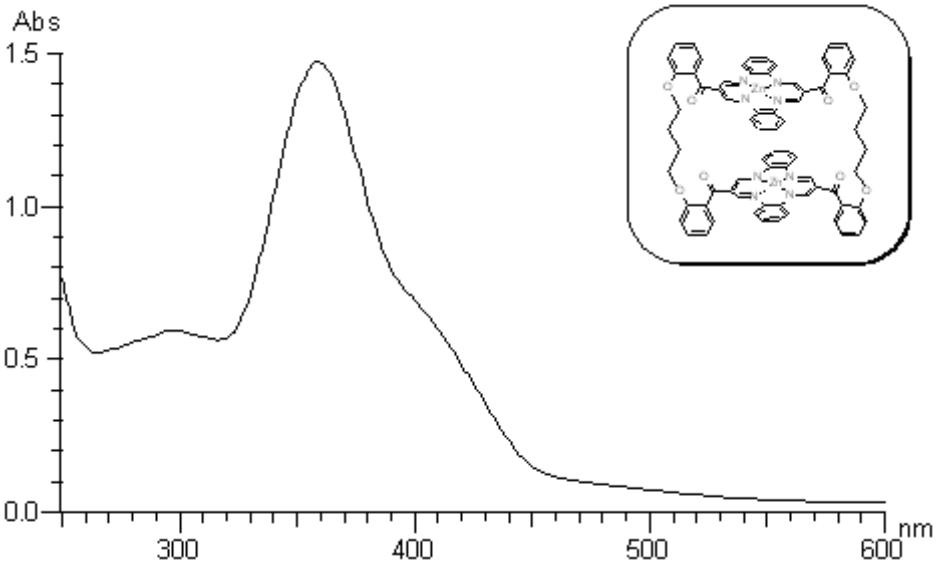


Figure S30. UV-vis absorption spectrum of the zinc(II) complex **8** (Zn_2-DBTAA-dim-4) in chloroform.

d) Cofacial dimer DBTAA-dim-3asym (9)

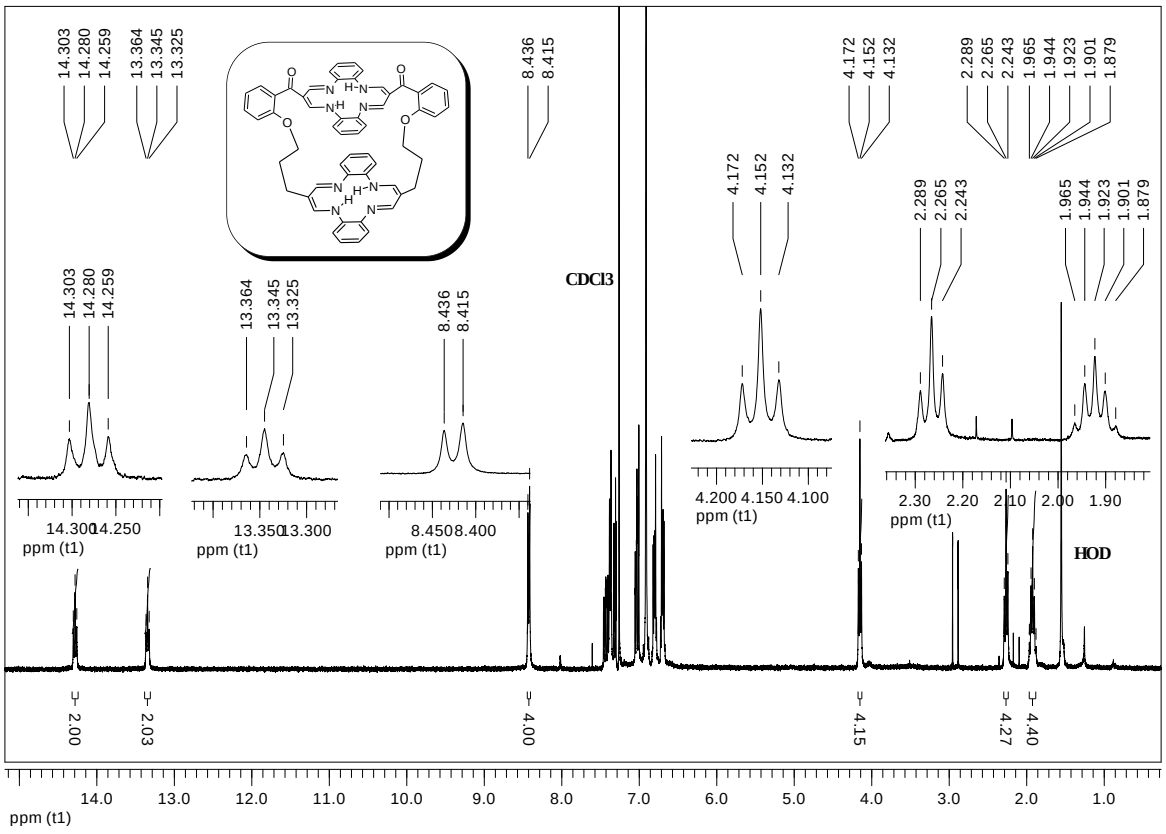


Figure S31. ^{1}H NMR spectrum of (**9**) (DBTAA-dim-3asym), recorded in $CDCl_3$.

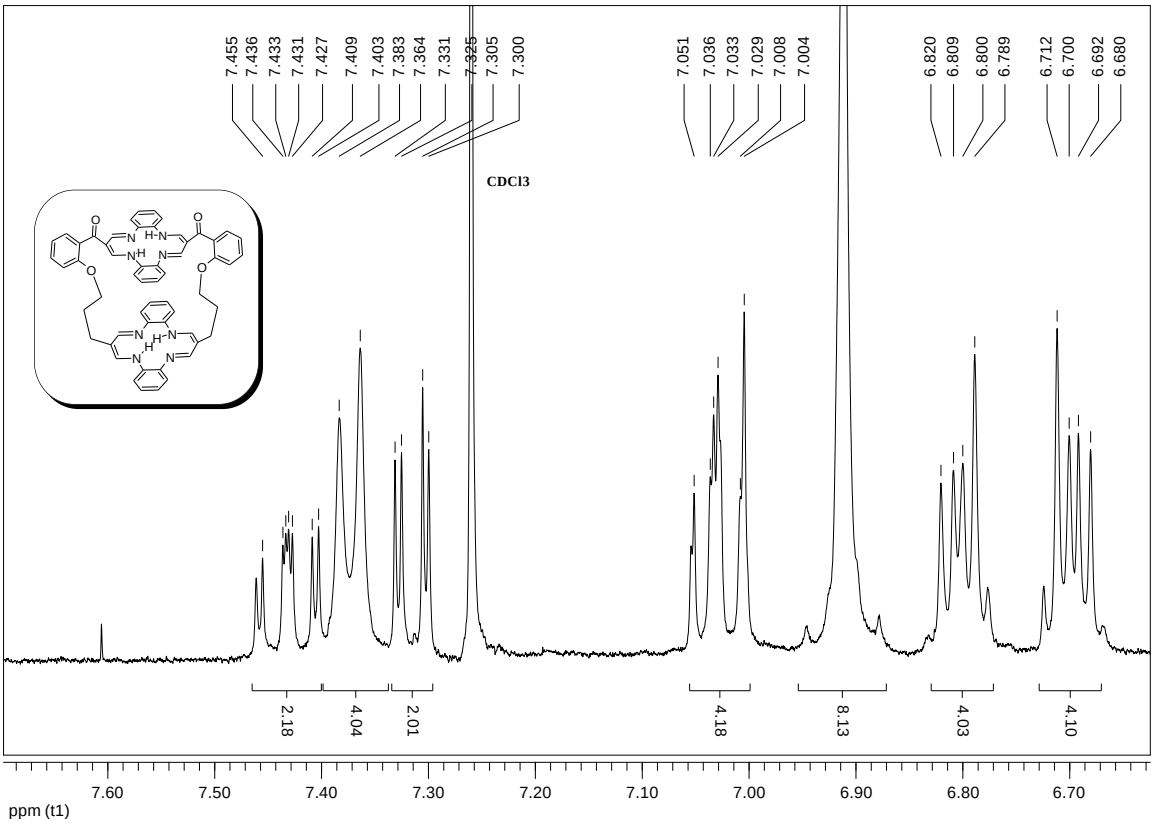


Figure S32. Aromatic region of the ^{1}H NMR spectrum of **9** (DBTAA-dim-3asym) recorded in $CDCl_3$.

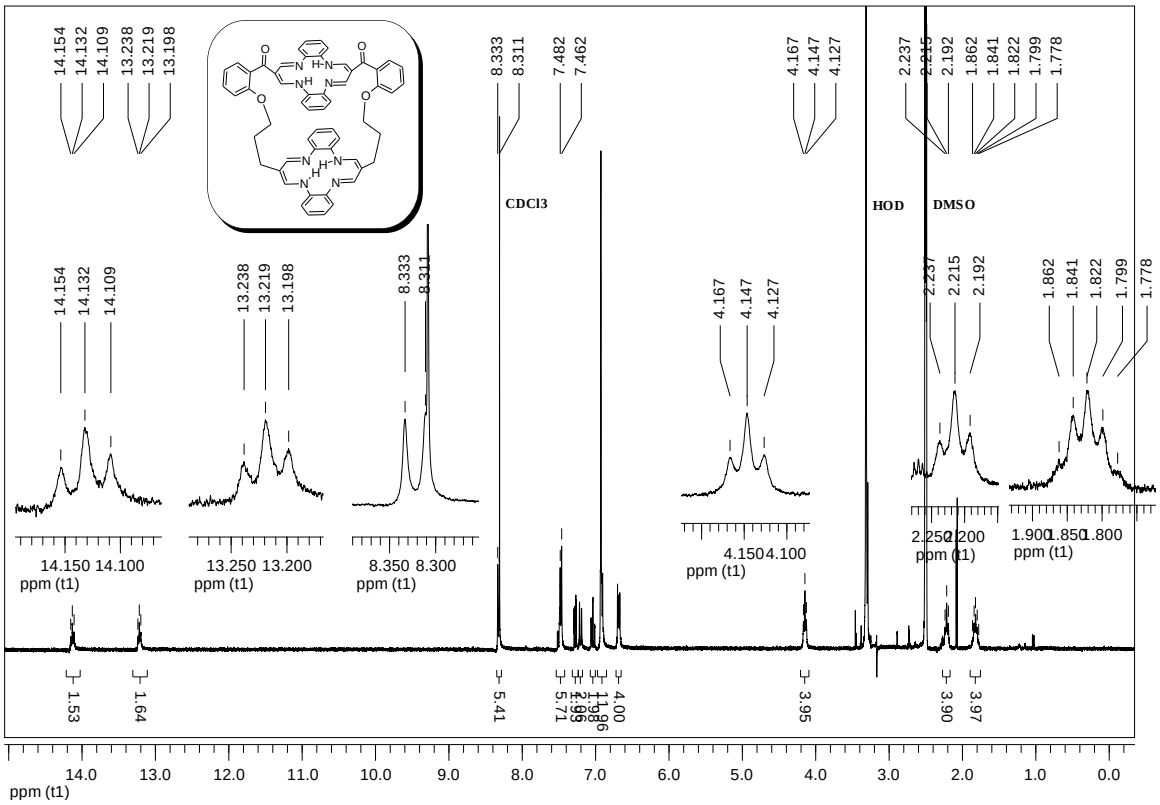


Figure S33. ^{1}H NMR spectrum of **9** (DBTAA-dim-3asym), recorded in DMSO-d_6.

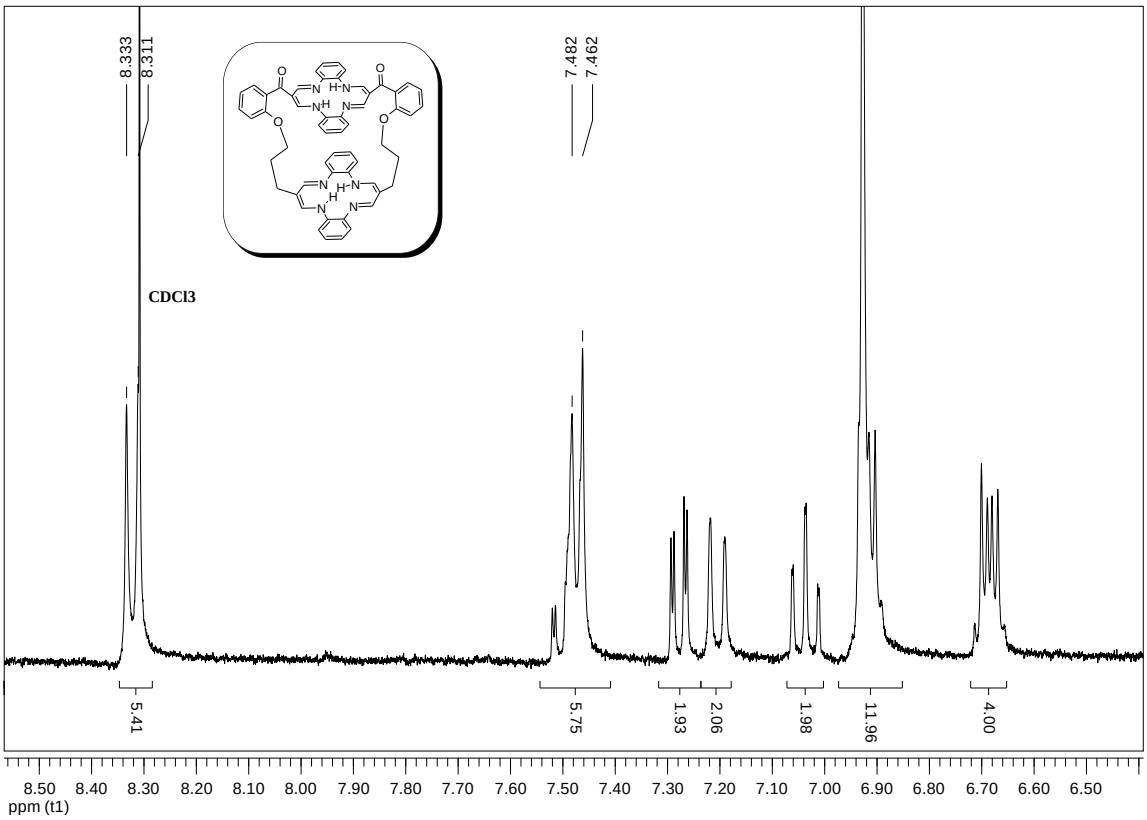
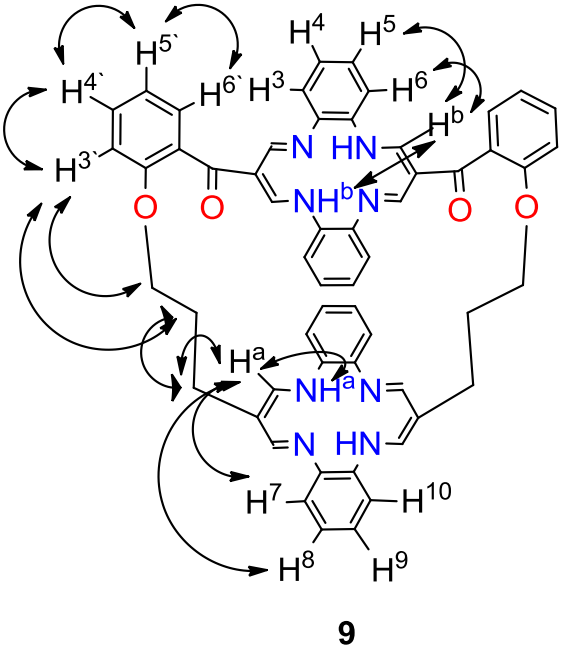


Figure S34. Aromatic region of the ^{1}H NMR spectrum of **9** (DBTAA-dim-3asym), recorded in DMSO-d_6.

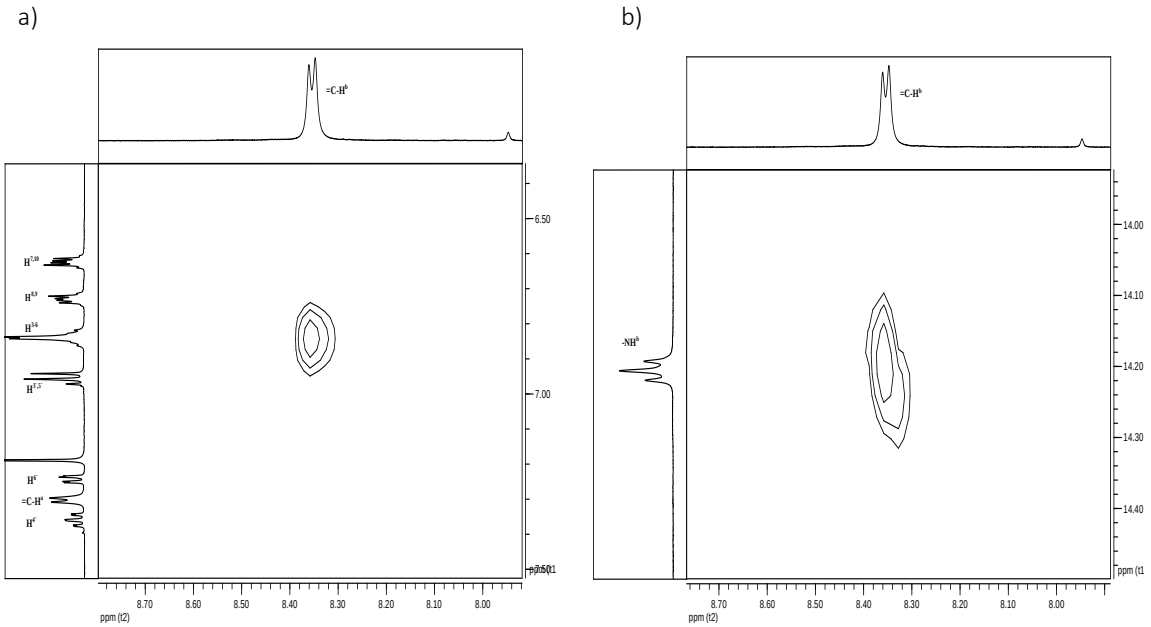
ROESY experiment

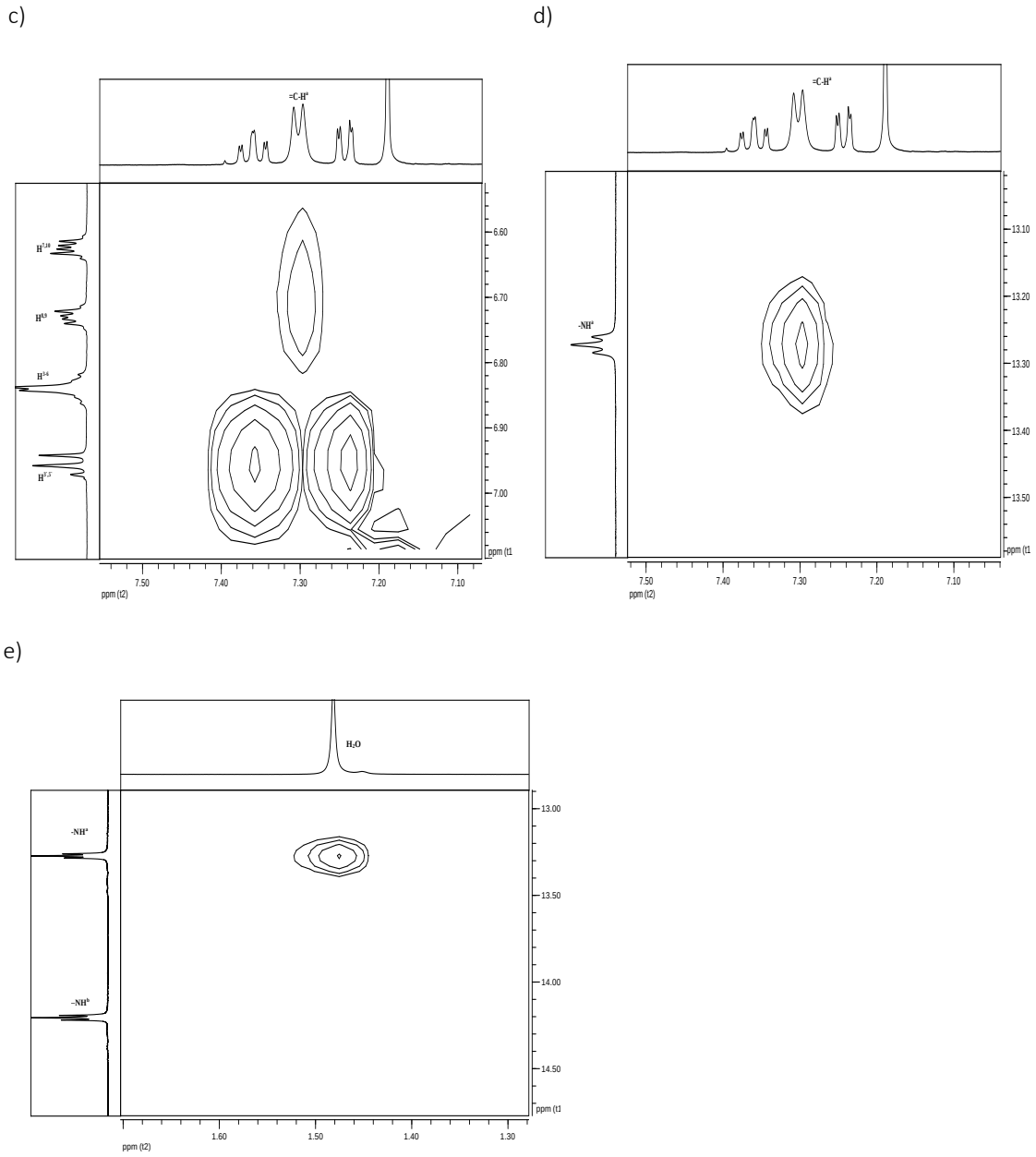
The presence and location of tightly bound water molecule in the solution of the cofacial dimer **9** have been investigated by means of the 2D ROESY spectroscopy. Interactions between amine protons =NH and a tightly bound water molecule separated by the distance of less than 3.5 Å can be easily inferred from the simple chemical exchange process, since cross-peaks for these two distinctive processes are of opposite sign.



9

Figure S35. ROESY correlations of **9** (DBTAA-dim-3asym)





Figures S36. Partial contour plot of two-dimensional 2D-ROESY spectrum of the cofacial dimer **9** (DBTAA-dim-3asym), in $CDCl_3$ (0.003 mM) at 298 K, showing intramolecular cross-peaks observed between: a) β-protons (=C-H^A) (f_1) and aromatic protons H3-6, b) β-protons (=C-H^A) (f_1) and amine -NH^A (f_2) protons, c) β-protons (=C-H^B) (f_1) and aromatic protons, d) β -protons =C-H^B (f_1) and amine –NH^B (f_2) protons, e) amine –NH^B (f_2) protons and bound water molecule.

Water exchange experiment

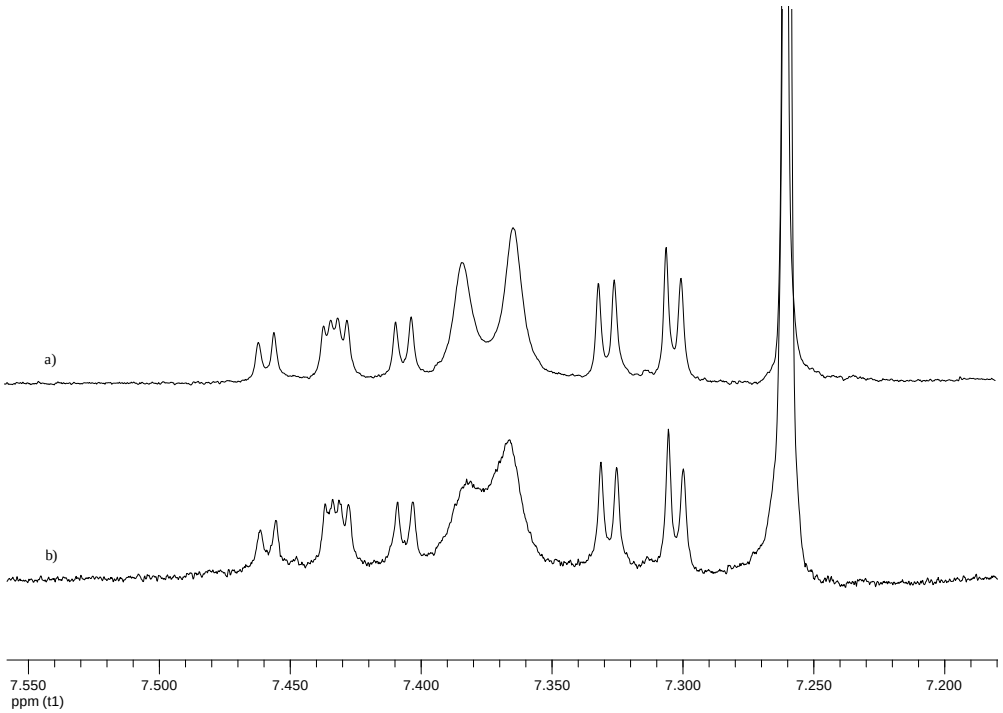


Figure S37. Aromatic region of ^{1}H NMR spectrum of the cofacial dimer **9** (DBTAA-dim-3asym) showing signals of aromatic and β-protons (=C-H^{A}) protons, recorded in $CDCl_3$: a) deacidified, and b) as received.

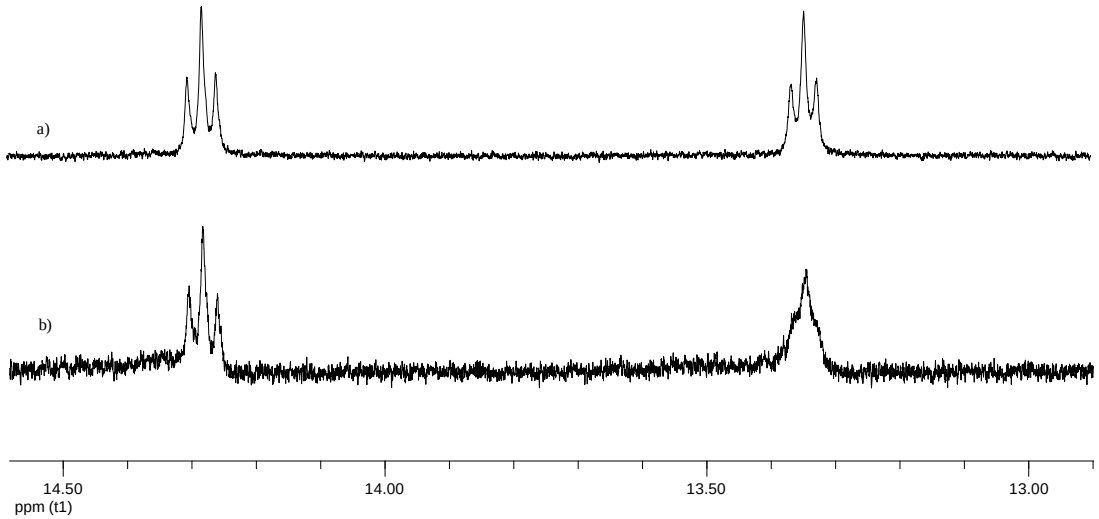


Figure S38. Downfield region of the ^{1}H NMR spectrum of the cofacial dimer **9** (DBTAA-dim-3asym) showing signals of amine NH^{A} and NH^{B} protons, recorded in $CDCl_3$: a) deacidified, and b) as received.

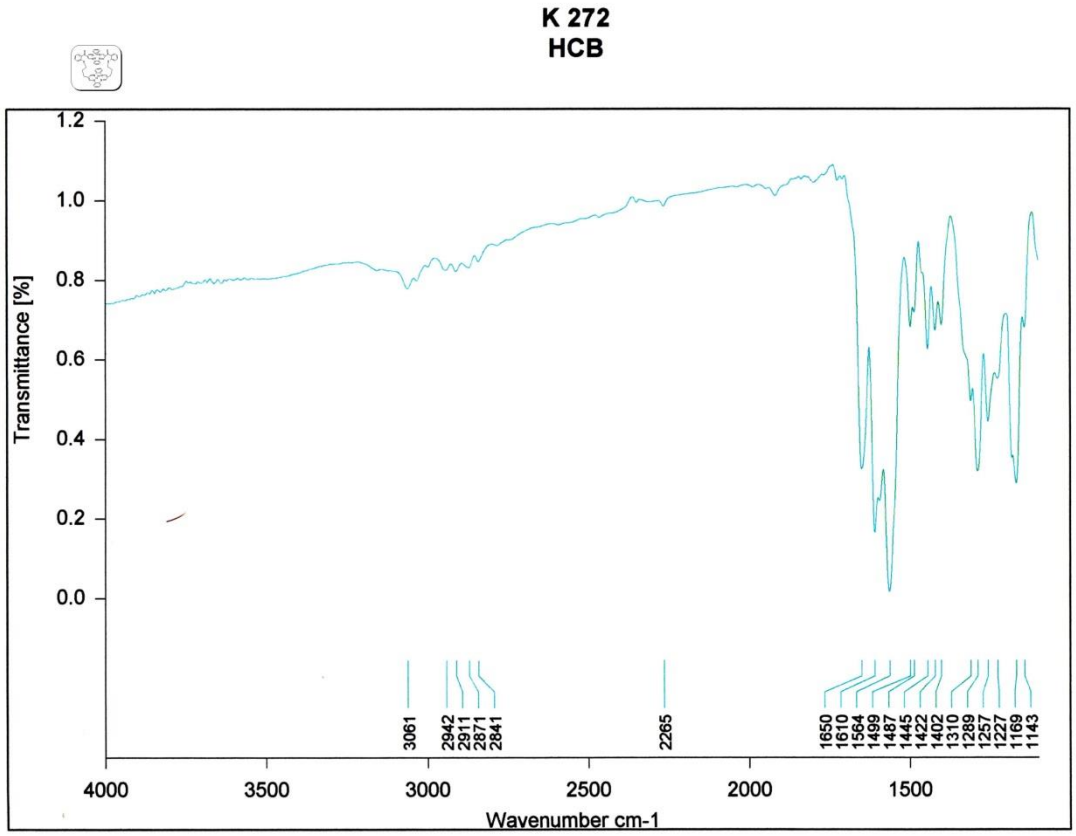


Figure S39. IR spectrum of the cofacial dimer **9** DBTAA-Dim3asym in hexachlorobutadiene (HCB).

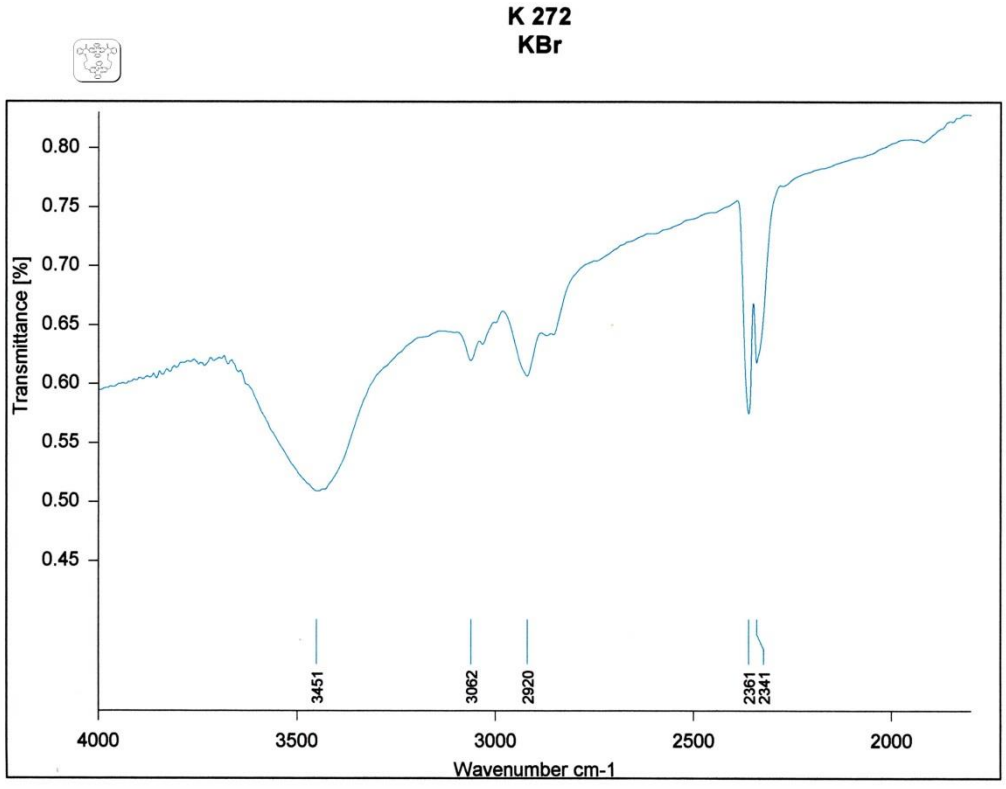


Figure S40. IR spectrum of the cofacial dimer **9** (DBTAA-dim-3asym) in a KBr pellet, in a range 4000-1800 cm^{-1}.

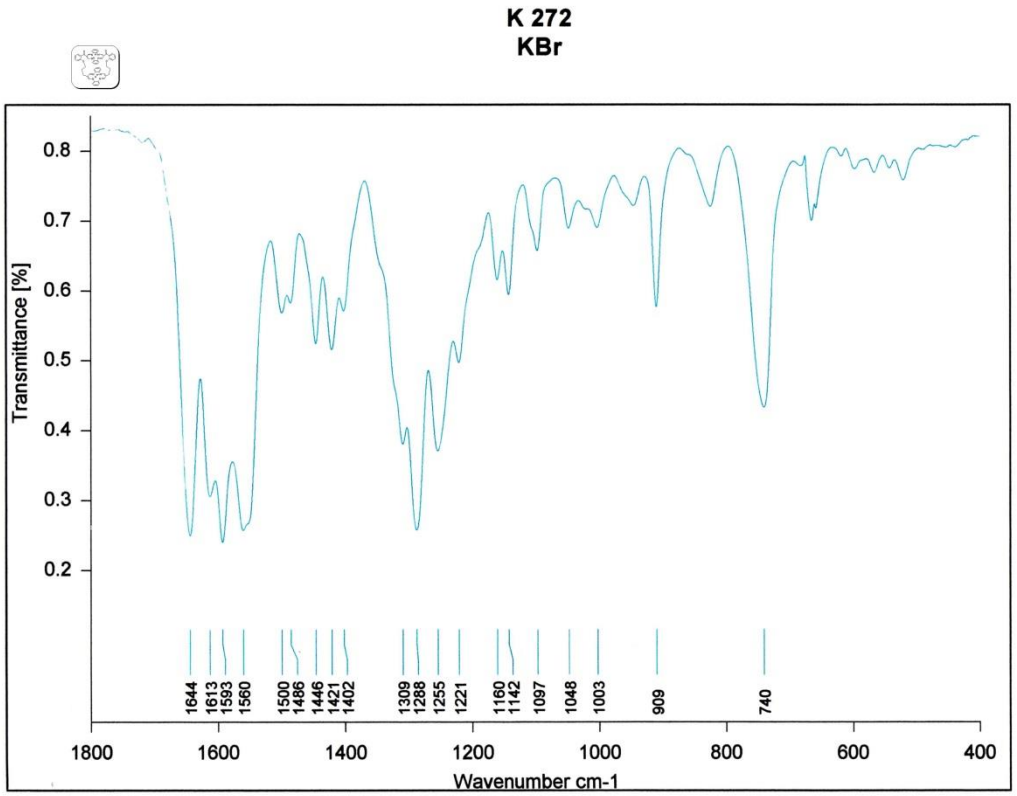


Figure S41. IR spectrum of the cofacial dimer **9** (DBTAA-dim-3asym) in a KBr pellet, in a range 1800-400 cm^{-1}.

a) b)

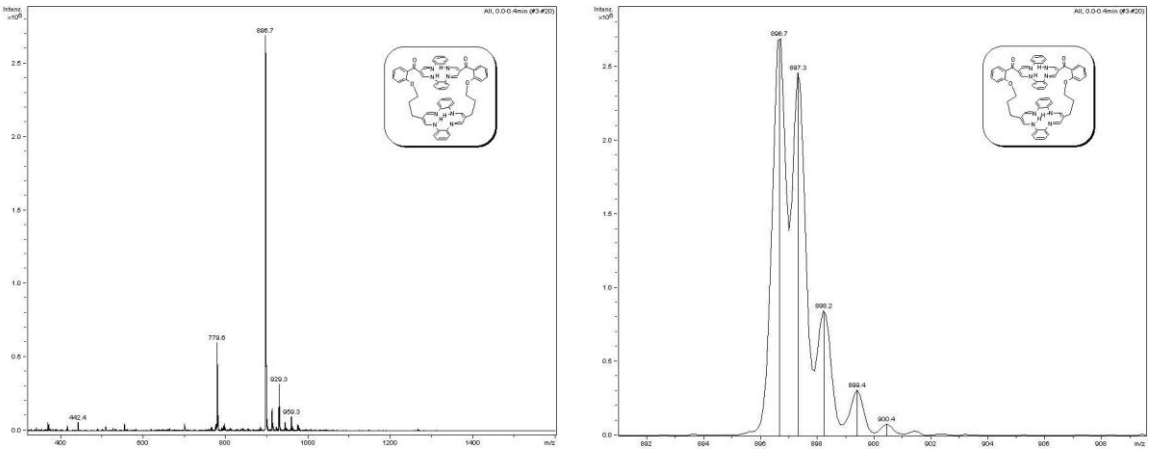


Figure S42. Electrospray mass spectrum of the cofacial dimer **9** (DBTAA-dim-3asym) recorded in a positive mode a) and observed isotopic distributions for the pseudomolecular ion $[M+1]^+$.

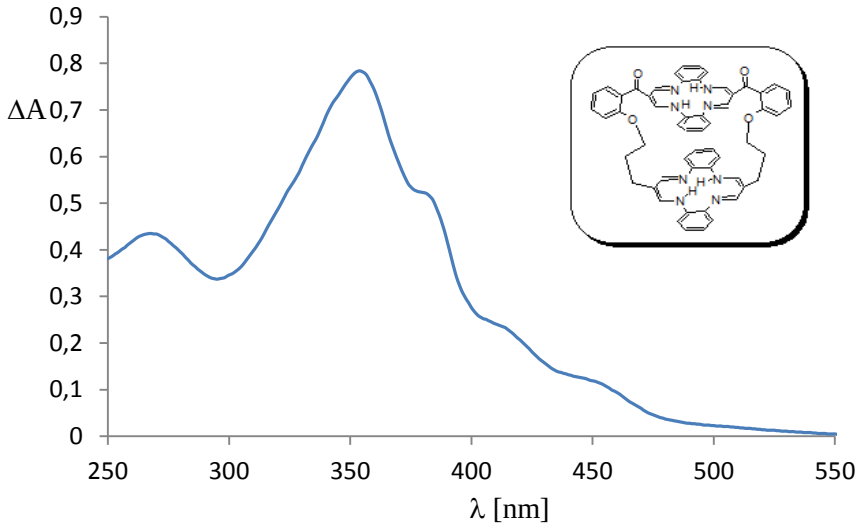


Figure S43. UV-vis absorption spectrum of the cofacial dimer **9** (DBTAA-dim-3asym) in chloroform.