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Molecular tweezers as synthetic receptors: molecular recognition of neutral and cationic aromatic substrates. A comparison between the supramolecular structures in crystal and in solution

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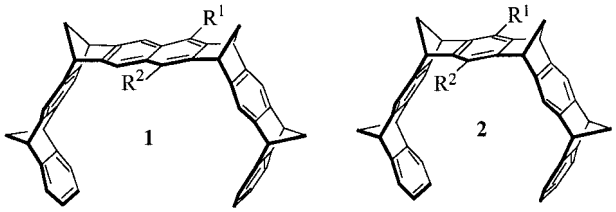
ABSTRACT: The synthesis of substituted naphthalene- and benzene-spaced tweezer molecules **1b** and **c** and **2e–j** is reported. They selectively bind electron-deficient neutral and cationic aromatic substrates. The structural parameters of the substrate–receptor complexes derived from ^{1}H NMR measurements in solution are in good agreement with those obtained from single-crystal structure analyses. The tweezer **2f** forms a stable complex with *N*,*N*-bis-(3,5-di-*tert*-butylbenzyl)-4,4′-bipyridinium **14**, a substituted viologen dication, that exhibits the structure of a *clipped* rotaxane with a wheel opened on one side. The benzene-spaced tweezer **2j** shows complexation of the cesium cation Cs^+ inside the cavity. Copyright © 2000 John Wiley & Sons, Ltd.

KEYWORDS: molecular tweezers; synthesis; supramolecular chemistry; ^{1}H NMR spectroscopy; single-crystal structure analysis

INTRODUCTION

The non-covalent interactions of arenes with other aromatic units (π–π or arene–arene interaction)[1] or with positively charged ions (cation –π interaction)[2] are of particular importance in the processes of molecular recognition and self-assembly. The design of efficient synthetic receptors with the ability of selective substrate binding requires precise control of their topological and electronic properties. Besides the frequently used cyclic and, hence, well preorganized receptors of the cyclophane-type, non-cyclic receptors with cavities of flexible size proved to be effective.[3] We have recently reported the synthesis and some supramolecular properties of the hydrocarbon compounds **1a** and **2a**.[4] Owing to their ability to bind selectively electron-deficient aromatic and aliphatic substrates and organic cations, the receptors **1a** and **2a** can be regarded as molecular tweezers. Here we report the synthesis of the substituted tweezer molecules **1b** and **c** and **2e–j** and a comparison between the supramolecular structures of several complexes in the crystalline state and in solution derived either from single-crystal structure analyses or ^{1}H NMR investigations in solution.



R^1	H	OAc	OMe	OH	$OCH_2CO_2CH_2CH_3$	$OCH_2CO_2^-$
R^2	H	OAc	OMe	OH	$OCH_2CO_2CH_2CH_3$	$OCH_2CO_2^-$
	a	**b**	**c**	**d**	**e**	**f**

R^1	OAc	OAc	OH	OH
R^2	OH	$OCH_2CO_2CH_2CH_3$	OCH_2CO_2H	$OCH_2CO_2^-$
	g	**h**	**i**	**j**

RESULTS AND DISCUSSION

Synthesis of substituted naphthalene- and benzene-spaced tweezers

The substituted naphthalene-spaced tweezers **1b** and **c** can be synthesized in two steps starting from the known

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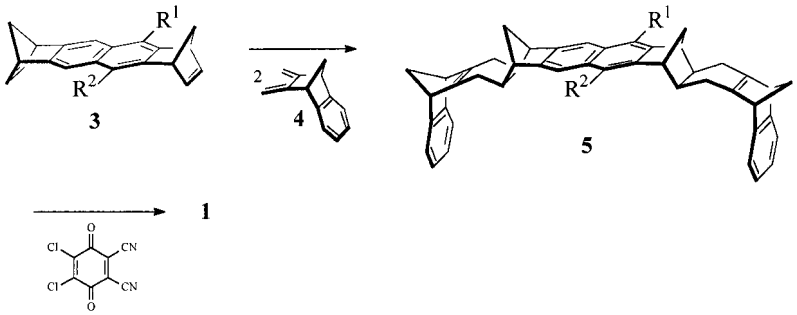
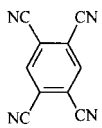
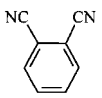
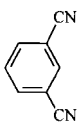
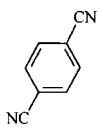
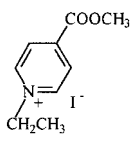
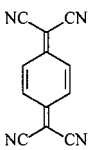
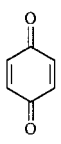
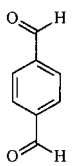


bisdienophiles **3b** and **c**[5] in overall yields of 53 and 29%, respectively, analogously to the parent hydrocarbon **1a**.[4] Repetitive Diels–Alder reactions of **3b** and **c** with diene **4** proceed stereospecifically to yield the bisadducts **5b** and **c** which can be converted in to the tweezer molecules **1b** and **c** by oxidative dehydrogenation with 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ).

The starting material for the synthesis of substituted benzene-spaced tweezer molecules **2e–j** is the diacetate **2b**.[4] $LiAlH_4$ reduction of **2b** leads to the hydroquinone **2d**[4] which can be substituted by ethyl α-bromoacetate in the presence of K_2CO_3 to give **2e** in a yield of 92% (the synthesis of **2e** via a different route has been reported[6]). Ester hydrolysis of **2e** with KOH or CsOH gives the potassium or cesium salt of **2f** in almost quantitative yield. The diacetate **2b** can be hydrolyzed by NaOH in dioxane to produce the hydroquinone monoacetate **2g** in 87% yield.[7] Substitution of **2g** by ethyl α-bromoacetate and subsequent hydrolysis of the two ester functions gives the acid **2i**, which can be neutralized by CsOH leading to the cesium salt (Cs^+**2j**).

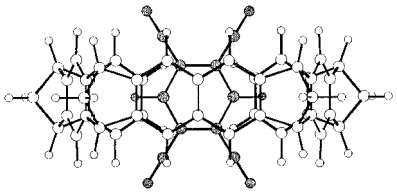
Table 1. Association constants K_a (mol l^{-1}) of the complexes at 21 °C in $CDCl_3$ determined by the method of ^{1}H NMR titration[4]

Substrate				
	6	**7**	**8**	**9**
K_a	$>10^5$	40 ± 4	85 ± 9	110 ± 11
Substrate				
	10	**11**	**12**	**13**
K_a	1000 ± 100	$>10^5$	20 ± 2	25 ± 4

Naphthalene-spaced tweezers 1a–c as receptors for neutral and cationic aromatic substrates

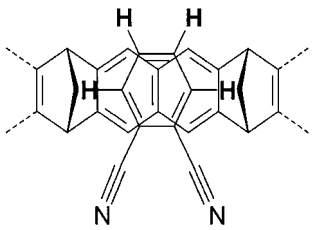
Because of its ribbon-type concave topology, the five arene units of the tweezer molecule **1** or **2** define a cavity in which an aromatic substrate molecule can be bound by multiple arene–arene interactions (Table 1). The magnetic anisotropy of the arene units makes ^{1}H NMR spectroscopy a very sensitive probe for uncovering the complexation of substrate molecules inside the cavity of **1** or **2**. Inspection of the maximum chemically induced shifts ($\Delta\delta_{max}$) determined by the method of ^{1}H NMR titration for the different aromatic and quinoid substrates in the complexes with the parent hydrocarbon naphthalene-spaced tweezer **1a**, which have been already reported,[4] provides qualitative insight into the complex geometries. (Structural parameters of supramolecular complexes can be calculated from the complexation-induced changes in ^{1}H NMR chemical shifts by the use of empirical shift parameters, as reported by Hunter *et al.*[8] most recently. This kind of calculation will be applied to the complexes reported here.)

The large $\Delta\delta_{max}$ values found for the complexes **6@1a, 7@1a** and **8@1a**[4] indicate that the two hydrogen atoms of the substrates, which are inside the cavity, point toward the centers of the opposite benzene rings of the receptor which are adjacent to the central naphthalene spacer unit. These findings are in good agreement with the single-crystal structure analysis of **6@1a**[4] depicted here only from top view. Tetracyanobenzene **6** forms with all three naphthalene-spaced tweezers **1a–c** very stable complexes which are bright yellow in the case of **6@1a** and **6@1b** ($\Delta\delta_{max} = 5.9$) and red in the case of **6@1c** ($\Delta\delta_{max} = 5.9$) due to the CT absorption at $\lambda_{max} = 422$, 420 and 478 nm, respectively ($\epsilon = 794$, 178 or 158). The mutual complexation–decomplexation reaction between **6** and **1a–c** is slow with respect to the NMR time-scale so that at room temperature, if $[\mathbf{6}]_0 < [\mathbf{1}]_0$, separate ^{1}H NMR signals of free and complexed receptor **1a, b** or **c** are observed, which show a coalescence at 90, 60, and 60 °C, respectively. From the analysis of the temperature-dependent lineshapes of these signals the Gibbs enthalpy of activation was calculated at the temperature of coalescence to be $\Delta G^{\neq} = 16.7 \pm 0.2$, 16.2 ± 0.2 and 15.9 ± 0.2 kcal mol^{-1} for the formation



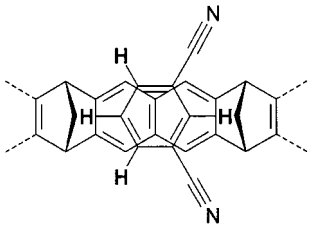
6@1a (crystal structure)

$\Delta\delta_{max}$ = 5.9



7@1a

$\Delta\delta_{max}$ = 5.2

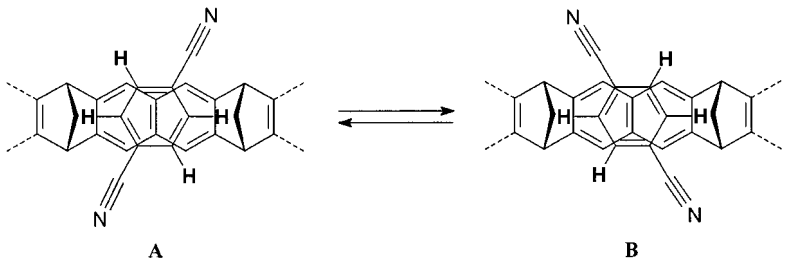


8@1a

$\Delta\delta_{max}$ = 5.3

of the complexes **6@1a**, **6@1b** and **6@1c**, respectively. The mutual complexation–decomplexation reactions of the weaker complexes between the substrates **7**–**13** and **1a**–**c** as receptors are rapid on the NMR time-scale at room temperature so that in each case only averaged ^{1}H NMR signals are observed.

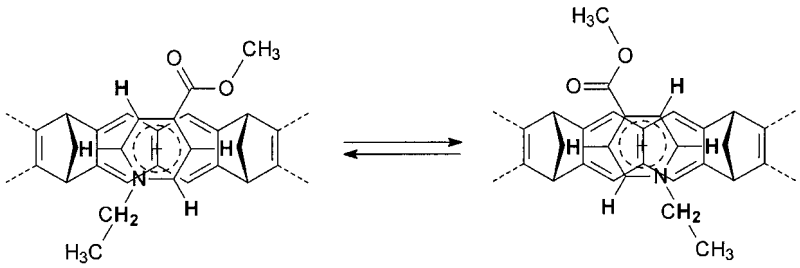
According to the single-crystal structure analysis,[4] the geometry of complex **9@1a** is similar to that of **6@1a**. The observation, that $\Delta\delta_{max}$ in **9@1a** is significantly smaller than the corresponding $\Delta\delta_{max}$ values in **6@1a**, **7@1a** or **8@1a** can be explained by the rapid equilibration between the two structures **A** and **B** leading to an averaging of the pairwise non-equivalent hydrogen atoms in **A** and **B**, respectively. The $\Delta\delta_{max}$ values observed for the complex **10@1a** can be explained in a similar fashion. If the hydrogen atoms of the substrate point out of the cavity of the receptor, as it is shown from single-crystal structure analysis of the complex **11@1a**,[4] a further decrease in $\Delta\delta_{max}$ is expected. From the relatively small $\Delta\delta_{max}$ values found for the complexes of quinoid substrates **11@1a**, **12@1a** and the terephthalaldehyde **13@1a**, one can conclude that the geometries of these complexes in solution are similar to that of **11@1a** in the crystal.



A **B**

9@1a

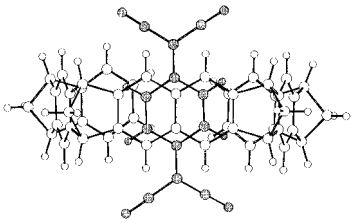
$\Delta\delta_{max}$ = 4.3



A **B**

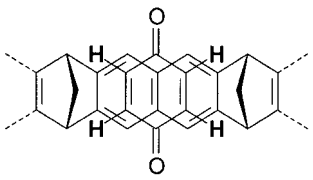
10@1a

$\Delta\delta_{max}(3,5\text{-}H_2) = 4.24$, $\Delta\delta_{max}(2,6\text{-}H_2) = 4.14$, $\Delta\delta_{max}(CH_2) = 0.98$



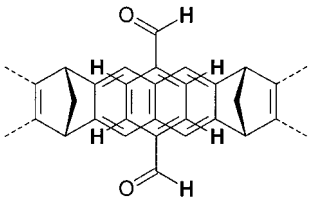
11@1a (crystal structure)

$\Delta\delta_{max}$ = 3.7



12@1a

$\Delta\delta_{max}$ = 2.8



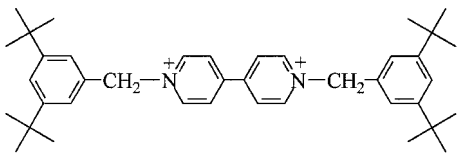
13@1a

$\Delta\delta_{max}$ (2,3,5,6-H_4)= 1.6 , $\Delta\delta_{max}$ (CHO)= 0.6

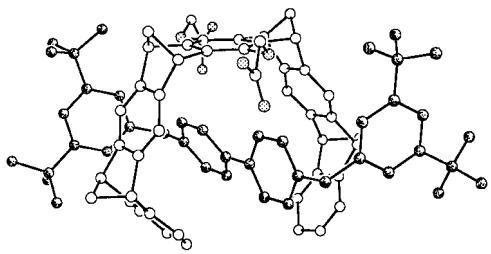
The Kosower salt **10** is also applied as a probe of solvent polarity comparable to the commonly used Dimroth–Reichardt E_T scale.[9] A blue shift in the CT absorption of **10** is observed with increasing solvent polarity. A blue shift is also found from **CT** = 453 nm of free **10** in $CHCl_3$ to 425 nm (shoulder) in the complex **10@1a**. Provided that the geometry of the salt **10** (distance between the cationic and anionic center) is not changed in the process of complexation, the polarity inside the tweezer cavity can be calculated to be in the range of *N*,*N*-dimethylacetamide in the bulk phase (λ_{CT} = 427 nm). This result is consistent with the finding that the tweezer molecules **1** and **2** serve as receptors only for acceptor-substituted neutral and cationic substrates, which can be explained by quantum mechanical calculations.[10] The electrostatic potentials are calculated to be surprisingly negative on the concave side of the tweezer molecules and they are complementary to those of the electron-deficient substrates.

Benzene-spaced tweezers 1 as receptor for cations

Recently, we found for the formation of the complex between the benzene-spaced tweezer **1a** and the viologene dication **14** that the substrate enters the receptor cavity by a clipping process through the bottom after a spreading of the tweezer's tips and not, as expected, via a threading of the substrate through one of its open sides.[11] For that reason, the complex **14@1a** is kinetically not stable in solution despite of the bulky stopper groups in **14**, which should certainly prevent the dissociation of **14@1a** via the threading mechanism. Now we were able to grow single crystals of the complex **14@2f** which are stable at room temperature. The crystal structure analysis of this complex shows the structure of a *clipped* rotaxane with a wheel opened on one side.



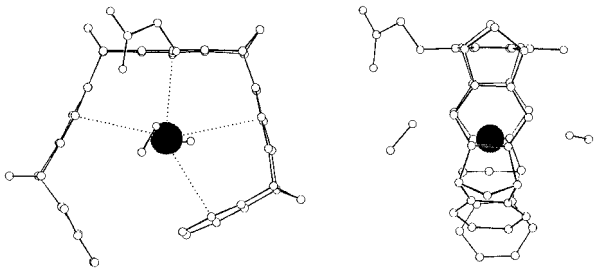
14



14@2f

The benzene-spaced tweezer **1** is also able to form complexes with the alkali metal cation Cs^+. The downfield shift ($\Delta\delta = -0.15$) of the $OCH_2CO_2^-$ signal in ^{1}H NMR spectrum of the salt $(Cs^+)_2$**2f** [compared with the corresponding spectrum of the potassium salt $(K^+)_2$**2f**] is a first indicator for complexation of the cation Cs^+. The single-crystal structure analysis of the salt Cs^+**2j** shows unambiguously the complexation of Cs^+ inside the cavity of **2j**. Accordingly, the Cs^+ cation interacts with four of the five benzene units inside the tweezer cavity. Cs^+ has obviously the optimum size (ionic radius 167 pm)[12] whereas K^+ (133 pm) is too small for these multiple attractive cation–arene interactions so that the stability usually observed for the 1:1 alkali metal cation–arene complexes ($Li^+ > Na^+ > K^+ > Cs^+$)[2] is

reversed in the case of $K^+ < Cs^+$.



Cs^+@2j (front view) **Cs^+@2j** (side view)

CONCLUSION

The naphthalene- and benzene-spaced tweezer molecules reported here preferentially bind electron-deficient neutral and cationic aromatic substrates. The structural parameters of the non-covalently bound complexes derived from ^{1}H NMR measurements in solution are in good agreement with those obtained from single-crystal structure analyses. The benzene-spaced tweezer **2f** forms a stable complex with the viologen dication **14** that exhibits the structure of a *clipped* rotaxane with a wheel opened on one side. The crystal structure analysis of the cesium salt of the tweezer **2j** shows the complexation of Cs^+ inside the cavity of **2j**.

EXPERIMENTAL

General The following instrumentation was used: IR, Bio-Rad FTS 135; UV, J + M Tidas FG Cosytec RS 422; MS, Fison Instruments VG ProSpec 3000 (70 eV); ^{1}H NMR, ^{13}C NMR, DEPT H,H COSY, C,H COSY, NOESY, HMQC and HMBC, Bruker AMX 300; ^{1}H NMR titration experiments, Varian Gemini XL 200. The undeuterated solvent was used as an internal standard. Positions of the protons of the methano bridges are indicated by the letters i (*innen*, towards the center of the molecule) and a (*aussen*, away from the center of the molecule). All melting-points are uncorrected. Column chromatography was carried out using silica gel, 0.063–0.2 mm. All solvents were distilled prior to use. Ampoules were sealed *in vacuo* after three freeze (2-propanol–dry ice) and thaw cycles using argon as an inert gas.

Synthesis of 1b

*8,21-Diacetoxy-(5,6,6a,7,10,10a,11,12,17,18,18a,19,22,22a,23,24-hexadecahydro-5,24:7,22:10,19:12,17-tetramethanodecacene (**5b**).* A solution of diene **4** (673 mg, 4 mmol), bisdienophile **3b** (372 mg, 1 mmol), and anhydrous triethylamine (0.1 ml) in anhydrous toluene (10 ml) was heated at 160 °C for 6 d in a sealed ampoule. The reaction mixture was concentrated *in vacuo* and the crude product was purified by column chromatography [silica gel, cyclohexane–ethyl acetate (5:1)] leading to **5b** as colorless solid (510 mg, 72%). MS (70 eV): *m/z* (%) 709 (78) [M^+], 667 (55) [$M^+ - COCH_3$], 625 (52) [$M^+ - 2COCH_3$], 473 (38) [$M^+ - COCH_3 - C_{15}H_{14}$], 430 (90) [$M^+ - 2COCH_3 - C_{15}H_{14}$], 236 (100) [$M^+ - 2COCH_3 - 2C_{15}H_{14}$]. HR-MS (70 eV): calculated ($C_{50}H_{44}O_4$) 592.3130; found 592.3133. ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.72 (m, 4 H, 6a-H, 10a-H, 18a-H, 22a-H), 1.77 (m, 2 H, 26-H^a, 27-H^a), 2.08 (m, 2 H, 26-H^i, 27-H^i), 2.23 (m, 4 H, 25-H^i, 25-H^a, 28-H^i, 28-H^a), 2.37 (m, 8 H, 6-H, 11-H, 18-H, 23-H), 2.46 (s, 6 H, -CH_3), 3.02 (s, 2 H, 10-H, 19-H), 3.05 (s, 2 H, 7-H, 22-H), 3.58 (m, 2 H, 5-H, 24-H), 3.59 (m, 2 H, 12-H, 17-H), 6.81 (m, 4 H, 2-H, 3-H, 14-H, 15-H), 7.10 (m, 4 H, 1-H, 2-H, 14-H, 15-H), 7.36 (s, 2 H, 9-H, 20-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.77 (q, —OCO*C*H$_3$), 29.55 (t, C-6, C-11, C-18, C-23), 38.99 (d, C-6a, C-22a), 40.39 (d, C-10a, C-18a), 44.06 (t, C-26, C-27), 49.85 (d, C-7, C-22), 52.62 (d, C-10, C-19), 53.50 (d, C-5, C-24), 53.55 (d, C-12, C-17), 66.31 (t, C-25), 66.70 (t, C-28), 111.57 (d, C-9, C-20), 120.58 (d, C-1, C-4), 120.63 (d, C-13, C-16), 123.93 (d, C-2, C-3), 123.96 (d, C-14, C-15), 125.67 (s, C-8a, C-22a), 136.12 (s, C-8, C-21), 136.79 (s, C-7a, C-21a), 147.11 (s, C-5a, C-23a), 147.36 (s, C-11a, C-17a), 151.80 (s, C-9a, C-19a), 151.83 (s, C-4a, C-12a, C-16a, C-24a), 169.06 (s, —O*C*OCH$_3$).

*8,21-Diacetoxy-(5,7,10,12,17,19,22,24-octahydro-5,24:7,22:10,19:12,17-tetramethanodecacene (**1b**).* DDQ (1.59 g, 0.95 mmol) was added to a solution of **5b** (0.51 g, 0.72 mmol) in toluene (25 ml). The intensively stirred mixture was immediately placed in an oil bath preheated to 120 °C and kept at 120 °C for 3 h. The reaction mixture was allowed to cool to room temperature and the excess of DDQ was converted in to $DDQH_2$ by reaction with added 1,4-cyclohexadiene (0.3 ml). After filtration, the filtrate was concentrated *in vacuo* and the crude product was purified by column chromatography [silica gel, cyclohexane–ethyl acetate (2:1)], affording **1b** as a colorless solid (0.37 g, 73%), m.p. >300 °C. MS (70 eV): *m/z* (%) 700 (37) [M^+], 616 (100) [$M^+ - 2COCH_3$]. HR-MS (70 eV): calculated ($C_{50}H_{36}O_4$) 700.2614; found 700.2613. IR (KBr): $\tilde{\nu}$ (cm^{-1}) 2978 (CH), 2945 (CH), 1762 (C=O). ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.44 (s, 6 H, —CH_3), 2.46 (m, 6 H, 25-H^i, 25-H^a, 26-H^a, 27-H^a, 28-H^i, 28-H^a), 2.50 [dm, 1 H, ^2J(27-H^i, 27-H^a) = 8 Hz, 27-H^i], 2.55 [dm, 1 H, ^2J(26-H^i, 26-H^a) = 8 Hz, 26-H^i], 4.05 (s, 2 H, 12-H, 17-H), 4.07 (s, 2 H, 5-H, 24-H), 4.13 (s, 2 H, 10-H, 19-H), 4.15 (s, 2 H, 7-H, 22-H), 6.76 (m, 4 H, 2-H, 3-H, 14-H, 15-H), 7.04 (m, 4 H, 1-H, 4-H, 13-H, 16-H), 7.07 (s, 2 H, 11-H, 18-H), 7.10 (s, 2 H, 6-H, 23-H), 7.30 (s, 2 H, 9-H, 20-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.85 (q, —

COO*C*H$_3$), 48.15 (d, C-7, C-22), 50.59 (d, C-10, C-19), 51.01 (d, C-5, C-12, C-17, C-24), 64.00 (t, C-26), 64.80 (t, C-27), 67.59 (t, C-25), 67.66 (t, C-28), 113.12 (d, C-9, C-20), 116.27 (d, C-6, C-23), 116.77 (d, C-11, C-18), 121.56 (d, C-1, C-4), 121.60 (d, C-13, C-16), 124.16 (d, C-2, C-3, C-14, C-15), 124.90 (d, C-8a, C-20a), 137.16 (s, C-8, C-21), 137.76 (s, C-7a, C-21a), 145.61 (s, C-5a, C-23a), 146.58 (s, C-11a, C-17a), 147.82 (s, C-6a, C-22a), 147.92 (s, C-10a, C-18a), 148.39 (s, C-4a, C-12a, C-16a, C-24a), 150.50 (s, C-9a, C-19a), 168.92 (s, —*C*OOCH$_3$).

Synthesis of 1c

*8,21-Dimethoxy-5,6,6a,7,10,10a,11,12,17,18,18a,19,22,22a,23,24-hexadecahydro-5,24:7,22:10,19:12,17-tetramethanodecacene (**5c**).* A solution of diene **4** (673 mg, 4 mmol), bisdienophile **3c** (295 mg, 0.9 mmol) and anhydrous triethylamine (0.1 ml) in anhydrous toluene (10 ml) was heated at 160 °C for 6 d in a sealed ampoule. The reaction mixture was concentrated *in vacuo* and the crude product was purified by column chromatography [silica gel, cyclohexane–ethyl acetate (40:1)] leading to **5c** as colorless solid (393 mg, 67%). MS (70 eV): *m/z* (%) 652 (100) [M^+], 637 (45) [$M^+ - CH_3$], 622 (32) [$M^+ - 2CH_3$]. ^{1}H NMR (300 MHz, $CDCl_3$): δ 1.62 (m, 4 H, 6a-H, 10a-H, 18a-H, 22a-H), 1.68 (m, 2 H, 26-H^a, 27-H^a), 2.09 (m, 2 H, 26-H^i, 27-H^i), 2.23 (m, 4 H, 25-H^i, 25-H^a, 28-H^i, 28-H^a), 2.34 (m, 8 H, 6-H, 11-H, 18-H, 23-H), 3.09 (s, 2 H, 10-H, 19-H), 3.35 (s, 2 H, 7-H, 22-H), 3.60 (s, 4 H, 5-H, 12-H, 17-H, 24-H), 3.88 (s, 6 H, -CH_3), 6.81 (m, 4 H, 2-H, 3-H, 14-H, 15-H), 7.12 (m, 4 H, 1-H, 4-H, 13-H, 16-H), 7.68 (s, 2 H, 9-H, 20-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 29.63 (t, C-6, C-11, C-18, C-23), 40.67 (d, C-6a, C-22a), 40.80 (d, C-10a, C-18a), 43.68 (t, C-26), 44.12 (t, C-27), 49.27 (d, C-7, C-22), 52.51 (d, C-10, C-19), 53.51 (d, C-5, C-24), 53.54 (d, C-12, C-17), 61.67 (q, -CH_3), 66.48 (t, C-25), 66.53 (t, C-28), 112.26 (d, C-9, C-20), 120.57 (d, C-1, C-4), 120.60 (d, C-13, C-16), 123.86 (d, C-2, C-3), 123.91 (d, C-14, C-15), 126.60 (s, C-8a, C-20a), 135.35 (s, C-7a, C-21a), 144.06 (s, C-8, C-21), 146.92 (s, C-9a, C-19a), 147.28 (s, C-5a, C-23a), 147.48 (s, C-11a, C-17a), 151.93 (s, C-4a, C-24a), 152.02 (s, C-12a, C-16a).

*8,21-Dimethoxy-(5,7,10,12,17,19,22,24-octahydro-5,24:7,22:10,19:12,17-tetramethanodecacene (**1c**).* DDQ (908 mg, 4 mmol) was added to a solution of **5c** (313 mg, 0.48 mmol) in toluene (20 ml). The intensively stirred mixture was immediately placed in an oil bath preheated to 120 °C and kept at 120 °C for 3 h. The reaction mixture was allowed to cool to room temperature and the excess of DDQ was converted to $DDQH_2$ by reaction with added 1,4-cyclohexadiene (0.3 ml). After filtration, the filtrate was concentrated *in vacuo* and the crude product was purified by column chromatography [silica gel, cyclohexane–ethyl acetate (10:1)] affording **1c** as colorless solid (133 mg, 43%), m.p. 227 °C. MS (70 eV): *m/z* (%) 644 (100) [M^+], 629 (32) [$M^+ - CH_3$], 614 (22) [$M^+ - 2CH_3$]. IR (KBr): $\tilde{\nu}$ (cm^{-1}) 2978 (CH), 2946 (CH), 1272 (C—O). ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.46 (m, 7 H, 25-H^i, 25-H^a, 26-H^a, 27-H^i, 27-H^a, 28-H^i, 28-H^a), 2.54 [dm, 1 H, ^2J(26-H^i, 26-H^a) = 8 Hz, 26-H^i], 3.80 (s, 6 H, —CH_3), 4.07 (s, 4 H, 5-H, 12-H, 17-H, 24-H), 4.19 (s, 2 H, 10-H, 19-H), 4.50 (s, 2 H, 7-H, 22-H), 6.77 (m, 4 H, 2-H, 3-H, 14-H, 15-H), 7.05 (m, 4 H, 1-H, 4-H, 13-H, 16-H), 7.10 (s, 2 H, 11-H, 18-H), 7.12 (s, 2 H, 6-H, 23-H), 7.62 (s, 2 H, 9-H, 20-H). ^{13}C-NMR (75 MHz, $CDCl_3$): δ 47.53 (d, C-7, C-22), 50.65 (d, C-10, C-19), 51.04 (d, C-5, C-12, C-17, C-24), 61.70 (q, —OCH_3), 63.53 (t, C-26), 65.00 (t, C-27), 67.58 (t, C-25), 67.64 (t, C-28), 113.85 (d, C-9, C-20), 116.17 (d, C-6, C-23), 116.21 (d, C-11, C-18), 121.53 (d, C-1, C-4), 121.61 (d, C-13, C-16), 124.05 (d, C-2, C-3), 124.11 (d, C-14, C-15), 125.88 (s, C-8a, C-20a), 135.49 (s, C-7a, C-21a), 145.30 (s, C-5a, C-23a), 146.59 (s, C-8, C-21), 147.02 (s, C-11a, C-17a), 147.44 (s, C-6a, C-22a), 147.53 (s, C-10a, C-18a), 147.86 (s, C-9a, C-19a), 150.54 (s, C-4a, C-24a), 150.72 (s, C-12a, C-16a).

Synthesis of 2e–j

*Diethyl 8,19-dioxy-5,7,9,11,16,18,20,22-octahydro-5,22:7,20:9,18:11,16-tetramethanononacene-O,O′-diacetate (**2e**).* Anhydrous K_2CO_3 (50 mg, 0.36 mmol) and a small amount of KI were suspended in a solution of **2d** (50 mg, 0.088 mmol) and ethyl bromoacetate (37 mg, 0.22 mmol) in anhydrous acetone (8 ml) and the mixture was stirred for 4 d at room temperature. The reaction mixture was extracted with dichloromethane and the organic layer was washed successively with saturated aqueous solutions of NH_4Cl and $NaHCO_3$ and water. The organic layer was dried over anhydrous Na_2SO_4, filtered and the filtrate concentrated *in vacuo* to afford **2e** as a colorless solid (60 mg, 92%). MS (70 eV): *m/z* (%) 738 (100) [M^+], 651 (52) [$M^+ - CH_2COOEt$], 564 (23) [$M^+ - 2CH_2COOEt$]. IR (KBr): $\tilde{\nu}$(cm^{-1})3065 (CH), 3046 (CH), 2976 (CH), 2935 (CH), 2863 (CH), 1759 (C═O), 1734 (C═O), 1290 (C—O), 1263 (C—O), 1202 (C—O), 1179 (C—O). ^{1}H NMR (300 MHz, CDCl3): δ −0.27 [t, 6 H, ^3J(30-H, 29-H) = 7.2 Hz, 30-H, 34-H], 2.34 [dd, 4 H, ^2J(24-H, 25-H) = 4.0 Hz, 24-H, 25-H], 2.40 (s, 4 H, 24-H, 26-H), 3.37 (q, 4 H, 29-H, 33-H), 4.03 (s, 4 H, 5-H, 11-H, 16-H, 22-H), 4.23 (s, 4 H, 7-H, 9-H, 18-H, 20-H), 4.45 (s, 4 H, 27-H, 31-H), 6.76 [m, 4 H, ^3J(2-H, 1-H) = 3.2 Hz, ^3J(2-H, 3-H) = 3.0 Hz, 2-H, 3-H, 13-H, 14-H], 7.04 (m, 4 H, 1-H, 4-H, 12-H, 15-H), 7.05 (s, 4 H, 6-H, 10-H, 17-H, 21-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 12.26 (q, C-30, C-34), 48.09 (d, C-7, C-9, C-18, C-20), 51.08 (d, C-5, C-11, C-16, C-22), 60.99 (t, C-29, C-33), 68.17 (t, C-24, C-25), 68.53 (t, C-23, C-26), 69.96 (t, C-27, C-31), 116.12 (d, C-6, C-10, C-17, C-21), 121.23 (d, C-1, C-4, C-12, C-15), 124.60 (d, C-2, C-3, C-13, C-14), 139.70 (s, C-7a, C-8a, C-18a, C-19a), 143.84 (s, C-8, C-19), 147.11 (s, C-6a, C-9a, C-17a, C-20a), 147.51 (s, C-5a, C-10a, C-16a, C-21a),

150.65 (s, C-4a, C-11a, C-15a, C-22a), 169.21 (s, C-28, C-32).

*Dicesium 8,19-dioxy-5,7,9,11,16,18,20,22-octahydro-5,22:7,20:9,18:11,16-tetramethanononacene-O, O′-diacetate [$(Cs^+)_2$**2f**].* Aqueous CsOH (0.1 M, 2.8 ml) was added to a stirred suspension of **2e** (200 mg, 0.27 mmol) in ethanol (10 ml) and the mixture was refluxed for 2 h. After evaporation of the solvent *in vacuo* the solid was dried over $CaCl_2$ in desiccator to afford $(Cs^+)_2$**2f** as a colorless solid (260 mg, 100%). ^{1}H NMR (300 MHz, CD_3OD): δ 2.27 [dm, 2 H, ^2J(24i-H, 25i-H) = 8.8 Hz, 24i-H, 25i-H), 2.34 (dm, 2 H, 24a-H, 25a-H), 2.35 (s, 4 H, 23-H, 26-H), 4.06 (s, 4 H, 5-H, 11-H, 16-H, 22-H), 4.24 (s, 4 H, 27-H, 29-H), 4.30 (s, 4 H, 7-H, 9-H, 18-H, 20-H), 6.82 (m, 4 H, 2-H, 3-H, 13-H, 14-H), 7.09 (m, 4 H, 1-H, 4-H, 12-H, 15-H), 7.20 (s, 4 H, 6-H, 10-H, 17-H, 21-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 48.02 (d, C-7, C-9, C-18, C-20), 51.20 (d, C-5, C-11, C-16, C-22), 68.76/68.23 (t, C-23, C-26, C-24, C-25), 73.70 (t, C-27, C-29), 116.90 (d, C-6, C-10, C-17; C-21), 122.17 (d, C-1, C-4, C-12, C-15), 125.93 (d, C-2, C-3, C-13, C-14), 141.70 (s, C-8a, C-8a, C-18a, C-19a), 145.44 (s, C-8, C-19), 149.11 (s, C-6a, C-9a, C-17a, C-20a), 151.93 (s, C-4a, C-11a, C-15a, C-22a), 177.05 (s, C-28, C-30).

*8-Acetoxy-19-hydroxy-5,7,9,11,16,18,20,22-octahydro-5,22:7,20:9,18:11,16-tetramethanononacene (**2g**).* 3.0 ml of 1 M aqueous NaOH was slowly added to an intensively stirred solution of diacetate **2b** (210 mg, 0.32 mmol) in dioxane (20 ml) and kept at room temperature for 30 min. The yellow reaction mixture was poured into a 1:1 mixture of saturated aqueous NH_4Cl and 5 M aqueous HCl (50 ml) and extracted three times with dichloromethane. The combined organic layers were washed with water and brine and dried over anhydrous $NaSO_4$. After evaporation of the solvent *in vacuo*, **2g** was obtained as a colorless solid (189 mg, 96%), m.p. 285–287 °C. MS (70 eV): *m/z* (%) 608 (82) [M^+], 566 (100) [$M^+ - COCH_3$]. HR-MS (70 eV): calculated ($C_{46}H_{34}O_4$) 608.2351; found 608.2350. IR (KBr): $\tilde{\nu}$ (cm^{-1}) 3420 (OH), 3009 (CH), 2970 (CH), 2936 (CH), 2863 (CH), 1762 (C=O); ^{1}H-NMR (300 MHz, $CDCl_3$): δ 2.32 (s, 3 H, $COCH_3$), 2.35 [d, 2 H, ^2J(24i-H, 24a-H) = 7.5 Hz, 24i-H, 25i-H], 2.40 (s, 4 H, 23-H, 26-H), 2.44 (d, 2 H, 24a-H, 25a-H), 3.96 (s, 2 H, 7-H, 9-H), 4.08 (s, 4 H, 5-H, 11-H, 16-H, 22-H), 4.20 (s, 2 H, 18-H, 20-H), 4.49 (s, 1 H, O-H), 6.74 (m, 4 H, 2-H, 3-H, 13-H, 14-H), 7.07 (m, 4 H, 1-H, 4-H, 12-H, 15-H), 7.11 (s, 2 H, 6-H, 10-H), 7.14 (s, 2 H, 17-H, 21-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 20.81 (q, —CH_3), 47.29 (d, C-18, C-20), 48.66 (d, C-7, C-9), 51.20 (d, C-5, C-11, C-16, C-22), 68.87 (t, C-24, C-25), 70.14 (t, C-23, C-26), 116.25 (d), 116.52 (d), 121.40 (d), 121.48 (d), 124.59 (d), 124.62 (d), 133.63 (s), 135.30 (s), 140.79 (s), 141.95 (s), 146.43 (s), 146.63 (s), 147.49 (s), 147.53 (s), 150.24 (s), 150.26 (s), 169.44 (s, C=O).

*Ethyl 8-acetoxy-19-oxy-5,7,9,11,16,18,20,22-octahydro-5,22:7,20:9,18:11,16-tetramethanononacene-O-acetate (**2h**).* Anhydrous K_2CO_3 (17 mg, 0.12 mmol) and a small amount of KI were suspended in a solution of **2g** (115 mg, 0.19 mmol) and ethyl bromoacetate (37 mg, 0.22 mmol) in anhydrous acetone (5 ml) and the mixture was stirred for 4 d at room temperature. The reaction mixture was diluted with dichloromethane (50 ml) and the organic layer was washed successively with saturated aqueous solutions of NH_4Cl, $NaHCO_3$, and water. The organic layer was dried over anhydrous Na_2SO_4, filtered and the filtrate was concentrated *in vacuo* affording **2h** as a colorless solid (113 mg, 84%). MS (70 eV): *m/z* (%) 694 (100) [M^+], 651 (46) [$M^+ - COCH_3$], 564 (22) [$M^+ - COCH_3 - CH_2CO_2Et$]. IR (KBr): $\tilde{\nu}$ (cm^{-1}) 3065 (CH), 3040 (CH), 2977 (CH), 2922 (CH), 1762 (C=O). ^{1}H NMR (300 MHz, $CDCl_3$): δ −1.64 [t, 3 H, ^3J(32-H, 31-H) = 7.2 Hz, 32-H], 2.32 [dm, 2 H, ^2J(24i-H, 24a-H) = 9.0 Hz, 24a-H, 25a-H], 2.35 (s, 3 H, 28-H), 2.42 (m, 4 H, 23-H, 26-H), 2.46 (dm, 2 H, 24i-H, 25i-H), 2.62 (q, 2 H, 31-H), 3.93 (s, 2 H, 7-H, 9-H), 4.04 (s, 4 H, 5-H, 11-H, 16-H, 22-H), 4.27 (s, 2 H, 18-H, 20-H), 4.68 (s, 2 H, 29-H), 6.74 (m, 4 H, 2-H, 3-H, 13-H, 14-H), 7.05 (m, 4 H, 1-H, 4-H, 12-H, 15-H), 7.09/7.11 (s, 2 H, 6-H, 10-H and 17-H, 21-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 10.76 (q, C-32), 21.07 (q, C-28), 48.29/48.76 (d, C-7, C-9 and C-18, C-20), 51.32 (d, C-5, C-11, C-16, C-22), 61.30 (t, C-31), 68.48 (t, C-24, C-25), 68.52 (t, C-29), 69.06 (t, C-23, C-26), 116.23/116.27 (d, C-6, C-10 and C-17, C-21), 121.23/121.27 (d, C-1, C-4 and C-12, C-15), 124.56/124.71 (d, C-2, C-3 and C-13, C-14), 139.04 (s, C-17a, C-18a), 141.08 (s, C-7a, C-8a), 145.26 (s, C-8), 146.71 (s, C-19), 146.80 (s, C-6a, C-9a, C-17a, C-20a), 147.48/147.59 (s, C-5a, C-10a and C-16a, C-20a), 150.43/150.64 (s, C-4a, C-11a and C-15a, C-22a), 168.96/169.02 (s, C-27 and C-30).

*8-Hydroxy-19-oxy-5,7,9,11,16,18,20,22-octahydro-5,22:7,20:9,18:11,16-tetramethanononacene-O-acetic acid (**2i**).* Aqueous NaOH (1 M, 3.0 ml), was slowly added to an intensively stirred solution of **2h** (110 mg, 0.15 mmol) in ethanol (20 ml). The mixture was refluxed for 2 h and then neutralized with aqueous HCl (1 M, 3.0 ml) and extracted with dichloromethane. The combined organic layers were washed with water and brine and dried over anhydrous $NaSO_4$. After evaporation of the solvent *in vacuo*, the crude product was recrystallized from ethanol to obtain **2i** as a colorless solid (89 mg, 96%). ^{1}H NMR (300 MHz, $CDCl_3$): δ 2.37 [dm, 2 H, ^2J(24i-H, 24a-H) = 9.0 Hz, 24a-H, 25a-H], 2.39 (s, 3 H, 28-H), 2.41 (m, 4 H, 23-H, 26-H), 2.43 (dm, 2 H, 24i-H, 25i-H), 4.07 (s, 4 H, 5-H, 11-H, 16-H, 22-H), 4.20 (s, 2 H, 18-H, 20-H), 4.27 (s, 2 H, 7-H, 9-H), 4.43 (s, 2 H, 29-H), 6.76 (m, 4 H, 2-H, 3-H, 13-H, 14-H), 7.07 (m, 4 H, 1-H, 4-H, 12-H, 15-H), 7.15/7.16 (s, 2 H, 6-H, 10-H and 17-H, 21-H). ^{13}C NMR (75 MHz, $CDCl_3$): δ 48.29/48.76 (d, C-7, C-9 and C-18, C-20), 51.32 (d, C-5, C-11, C-16, C-22),

68.48 (t, C-24, C-25), 68.52 (t, C-29), 69.06 (t, C-23, C-26), 116.23/116.27 (d, C-6, C-10 and C-17, C-21), 121.23/121.27 (d, C-1, C-4 and C-12, C-15), 124.56/124.71 (d, C-2, C-3 and C-13, C-14), 139.04 (s, C-17a, C-18a), 141.08 (s, C-7a, C-8a), 145.26 (s, C-8), 146.71 (s, C-19), 146.80 (s, C-6a, C-9a, C-17a, C-20a), 147.48/147.59 (s, C-5a, C-10a and C-16a, C-20a), 150.43/150.64 (s, C-4a, C-11a and C-15a, C-22a), 174 (s, C-30). The cesium salt Cs^+**2j** was obtained by reaction of the acid **2e** with an equimolar amount of CsOH.

X-ray crystal structure determinations *'Clipped rotaxane'* ***14@2f*** *×4(CH₃OH).* Measured on a Siemens (Bruker) SMART diffractometer with Mo Kα radiation. Cell dimensions, $a = 15.797(3)$, $b = 16.319(3)$, $c = 17.475(4)$ Å, $\alpha = 76.18(1)$, $\beta = 88.417(4)$, $\gamma = 62.082(4)°$, $V = 3846.7(1)$ Å^3; triclinic crystal system, $Z = 2$, $d_{cal.} = 1.182$ g cm^{-3}, $\mu = 0.08$ mm^{-1}, space group $P\bar{1}$, data collection of 34 669 intensities ($2\Theta_{max} = 50°$), 11677 independent ($R_{merg} = 0.0758$), 4596 observed [$F_o > 4\sigma(F)$], empirical absorption correction on equivalent reflections (Siemens-SADABS), structure solution with direct methods and refinement on F^2 (Siemens-SHELXS-Plus package and SHELXL-97, 871 parameters), constraint refinement on ideal geometries applied to the phenyl groups, hydrogen atom positions calculated and refined as riding groups with the 1.2-fold (1.5-fold for methyl groups) isotropic U-value of the equivalent U-value from the corresponding C-atoms. $R1 = 0.0849$, $wR2 = 0.266$, maximum residual electron density = 0.60 e Å^{-3}.

*Cs^+**@2j** × 2(CH₃OH).* Measured on a Siemens (Bruker) SMART diffractometer with Mo Kα radiation at −158 °C. Cell dimensions, $a = 11.9689(1)$, $b = 10.4213(2)$, $c = 33.2609(2)$ Å, $\beta = 97.940(1)°$, $V = 4109.91(1)$ Å^3; monoclinic crystal system, $Z = 4$, $d_{cal.} = 1.322$ g cm^{-3}, $\mu = 0.94$ mm^{-1}, space group $P2_1/c$, data collection of 11 284 intensities ($2\Theta_{max} = 56.3°$), 7734 independent ($R_{merg} = 0.0795$), 5029 observed [$F_o > 4\sigma(F)$], empirical absorption correction on equivalent reflections (Siemens-SADABS) structure solution with direct methods and refinement on F^2 (Siemens-SHELXS-Plus package and SHELXL-97, 510 parameters), constraint refinement on ideal geometries applied to the hydrogen atom positions with the 1.2-fold (1.5-fold for methyl groups) isotropic U-value of the equivalent U-value from the corresponding C-atoms. $R1 = 0.1019$, $wR2 = 0.267$, maximum residual electron density = 3.9 e Å^{-3} at a distance of 1.06 Å from Cs.

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