Molecular Signal Transduction by Conformational Transmission: Use of Tetrasubstituted Perhydroanthracenes as Transducers

Hans-Georg Weinig, Rolf Krauss, Matthias Seydack, Jürgen Bendig, and Ulrich Koert*[a]

Abstract: 2,3,6,7-Tetrasubstituted *cis-anti-cis* perhydroanthracenes have been studied as conformational transducers for molecular signal transduction. 2,2′-Bipyridine groups attached to the perhydroanthracene through ether linkages were chosen as receptor substituents, while pyrene groups were selected as effectors. A chelation-induced triple ring flip of the perhydroanthracene could be achieved by the complexation of zinc(II) ions at the bipyridine sites of ligands **13** and **15**. It was found that two pyrene substituents attached to the perhydroanthracene via a linker with an *E* double bond and an ester group could be used to monitor the triple ring flip. In the equatorial positions, the pyrenes are sufficiently close to form an excimer in the excited state, giving a fluorescence signal at 480 nm. In the axial positions, they are far away from each other and give mainly a monomer fluorescence signal at 380 nm. Both the bipyridine receptor and the pyrene effector are present in compound **33**. The conformational switching **34** → **35** (the two conformers of **33**) has successfully been used for a signal transduction over a signal distance of 2 nm.

Keywords: conformation analysis · fluorescence · molecular switch · perhydroanthracene · signal transduction

Introduction

A complex molecular system requires the controlled exchange of information between its component parts and the environment.[1] Biomolecular signals have to be transduced, for example, across a cell membrane or through cytoplasm to the nucleus of a cell.[2, 3] While many processes in biological signal transduction are based on the diffusion of a second messenger to the effector site, a molecular transducer that links the receptor and the effector site offers several advantages: a predictable signal distance defined by the molecular length of the transducer, a predictable signal direction from the receptor to the effector site, and a signal speed that is determined by the nature of the transduction process.

Conformational transmission[4, 5] is one possible mechanism for connecting the receptor site to the effector site (Figure 1a). The signal stimulus leads to a conformational change at the receptor site, which is transmitted by the transducer to the effector site. There, another conformational change results in a readable effect. Promising candidates as transducers are biconformational molecules.[5, 6] A conformational switch[7, 8] between their two low-energy conformers could be used to transfer the signal. In order to achieve a long signal distance, we focused on the biconformational *cis-anti-cis* perhydroanthracene.[5, 9, 10] Conformational transmission by the perhydroanthracene can be envisaged as proceeding through a triple ring flip (Figure 1b). A tetrasubstituted *cis-*

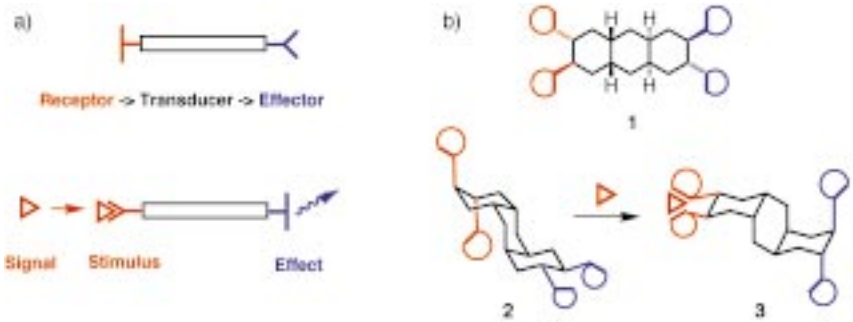

Figure 1. Molecular signal transduction through conformational transmission: a) The signal causes a conformational change at the receptor, which is transduced to the effector; b) General structure of a tetrasubstituted perhydroanthracene transducer **1** with the two receptor sites shown in red and the two effector sites shown in blue. Upon binding of the signal compound, the all-chair conformer **2** is converted through a triple ring flip to the all-chair conformer **3**. The equatorial-to-axial change of the effector substituents leads to a readable response.

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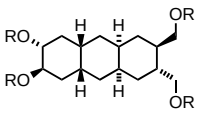
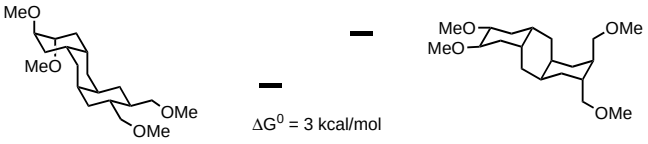
  0947-6539/01/0710-2075 $ 17.50+.50/0

anti-cis-perhydroanthracene of type **1** with two receptor substituents (red) and two effector substituents (blue) was chosen as a transducer.[9] In conformer **2**, the receptor substituents are axial and the effector substituents are equatorial. Binding of the signal compound in a chelation mode enforces the conformational switching **2** → **3**. In conformer **3**, the orientations of the substituents are interchanged, with the receptors being in equatorial positions and the effectors adopting the axial positions. Conformational transmission through a double ring flip of the shorter *cis*-decalin system has recently been investigated by our group.[11] Several studies concerning the conformational control of cyclohexane derivatives have been reported.[12]



4a R = H
4b R = Me



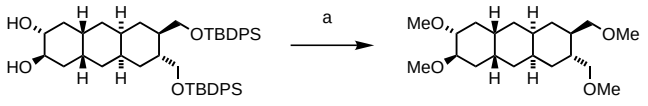
5 **6**

Figure 2. 2,3-*C*,6,7-*O*-Tetrasubstituted perhydroanthracenes of type **4** as suitable candidates for the conformational transmission. The tetramethyl ether **4b** has two low-energy all-chair conformations **5** and **6**.

Results and Discussion

Choice of the 2,3,6,7-substituents: A number of criteria were important for an appropriate choice of the four substituents at the 2,3,6,7-positions of the *cis-anti-cis* perhydroanthracene. First, one has to distinguish between the receptor and effector sites. Therefore, a selective attachment of the receptor and effector groups is necessary. Second, with respect to the conformational balance between **2** and **3**, it would be advantageous to shift the equilibrium to one side, for example, towards **2**, in a predictable manner. In this way, the conformer **2** could serve as a defined starting point for the molecular switch **2** → **3**. Both these requirements are fulfilled by tetrasubstituted perhydroanthracenes of type **4** (Figure 2).

The *cis-anti-cis* perhydroanthracene **4** bears carbon substituents at the 2- and 3-positions and oxygen substituents at the 6- and 7-positions. Compound **4a** should be well-suited for the selective attachment of the receptor and effector substituents as its primary and secondary hydroxy functions can be readily distinguished. The choice of a 2,3-carbon-6,7-oxygen substitution pattern should shift the equilibrium between the two all-chair conformers **2** and **3** in favor of the conformer **2** with equatorial *C*-substituents in the 2- and 3-positions and axial *O*-substituents in the 6- and 7-positions. The tetramethyl ether **4b** was selected to test this hypothesis and to investigate the position of the equilibrium (**5** ⇌ **6**). The most unfavourable interaction in conformer **5** is an O – C 1,3-diaxial interaction, while in conformer **6** it is a C – C 1,3-diaxial interaction. The latter is disfavoured with respect to the former by 1 kcal mol^{-1}.[13] Molecular dynamics calculations on **4b** (INSIGHT/DISCOVER, cvff, 200 cycles, 300 K to 1000 K) found the two conformers **5** and **6** to be within 0 – 3 kcal mol^{-1} of each other, with **5** being energetically favored by 3 kcal mol^{-1}. Thus, at ambient temperature **5** should be populated to more than 99 %. The starting material for the synthesis of **4b** was the diol **7** (Scheme 1), which was stereoselectively prepared[14] by iterative use of the Lewis acid catalyzed Diels – Alder reaction as described previously.[5a]



7 **4b**

Scheme 1. a) 1. TBAF, THF, 50 °C, 3 h, 94 %; 2. NaH, DMF, 0 °C, 30 min, then CH_3I, 20 °C, 4 d, 67 %. TBAF = tetrabutylammonium fluoride.

The ^{1}H NMR spectra (300 MHz, [D$_8$]toluene) of **4b** recorded in the temperature range 213 – 363 K (Figure 3) show the presence of the all-chair conformer **5** and no detectable amount (< 5 %) of the other all-chair conformer **6**.[15] The two equatorial protons in the 6- and 7-positions give rise to broad pseudo singlets resulting from three small ^3J *gauche* couplings. Further characteristic signals of the perhydroanthracene skeleton of **5**, as marked in Figure 3, are those of the 9α, 9β, and 10α protons. For some signals, a temperature dependence of the chemical shift was observed and at low temperatures a broadening of the signals occurred,

Abstract in German: *2,3,6,7-Tetrasubstituierte cis-anti-cis Perhydroanthracene eignen sich als konformationelle Signalüberträger zur molekularen Signaltransduktion. 2,2′-Bipyridine, die über eine Etherbrücke mit dem Perhydroanthracen verbunden sind, wurden hierzu als Rezeptorsubstituenten ausgewählt. Ein Chelat-induzierter Tripel-Ring-Flip des Perhydroanthracens ließ sich mit den Verbindungen **13** und **15** durch Bildung eines Zink – Bipyridin Komplexes erreichen. Pyrene können dann als Effektoren verwendet werden, wenn sie eine E-Doppelbindung und einen Ester als Verknüpfungselement zum Perhydroanthracen aufweisen. In den equatorialen Positionen sind die Pyrene nahe genug beieinander, um im angeregten Zustand ein Excimer mit einer Fluoreszenz von 480 nm zu bilden. In den axialen Positionen sind beide Pyrene räumlich so weit voneinander entfernt, daß sie überwiegend eine Monomerfluoreszenz bei 380 nm zeigen. Verbindung **33** wurde hergestellt, bei der der Bipyridin-Rezeptor und der Pyreneffektor zusammen in einem Molekül integriert sind. Über das durch ein Zink-Signal ausgelöste konformationelle Umschalten **34** → **35** konnte eine erfolgreiche Signaltransduktion über eine Signaldistanz von 2 nm durchgeführt werden.*

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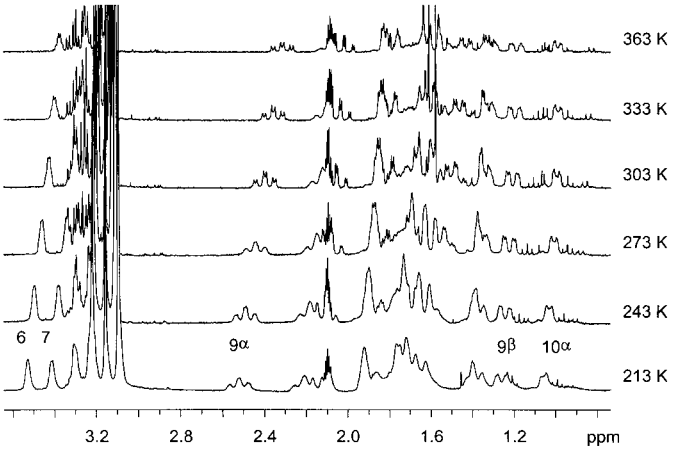
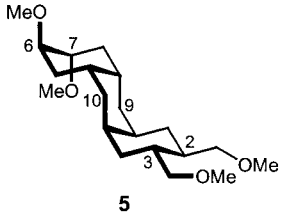


Figure 3. Temperature dependence of the ^{1}H NMR spectrum of the perhydroanthracene tetramethyl ether **4b** in [D_8]toluene.



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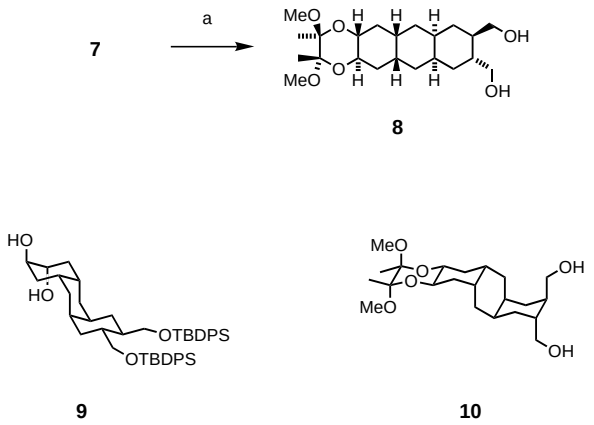
probably due to the increased solvent viscosity. The preferred all-chair conformation of the perhydroanthracene skeleton of **4** is identical to that found for **7**.[5a] NOESY data and a correlation with a related X-ray crystal structure were used to unambiguously assign the conformation of **7**.[5a] The results of the temperature-dependent NMR analysis of **4b** are in agreement with the theoretical prediction of an energy difference of 3 kcal mol^{-1} between **5** and **6**. Inspection of the conformational space produced by the molecular dynamics simulation revealed that other non-all-chair conformers are much higher in energy than **5** and **6**.

Covalently induced triple ring flip: A triple ring flip in perhydroanthracenes of type **4** can be induced in different ways, provided that a switching energy of at least 6 kcal mol^{-1} is applied to force the substituents at C-2 and C-3 from axial into equatorial positions.[16] One way of achieving this is to introduce a covalent clamp. It has been shown by X-ray crystallography and NMR studies that the bis-acetals originally introduced by Ley[17] are capable of undergoing a triple ring flip in the perhydroanthracene case.[5a] The diol **7** was treated with 2,2,3,3-tetramethoxybutane and camphorsulfonic acid in MeOH to produce the bis-acetal **8** (Scheme 2). This reaction corresponds to the triple ring flip from the all-chair conformer **9** to the all-chair conformer **10**.

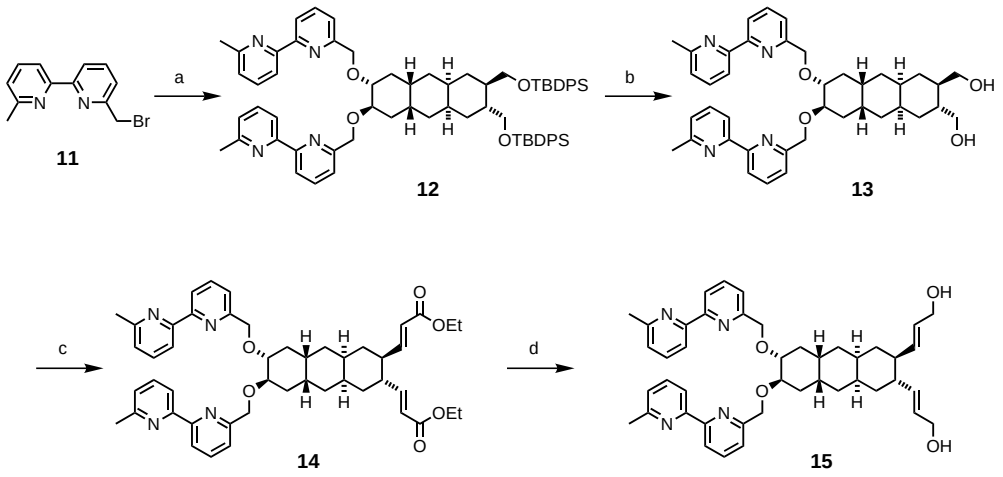
Chelation-induced triple ring flip: The transduction of a signal by the triple ring flip of the perhydroanthracene needs a fast and reversible response of the receptor. The formation of a metal-chelate complex with a binding energy greater than the switching energy of 6 kcal mol^{-1} could be used for this



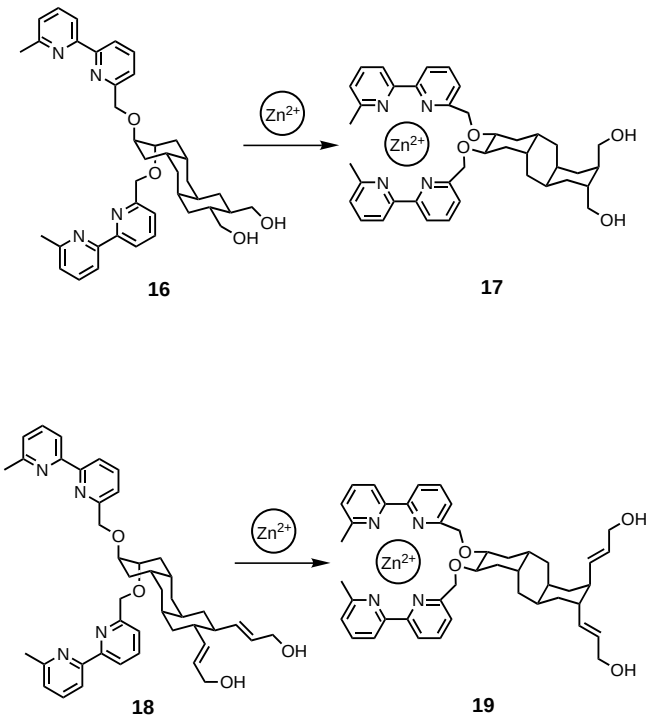
Scheme 2. Covalently induced triple ring flip **9** → **10**; a) 2 equiv 2,2,3,3-tetramethoxybutane, 4 equiv trimethyl orthoformate, catalytic amount camphorsulfonic acid, MeOH, 20 h, 50 °C, 97 %.

purpose. 2,2′-Bipyridines form strong chelate complexes.[18] Harding et al. found that zinc(II) ions and bis(2,2′-bipyridyl-6-methyl ether) ligands can form chelate complexes with the zinc(II) ion six-coordinated by two bipyridyl groups and two oxygens of the ether linkers.[19] Two perhydroanthracene derivatives **13** and **15** with ether-linked bipyridine receptors in the 6- and 7-positions were chosen as synthetic targets (Scheme 3). 6-Bromomethyl-6′-methyl-2,2′-bipyridine[20] (**11**) served as a building block to introduce the receptor groups. The perhydroanthracene diol **7** was converted into the bis-bipyridyl derivative **12** by means of a Williamson reaction. Fluoride-mediated deprotection of the two *tert*-butyldiphenylsilyl (TBDPS) ethers led to the diol **13**. The latter was subjected to a double Swern oxidation[21] to give the corresponding dialdehyde, which was used in an *E*-selective Wittig reaction with ethoxycarbonylmethylene triphenylphosphorane to produce the α,β-unsaturated ester **14** in 79 % yield. Reductive cleavage of the ester groups of **14** furnished the diol **15**. The binding of zinc(II) ions by compounds **13** and **15** was monitored by ^{1}H NMR and UV spectroscopy. Addition of $Zn(OTf)_2$ to **13** in CD_3CN solution gave the complex [Zn-**13**]$(OTf)_2$. Analysis of the NMR spectra of [Zn-**13**]$(OTf)_2$ confirmed that the chelation-induced triple ring flip (**16** → **17**) had indeed occurred (Scheme 4).

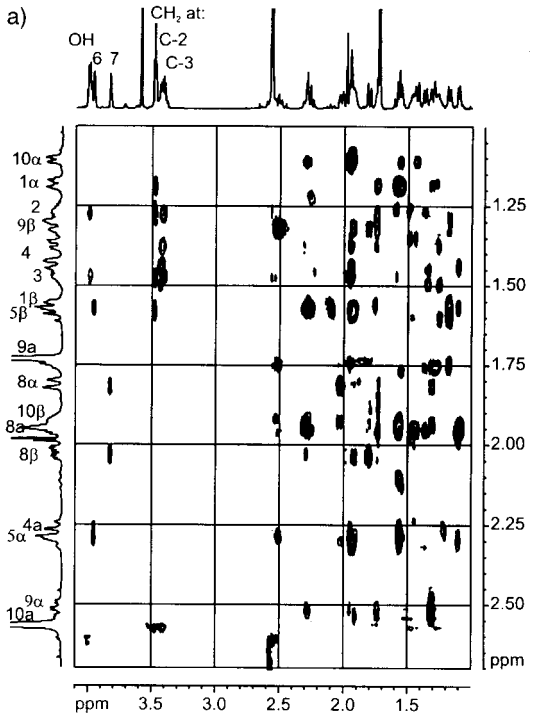
From the NOESY spectrum of the free ligand **13** (Figure 4a), one can extract the characteristic NOE contacts shown in Figure 4b; these clearly prove **16** to be the only detectable conformer. Analysis of the NOESY spectrum of the complex [Zn-**13**]$(OTf)_2$ (Figure 5a) revealed a number of characteristic NOE contacts, as shown in Figure 5b. These data demonstrate the occurrence of the chelation-induced triple ring flip and show **17** to be the only detectable conformer. Diagnostic ^{1}H NMR signals for monitoring the triple ring flip (**16** → **17**) are those of the protons at C-6 and C-7. In **16**, these protons are in equatorial positions and give rise to two pseudo singlets at $\delta = 3.9$ and $\delta = 3.8$, respectively, as a result of three small *gauche* ^3J couplings. After the triple ring flip to **17**, these protons are in axial positions. Here, they give rise to two double triplets at $\delta = 3.05$ and $\delta = 3.16$ as a result of two large *trans* couplings and one small *gauche* ^3J coupling. Addition of $Zn(OTf)_2$ to a solution of **15** in CD_3CN/



Scheme 3. Synthesis of perhydroanthracenes **13** and **15** bearing bipyridine receptor groups; a) **7**, NaH, DMSO, cat. amount nBu$_4$NI, THF, 3 d, 20 °C, 81 %; b) TBAF, THF, 2 h, 40 °C, 98 %; c) 1. oxalyl chloride, DMSO, EtNiPr$_2$, −78 °C → 0 °C, CH_2Cl_2, 30 min; 2. ethoxycarbonylmethylene triphenylphosphorane, toluene, 15 h, 90 °C, 79 % (two steps); d) DIBAH, −78 °C → 0 °C, CH_2Cl_2, 5 h, 69 %. DMSO = dimethyl sulfoxide, DIBAH = diisobutylaluminum hydride.



Scheme 4. Chelation-induced triple ring flips **16** → **17** and **18** → **19**.



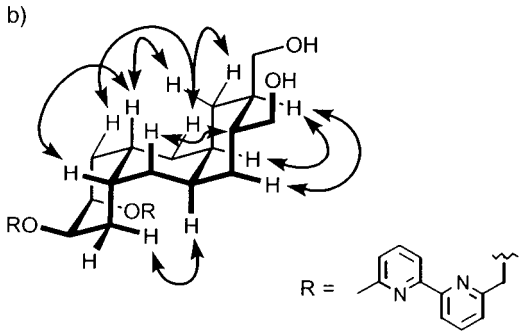


Figure 4. a) Parts of the NOESY spectrum of **13** (600 MHz, CD_3CN); b) preferred solution conformation **16** based on NOESY data. Selected NOESY cross-signals are indicated with double arrows.

$CDCl_3$ (1:1) gave the complex [Zn-**15**](OTf)$_2$. The NMR spectra of the product confirmed that the expected triple ring flip (**18** → **19**) had occurred. The stability of the complex [Zn-**15**](OTf)$_2$ was determined by UV titration[21] (Figure 6a), from which a binding energy of $\Delta G = 7.1$ kcal mol^{-1} in $CH_3CN/CHCl_3$ was derived[22] (see Supporting Information). The corresponding binding energy required to induce the double ring flip in the decalin series has been determined as $\Delta G = 6.8$ kcal mol^{-1}.[11] Both values exceed the limit for the switching energy of 6 kcal mol^{-1} estimated as the requirement for shifting the equilibrium **5** ⇌ **6** towards **6**. The triple ring flip (**18** → **19**) could be monitored by an ^{1}H NMR titration experiment on the reaction of **15** with Zn(OTf)$_2$ (Figure 6b).

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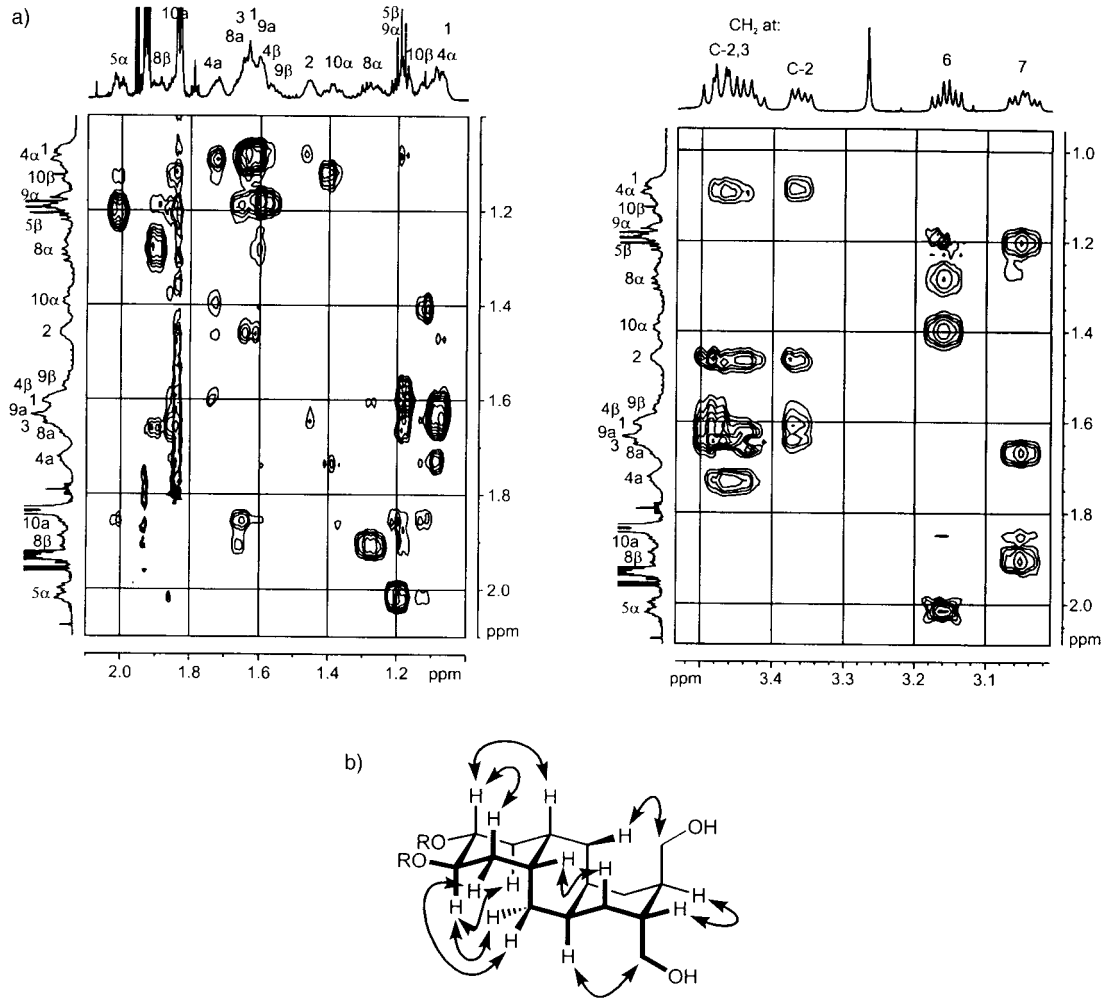


Figure 5. a) Parts of the NOESY spectrum of the complex Zn-**13**-$(OTf)_2$ (600 MHz, CD_3CN); b) preferred solution conformation **17** based on NOESY data. Selected NOESY cross-signals are indicated with double arrows.

The clean formation of conformer **19** was indicated by the diagnostic change in the bipyridine signals as well as by the diagnostic signals of the 6-H and 7-H protons, which showed the same change as discussed for the triple ring flip (**16** → **17**). It is noteworthy that in the millimolar range of the ^{1}H NMR experiment 1.1 equivalents of $Zn(OTf)_2$ proved sufficient for a complete triple ring flip, whereas in the micromolar range of the UV experiment 2.0 equivalents were necessary. This is a direct consequence of Ostwald's law of dilution, which predicts a higher dissociation of a complex at higher dilution. The sensitivity of the signal response is a function of the concentration range at which the signal transduction is carried out.

Pyrenes as fluorescence reporter groups at the effector site: Among the possible effector groups, photoactive units should be useful for the read-out of the signal transduction process. Pyrene groups[23, 24] were chosen as reporter groups to allow distinction of the axial and equatorial positions of the substituents at C-2 and C-3. The working hypothesis was that, through the choice of an appropriate linker, equatorial pyrene moieties, such as that in **20**, should lead predominantly to pyrene excimer formation with an excimer fluorescence at 480 nm (Scheme 5). After the triple ring flip to **21**, the pyrene substituents are in the axial positions, with a greater distance between them. Consequently, the fluorescence of the pyrene monomer at 380 nm becomes predominant. The optimal conditions for excimer formation are a parallel, sandwich-type alignment of the pyrene moieties, with an interplanar separation of 353 pm.[25]

To test our working hypothesis, pyrene **22** and a series of pyrene derivatives **23**–**29** were studied as reference compounds. The commercially available pyren-1-yl acetic acid **23** served as a common building block. In compounds **24** and **25**, the two pyrene units are connected by a linker lacking any stereochemical information. The cyclohexane derivatives **26** and **29** were chosen as reference compounds for equatorially oriented pyrene units, while the two bis-acetals **27** and **28** served as standards for the conformer with diaxial pyrene effector groups. Bis(acetal) **28** differs from **27** in that it has an additional *E* double bond in the linker between the perhydroanthracene and pyrene units. Compounds **24**, **25**, and **26** were prepared by standard transformations, while the synthesis of compounds **27**–**29** is summarized in Scheme 6. The fluorescence spectra of compounds **24**–**29** were recorded at low concentrations ($c = 10^{-5}$ mol L^{-1}), at which no intermo-

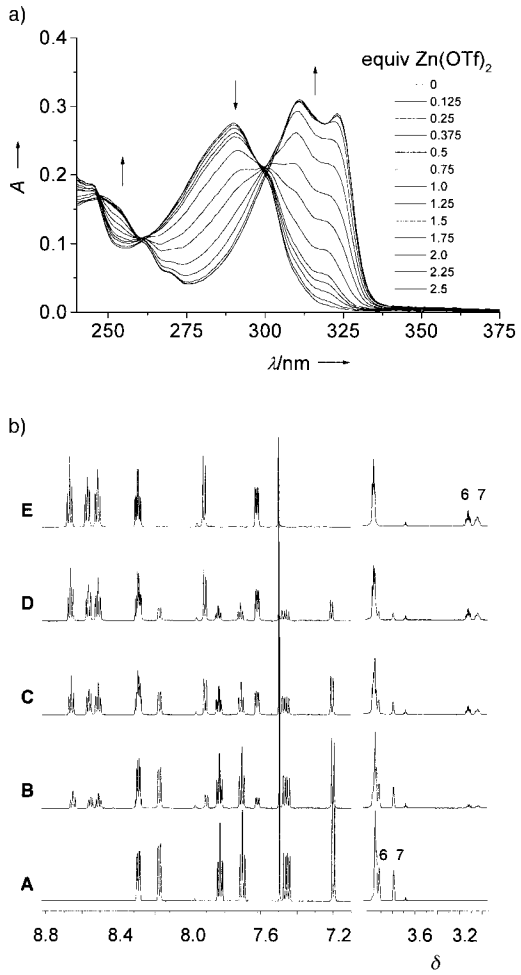
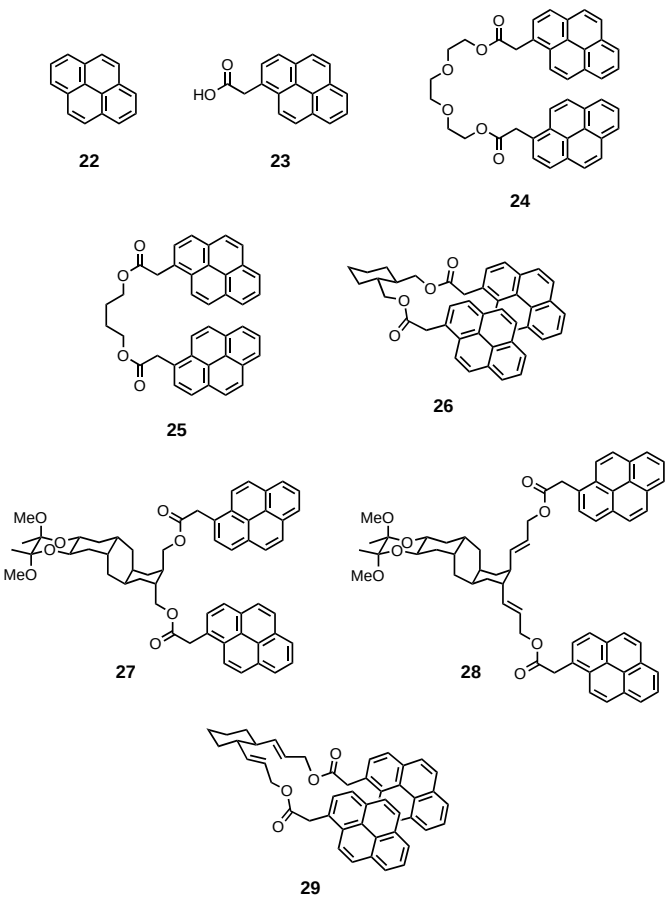
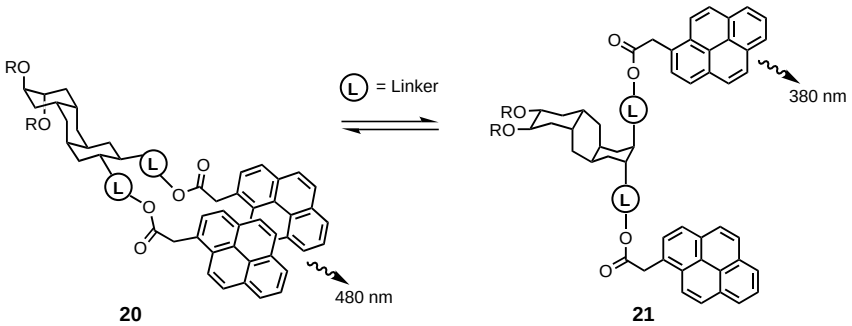


Figure 6. Analysis of the complexation-induced triple ring flip; a) UV/Vis titration of **15** with $Zn(OTf)_2$ ($CH_3CN/CHCl_3$, 1:1, $c = 8.1 \times 10^{-6}$ mol L^{-1}, $T = 298$ K); b) ^{1}H NMR titration of **15** with $Zn(OTf)_2$ ($CH_3CN/CHCl_3$, 1:1, $c = 2.9 \times 10^{-2}$ mol L^{-1} (A = 0 equiv $Zn(OTf)_2$, B = 0.3, C = 0.6, D = 0.9, E = 1.1).

lecular excimer formation occurred (Figure 7). The spectra were normalized with respect to the monomer band intensity at 380 nm. The strongest excimer formation was found for compound **29**, with a diequatorial orientation of the pyrene substituents, and for **24** with the triethylene glycol linker. The diaxial reference compound **27** exhibited a lower but still significant degree of excimer formation. The insertion of an *E* double bond into the linker to give **28** proved to be a successful means of largely suppressing excimer formation in the bis-axial conformer. In order to gain more insight into the conformational control of the excimer formation, the enthalpic and entropic contributions were determined for compounds **22**–**28** by means of temperature-dependent fluorescence studies. Two pyrene residues in the ground state show no interaction (besides van der Waals forces), and their orientation depends only on conformational constraints. Upon excitation of one pyrene residue, pyrene excimer formation occurs within the S_1 lifetime (Scheme 7). The ratio of the fluorescence quantum yields of monomer fluorescence φ_f^M and excimer fluorescence φ_f^E results from a competition between formation (k_{ME}) and decomposition (k_{EM}) processes[26] [Eq. (1)].



$$\varphi_f^E/\varphi_f^M = (k_f^{n,E} k_{ME} \tau_f^E)/[k_f^{n,M} (1 + k_{EM} \tau_f^E)] \quad (1)$$



Scheme 5. Pyrene groups as effectors in molecular signal transduction through the triple ring flip of the perhydroanthracene.

The rate constants $k_f^{n,M}$ and $k_f^{n,E}$ describe the probability of a radiative transition of the monomer and the excimer, respectively. They are not temperature dependent, whereas for k_{ME} (excimer formation rate) and for k_{EM} (excimer decomposition rate), a dependence on temperature and environment (e.g., solvent polarity) can be expected. The excimer associa-

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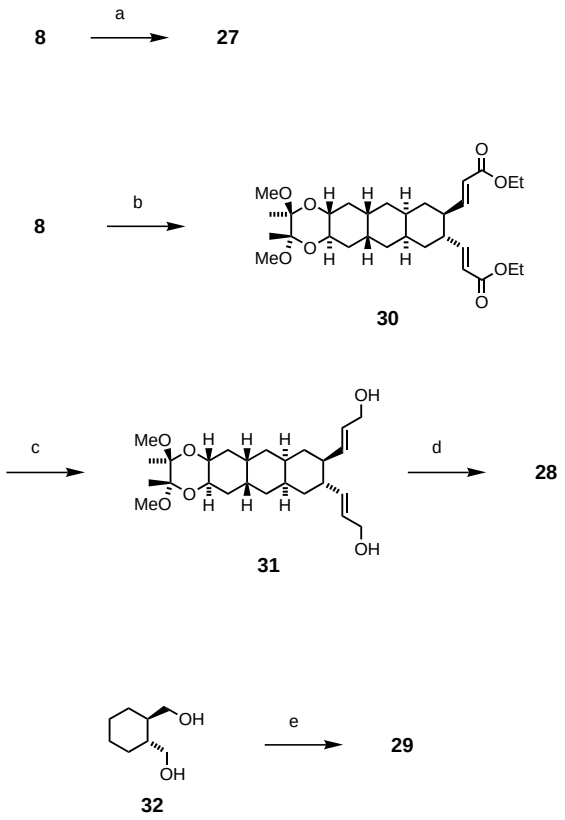


Scheme 6. a) Pyren-1-yl acetic acid, DMAP, EDC, CH_2Cl_2, 0 °C, 2 h, 88 %; b) 1. oxalyl chloride, DMSO, NEt_3, CH_2Cl_2, −78 → 0 °C; 2. ethoxycarbonylmethylene triphenylphosphorane, CH_2Cl_2, 20 °C, 14 h, 73 % over two steps; c) 12 equiv DIBAH, CH_2Cl_2, −78 → 0 °C, 4 h, 64 %; d) 10 equiv pyrene acetic acid, 15 equiv DMAP, 10 equiv EDC, CH_2Cl_2, 20 °C, 2 h, 70 %; e) 1. oxalyl chloride, DMSO, EtN*i*Pr$_2$, CH_2Cl_2, −78 → 0 °C; 2. ethoxycarbonylmethylene triphenylphosphorane, toluene, 100 °C, 15 h, 97 % over two steps; 3. DIBAH, CH_2Cl_2, −78 → 0 °C, 6 h; 4. pyren-1-yl acetic acid, DMAP, EDC, CH_2Cl_2, 20 °C, 3 h, 19 % over two steps. DMAP = 4-(dimethylamino)pyridine; EDC = *N*-ethyl-*N*′-(dimethylamino)propylcarbodiimide.

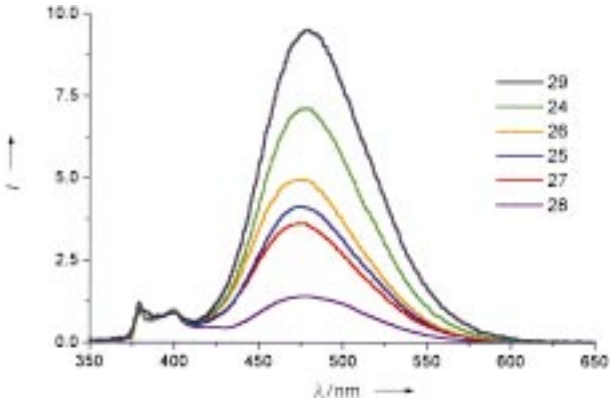
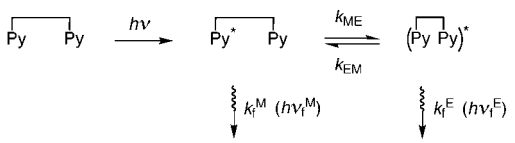


Figure 7. Fluorescence spectra of compounds **24**–**29** ($CHCl_3$, $T = 298$ K, excitation at 343 nm).



Scheme 7. Intramolecular pyrene excimer formation.

tion constant K is given by the relationship $k_{ME}/k_{EM} = K$. K is determined thermodynamically as shown in Equation (2).

$$-RT\ln K = \Delta H - T\Delta S \quad (2)$$

If the equilibrium is reached within the excimer lifetime τ_f^E (see Table 1), the temperature gradient for φ_f^E/φ_f^M can be described by the Eyring equation [Eq. (3)].[27]

$$\ln(\varphi_f^E/\varphi_f^M) = \ln(k_f^{n,E}/k_f^{n,M}) - \Delta H/RT + \Delta S/R \quad (3)$$

Table 1. Photophysical data of compounds **22**–**28**.

Compound	λ_{abs}^M [nm]	λ_f^M [nm]	λ_f^E [nm]	φ_f^M	φ_f^E	φ_f (overall)	τ_f^M [ns]	$k_f^{n,M}$ [10^6 s^{-1}]	τ_f^E [ns]	$k_f^{n,E}$ [10^6 s^{-1}]
22[a,b]	345	379	470	0.65[c]	0[c]	0.65	475	1.4	53.0	10.5
23[a]	344	384	476	0.40[c]	0[c]	0.40	300	1.3	45.0	10.5
24	345	380	477	0.04	0.40	0.44	15.4	1.3	36.0	10.8
25	344	380	474	0.03	0.40	0.44	24.7	1.5	38.0	10.5
26	345	378	475	0.02	0.38	0.41	17.4	1.5	32.5	11.7
27	345	379	483	0.09	0.34	0.43	25.0	1.6	35.5	11.3
28	345	379	477	0.02	0.39	0.41	65.0	1.4	31.5	10.8

[a] In ethanol. [b] B. Stevens, M. I. Ban, *Trans. Faraday Soc.* **1964**, *60*, 1515. [c] $c \approx 10^{-6}$ mol L^{-1}.

An increase in the temperature leads to a decrease in the excimer emission intensity and to an increase in the monomer emission band in the fluorescence spectrum. Figure 8a shows

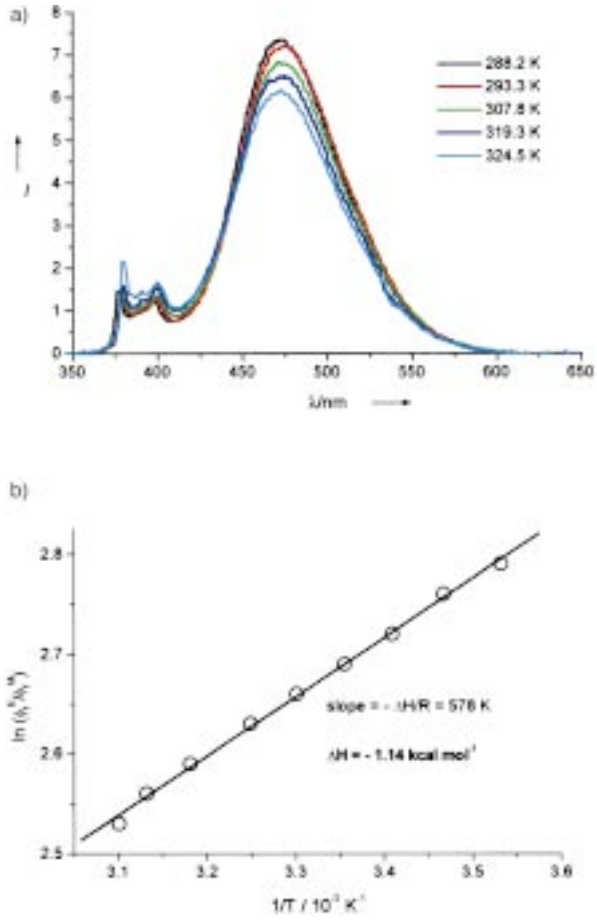


Figure 8. a) Temperature-dependent fluorescence spectra of **26** ($CHCl_3$, excitation at 343 nm); b) Arrhenius plot for **26** [$\ln(\varphi_f^E/\varphi_f^M)$ versus T^{-1}].

the fluorescence spectra of compound **26** in the range 288 to 325 K as a representative example. The dependence of $\ln(\varphi_f^E/\varphi_f^M)$ on $1/T$ [Eq. (3)] allows the determination of ΔH from the slope (Figure 8b). Additional time-resolved fluorescence decay measurements to determine the fluorescence lifetimes τ_f^M and τ_f^E enabled us to determine the rate constants $k_f^{n,M}$ and $k_f^{n,E}$ (Table 1) and, therefore, from Equation (4), the excimer association constant K as well.

$$\varphi_f^E/\varphi_f^M = (k_f^{n,E}/k_f^{n,M})\ K \quad (4)$$

With knowledge of K and ΔH, the entropic terms ΔS could be calculated (Table 2).

Table 2. Thermodynamic data for the pyrene excimer formation of compounds **22**–**28**.

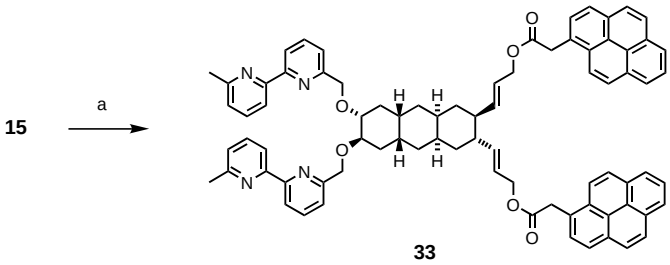
Compound	ΔH [kcal mol^{-1}]	ΔS [cal mol^{-1} K^{-1}]
22	−9.5	−18.5
23	−10.0	−19.2
24	−5.5	−16.8
25	−1.0	−2.4
26	−1.1	−2.5
27	−0.8	−2.2
28	+0.2	−0.8

For pyrene **22** and pyren-1-yl acetic acid **23**, intermolecular pyrene excimer formation is possible in the preferred sandwich arrangement. The ΔH values observed are of the order of -10 kcal mol^{-1}. The negative ΔS values around -19 cal mol^{-1} K^{-1} for **22** and **23** are understandable because the disordered contribution of single molecules is changed to a highly ordered excited dimer. For linked pyrene residues, two general trends are observed: 1) ΔH values are less negative than that observed for "free" pyrene because steric restraints largely inhibit formation of the sandwich-like arrangement, and 2) ΔS values are less negative than that observed for "free" pyrene because of a preorientation of the two pyrene residues in the ground state.

The flexible polyether compound **24** already shows these effects, and they become stronger in the more rigid compounds **25**–**28**. This is reflected in the smaller values of the ΔH and ΔS terms. A small ΔH term indicates that a sandwich-like pyrene–pyrene alignment cannot be attained because of steric restraints in the molecule. Small ΔS terms are the result of an intramolecular preorientation of the pyrene residues in the ground state.[26, 28] The variation in these terms among compounds **24**–**28** is in accordance with our model considerations. Compound **28** exhibits the strongest hindrance to intramolecular pyrene excimer formation with $\Delta H = +0.2$ kcal mol^{-1}. No significant structural changes in the pyrene–pyrene orientation are observed ($\Delta S = -0.8$ cal mol^{-1} K^{-1}).

Fluorescence studies on the various reference compounds showed the choice of the linker between the perhydroanthracene transducer and the pyrene effector to be crucial. An *E*-olefin spacer and an ester group were found to be best suited for largely suppressing excimer formation in the bis-axial conformer and for supporting excimer formation in the bis-equatorial conformer.

Molecular signal transduction through conformational transmission: After the separate elaboration of bipyridines as receptors and of pyrenes as suitable effectors, the two components were combined to investigate signal transduction through the triple ring flip of the perhydroanthracene transducer. Starting from compound **15**, with both bipyridine units already in place, the target molecule **33** was prepared. The two pyrene substituents and the *E* double bond in the linker of **33** were introduced by applying the Wittig protocol established in the syntheses of the reference compounds (Scheme 8).



Scheme 8. Synthesis of the perhydroanthracene **33**; a) DMAP, EDC, pyren-1-yl acetic acid, 2 h, 20 °C, 94 %.

^{1}H NMR spectroscopic analysis of uncomplexed **33** revealed conformer **34** to be the only detectable species (Figure 9a). The fluorescence spectrum of uncomplexed **33** displayed the expected weak pyrene monomer band at around 380 nm and the strong excimer band at 480 nm (Figure 10).

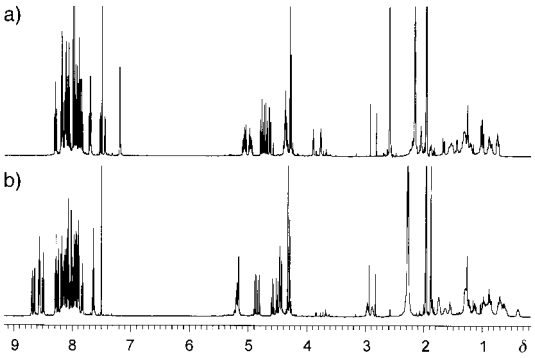


Figure 9. ^{1}H NMR spectra of a) uncomplexed **33** and b) the zinc(II) complex of **33**.

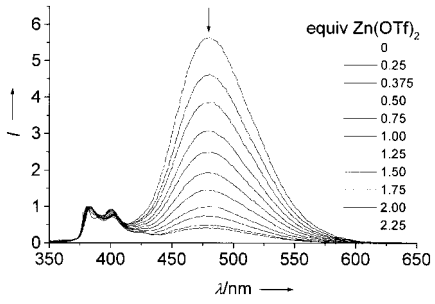


Figure 10. Photoresponse of **33** to a zinc(II) signal. Fluorescence spectrum of **33** in $CH_3CN/CHCl_3$ (1:1) as a function of added $Zn(OTf)_2$ (excitation at 343 nm, $c = 5.6 \times 10^{-6}$ mol L^{-1}, $T = 298$ K). Fluorescence spectra were normalized with respect to the monomer peak at 380 nm.

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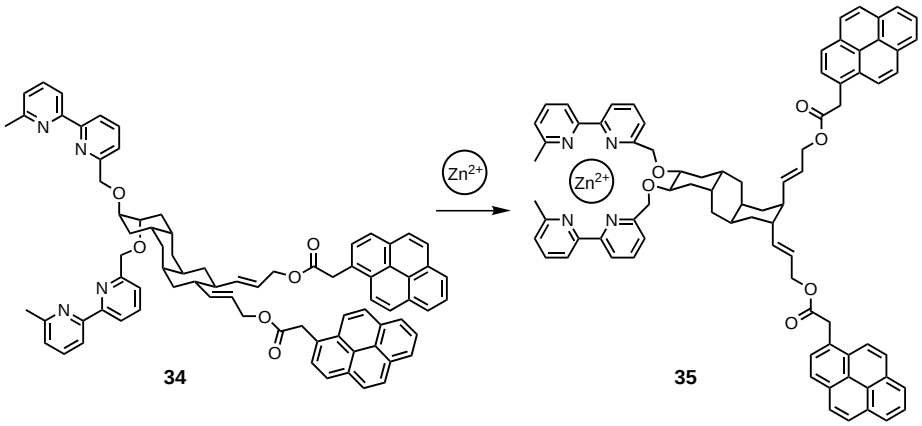
NMR analysis of the zinc(II) complex of **33** (Figure 9b) confirmed that a conformational switching from **34** to **35** had occurred (Scheme 9).



Scheme 9. Molecular signal transduction through conformational transmission by the triple ring flip **34** → **35**.

Addition of zinc(II) ions to compound **33** resulted in a distinct decrease in the intensity of the excimer band at 480 nm relative to that of the pyrene monomer fluorescence band at 380 nm (Figure 10). The zinc signal causes an axial-to-equatorial conformational change at the receptor site, which is transduced through a triple ring flip of the perhydroanthracene to the pyrene effector site, where the induced equatorial-to-axial flip yields the observed fluorescence photosignal.

Interfering interactions between the zinc(II) cation and the pyrene systems could be excluded by control experiments. The addition of excess zinc(II) triflate to a solution of **29** had no effect on the fluorescence spectrum (see Supporting Information). Furthermore, no change in the fluorescence spectrum was observed when zinc(II) triflate was added to a 1:1 mixture of the bipyridine-substituted perhydroanthracene **15** and the bis-pyrene **29** (see Supporting Information).

Functional signal transduction needs a switch-on and a switch-off. Addition of chelating agents (e.g., 6,6′-dimethyl-2,2′-bipyridine or ethylenediaminetetraacetic acid) to a solution of the zinc complex **35** resulted in a distinct increase in the intensity of the pyrene excimer emission relative to that of the monomer fluorescence (see Supporting Information). This is the expected photoresponse for the switch-off (**35** → **34**).

Conclusion

This study has shown that tetrasubstituted perhydroanthracenes of type **4** are suitable conformational transducers for molecular signals. Bipyridines have been used as receptors and pyrenes as effectors. An appropriate choice of the linker between the perhydroanthracene and the pyrene effectors has proved necessary to obtain conformational control of the pyrene excimer formation. In the given example, signal transduction by conformational transmission has been demonstrated with a particular receptor–effector pair. One can imagine a variety of stimuli at the receptor site, such as photoisomerization or a redox process. An interesting topic for investigation will be the induced dissociation of an ion or ligand at the effector side. The design, synthesis, and functional analysis of molecular devices is a major challenge for synthetic chemistry.[30] Compound **33** is a good example of such a functional molecular device and demonstrates the potential of organic synthesis in the preparation of functional nanoscale systems.

Experimental Section

General: All boiling and melting points are uncorrected. IR: Biorad FTS 3000MX. NMR: Bruker AM 300, DPX 300, and AMX 600. For ^{1}H NMR, $CDCl_3$ as solvent $\delta_H = 7.25$, [D$_4$]MeOH as solvent $\delta_H = 4.78$, CD_3CN as solvent $\delta_H = 1.93$; [D$_8$]THF as solvent $\delta_H = 3.58$, [D$_8$]toluene as solvent $\delta_H = 2.09$, [D$_6$]DMSO as solvent $\delta_H = 2.50$. For ^{13}C NMR, $CDCl_3$ as solvent $\delta_C = 77.0$, [D$_4$]MeOH as solvent $\delta_C = 49.0$, CD_3CN as solvent $\delta_C = 1.3$, [D$_8$]THF as solvent $\delta_C = 67.4$, [D$_8$]toluene as solvent $\delta_C = 20.4$, [D$_6$]DMSO as solvent $\delta_C = 39.5$. Elemental analysis: CHNS-932 Analyzer (Leco). HRMS: Finnigan MAT 95. HPLC: Rainin-Dynamax, SD-200 and SD-1, PDA1. All reactions were performed under an inert atmosphere of argon in oven- or flame-dried glassware. Dry solvents: THF and toluene were distilled from sodium/benzophenone. EtN(*i*Pr)$_2$, Et$_3$N, DMSO, and CH_2Cl_2 were distilled from CaH_2. All commercially available reagents were used without purification unless otherwise noted. All reactions were monitored by thin-layer chromatography (TLC) carried out on Merck F-254 silica-coated glass plates; spots were visualized with UV light and/or heat-gun treatment after spraying with 5% phosphomolybdic acid in EtOH. Column chromatography and flash column chromatography were performed on Merck silica gel 60 (70–200 mesh and 230–400 mesh). PE: light petroleum ether, b.p. 40–60 °C.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis(methoxymethyl)-6,7-bis(oxymethyl)perhydroanthracene (4b)** *Deprotection*: TBAF (141 mg, 447 μmol) was added to a solution of the diol **7** (85 mg, 112 μmol) in THF (3 mL). After 3 h at 50 °C, the solvent was removed in vacuo, and the residue was purified by flash chromatography on silica (10 g; $CHCl_3$/MeOH, 7:1). The tetraol **4a** was obtained in 94% yield as a colorless glassy oil. $R_f = 0.14$ ($CHCl_3$/MeOH, 7:1); ^{1}H NMR (300 MHz, [D$_6$]DMSO): $\delta =$ 0.89–1.51 (m, 10H), 1.53–1.87 (m, 5H), 1.90–2.11 (m, 2H), 2.12–2.32 (m, 1H) (1,2,3,4,4a,5,8,8a,9,9a,10,10a-H), 3.19–3.51 (m, 7H; 6-H or 7-H, 2-,3-CH_2, and OH), 3.53–3.63 (m, 1H; 6-H or 7-H), 4.29–4.45 (m, 2H; OH); ^{13}C NMR (75 MHz, [D$_6$]DMSO): $\delta = 28.3$, 28.5, 28.6, 28.8, 29.0, 31.3, 32.2, 33.5, 34.9, 35.4 (C-1,4,4a,5,8,8a,9,9a,10,10a), 35.5 (C-3), 41.6 (C-2), 64.1, 64.4 (2-,3-CH_2), 69.5, 69.7 (C-6,7).

Methylation: The tetraol **4a** (30 mg, 105 μmol) was dissolved in DMF (3 mL). At 0 °C, NaH (95%, 43 mg, 1.69 mmol) was added, and the reaction mixture was stirred at this temperature for 30 min. MeI (0.26 mL, 4.22 mmol) was then added. After 4 d at 20 °C, the mixture was neutralized by the addition of HCl (2 M). Most of the DMF was removed in vacuo, and the residue was partitioned between Et_2O (10 mL) and water (10 mL). The layers were separated, and the aqueous layer was extracted with Et_2O (3 × 10 mL). The combined organic layers were dried with $MgSO_4$, concentrated, and the residue was purified by flash chromatography on silica (5 g, PE/AcOEt, 10:1 → 8:1) to yield **4b** (24 mg, 71 μmol, 67%) as a colorless oil. $R_f = 0.08$ (hexane/AcOEt, 10:1); ^{1}H NMR (300 MHz, [D$_8$]toluene): $\delta =$ 0.95–1.02 (m, 1H; 10α-H), 1.20 (dd, $J = 13.7$, 3.5 Hz, 1H; 9β-H), 1.28–1.37 (m, 2H; 5β,9a-H), 1.42–1.92 (m, 11H; 1,2,3,4,4a,8,8a,10β-H), 2.04 (td, $J =$ 13.1, 2.3 Hz, 1H; 5α-H), 2.10–2.23 (m, 1H; 10a-H), 2.39 (td, $J = 13.5$,

4.0 Hz, 1H; 9α-H), 3.12–3.38 (m, 17H; CH_2O, CH_3, 7-H), 3.43–3.49 (m, 1H; 6-H); ^{13}C NMR (75 MHz, [D$_8$]toluene): $\delta = 25.3$ (C-5), 29.0 (C-8a), 29.3 (C-8), 29.5 (C-10a), 29.8 (C-1 or C-4), 29.8 (C-9a), 32.0 (C-10), 33.5 (C-9), 34.4 (C-4a), 36.3 (C-1 or C-4), 36.7 (C-3), 41.2 (C-2), 56.0 and 56.1 (6-,7-OCH_3), 58.6 and 58.6 (CH_3), 76.4 and 76.6 (2-,3-CH_2O), 77.5 (C-7), 78.3 (C-6); HRMS ($C_{20}H_{36}O_4$): *m*/*z* calcd for $[M]^+$ 340.2614; found 340.2610.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Dihydroxymethyl-6,7-*O*-(2′,3′-dimethoxybutan-2′,3′-diyl)perhydroanthracene-6,7-diol (8)**: 2,2,3,3-Tetramethoxybutane (48 mg, 268 μmol), trimethyl orthoformate (57 mg, 536 μmol), and a catalytic amount of camphorsulfonic acid were added to a solution of diol **7** (102 mg, 134 μmol) in MeOH (5 mL). The mixture was stirred at 50 °C for 20 h. After cooling to 20 °C, the reaction was quenched with powdered $NaHCO_3$ (20 mg) and the solvent was removed in vacuo. Column chromatography of the residue on silica (5 g; PE/AcOEt, 1:1) afforded 52 mg of the bis-acetal **8** (131 μmol, 97 %) as a white solid. M.p. 176 °C (MeOH); $R_f = 0.09$ (PE/AcOEt, 1:1); ^1H NMR (600 MHz, [D$_4$]MeOH, 50 °C): $\delta = 1.21$–1.25 (m, 3H; 1α,9β,10β-H), 1.23 (CH_3), 1.24 (CH_3), 1.30–1.34 (m, 1H; 4α-H), 1.39–1.41 (m, 1H; 8β-H), 1.53–1.55 (m, 2H; 5α,5β-H), 1.59–1.63 (m, 1H; 4β-H), 1.69–1.76 (m, 2H; 1β,8α-H), 1.80–2.00 (m, 8H; 2,3,4a,8a,9a,9α,10a,10α-H), 3.20 (s, 3H; OCH_3), 3.21 (s, 3H; OCH_3), 3.44–3.47 (m, 2H; 2-CH_2, 7-H), 3.56–3.86 (m, 4H; 2-,3-CH_2, 6-H); ^{13}C NMR (75 MHz, [D$_4$]MeOH, 50 °C): $\delta = 18.5$ (C-1′,4′), 25.6, 30.6, 31.0, 31.4, 31.5, 31.6, 33.4, 35.6, 35.8, 36.4, 38.8, 39.3 (C-1,2,3,4,4a,5,8,8a,9,9a,10,10a), 48.3 (2 × OCH_3), 65.8 (3-CH_2), 68.1 (2-CH_2), 69.2 (C-6), 73.8 (C-7), 101.2, 101.3 (C-2′,3′); HRMS ($C_{22}H_{38}O_6$): *m*/*z* calcd for $[M+Na]^+$ 421.1566; found 421.2604.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis(*tert*-butyldiphenylsiloxymethyl)-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene (12)**: NaH (7.3 mg, 0.3 mmol) and one drop of DMSO were added to a solution of the diol **7** (92 mg, 121 μmol) in THF (3 mL) at 0 °C. After stirring for 30 min, the bromide **11** (160 mg, 0.61 mmol) and a catalytic amount of nBu_4NI were added. After 3 d, the reaction was quenched by the addition of saturated aqueous $NaHCO_3$ solution (5 mL) and dichloromethane (5 mL). The phases were separated. The aqueous layer was extracted with CH_2Cl_2 (5 × 5 mL), and the combined organic layers were washed with brine and dried with $MgSO_4$. After removal of the solvent in vacuo, the remaining crude product was purified by column chromatography on silica (7 g, PE/AcOEt, 4:1) to yield **12** (110 mg, 97.7 μmol, 81 %) as a colorless glassy solid. $R_f = 0.19$ (hexane/AcOEt, 4:1); ^1H NMR (300 MHz, $CDCl_3$): $\delta = 0.73$–2.45 (m, 18H; 2,3,4,4a,5,8,8a,9,9a,10,10a-H), 0.97 (s, 9H; CH_3-TBDPS), 0.98 (s, 9H; CH_3-TBDPS), 2.61 (s, 6H; CH_3-bipy), 3.41–3.54 (m, 2H; CH_2-OTBDPS), 3.54–3.67 (m, 2H; CH_2-OTBDPS), 3.74–3.82 (m, 1H), 3.88–3.94 (m, 1H) (6-,7-H), 4.63–4.85 (m, 4H; CH_2-bipy), 7.13 (d, $J = 7.5$ Hz, 2H; bipy-H), 7.20–7.86 (m, 26H; Ar-H), 8.14 (d, $J = 7.7$ Hz, 2H; bipy-H), 8.25 (d, $J = 8.4$ Hz, 1H; bipy-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 19.3$ and 19.3 (TBDPS-*C*(CH_3)$_3$), 26.2 and 26.8 (TBDPS-CH_3), 24.6, 28.6, 28.7, 29.4, 29.5, 31.6, 33.2, 35.1, 35.1, 35.2 (C-1,4,4a,5,8,8a,9,9a,10,10a), 36.4 (C-3), 41.8 (C-2), 66.4 and 66.5 (CH_2-OTBDPS), 71.7 and 71.8 (CH_2-bipy), 75.9 and 76.7 (C-6,7), 118.1, 119.5, 119.5, 120.6, 120.8, 123.1, 123.2, 127.5, 129.4, 129.4, 133.9, 134.0, 135.5, 135.5, 136.9, 137.3, 137.4, 155.5, 155.6, 157.8, 158.7 (C-Ar); HRMS ($C_{72}H_{84}N_4O_4Si_2$): *m*/*z* calcd for $[M]^+$ 1124.6031; found 1124.6024.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis(hydroxymethyl)-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene (13)**: TBAF (203 mg, 643 μmol) was added to a solution of the silyl ether **12** (183 mg, 161 μmol) in THF (10 mL). After 2 h at 40 °C, the solvent was removed in vacuo. The residue was purified by column chromatography on silica (15 g, PE/AcOEt/MeOH, 10:10:1) to yield 103 mg (159 μmol, 98 %) of the alcohol **13**. $R_f = 0.19$ (hexane/AcOEt/MeOH, 10:10:1); ^1H NMR (600 MHz, [D$_8$]THF): $\delta = 1.10$ (d, $J = 9.3$ Hz, 1H; 10α-H), 1.17 (dt, $J = 12.9$, 3.4 Hz, 1H; 1α-H), 1.21–1.51 (m, 4H; 2,9β,4,3-H), 1.52–1.62 (m, 2H; 1β,5β-H), 1.74–1.77 (m, 1H; 9a-H), 1.80 (d, $J = 14.4$ Hz, 1H; 8α-H), 1.88–1.99 (m, 2H; 8a,10β-H), 2.02 (ddd, $J = 14.6$, 5.8, 3.6 Hz, 1H; 8β-H), 2.21–2.39 (m, 2H; 4a,5α-H), 2.51 (td, $J = 13.6$, = 4.8 Hz, 1H; 9α-H), 2.52–2.61 (m, 1H; 10a-H), 2.56 (s, 3H; CH_3), 2.56 (s, 3H; CH_3), 3.37–3.49 (m, 4H; CH_2OH), 3.82 (dt, $J = 2.6$, 2.5 Hz, 1H; 7-H), 3.95 (ddd, $J = 2.5$, 2.4, 2.2 Hz, 1H; 6-H), 4.67 (d, $J = 13.4$ Hz, 1H), 4.69 (d, $J = 13.4$ Hz, 1H), 4.77 (d, $J = 13.4$ Hz, 1H), 4.77 (d, $J = 13.4$ Hz, 1H) (AB systems, CH_2-bipy), 7.16 (d, $J = 7.5$ Hz, 2H; 5′-H of 6-bipy and 7-bipy), 7.46 (d, $J = 7.0$ Hz, 1H) and 7.48 (d, $J = 7.0$ Hz, 1H) (5-H of 6-bipy and 7-bipy), 7.66 (t, $J = 7.7$ Hz, 2H; 4′-H of 6-bipy and 7-bipy), 7.79 (t, $J = 7.7$ Hz, 1H) and 7.80 (t, $J = 7.8$ Hz, 1H) (4-H of 6-bipy and 7-bipy), 8.25 (d, $J = 7.9$ Hz, 2H; 3′-H of 6-bipy and 7-bipy), 8.37 (d, $J = 8.2$ Hz, 2H; 3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 24.6$ (CH_3, C-10a), 26.9 (C-5), 29.6 (C-8a), 30.0 (C-1), 30.5 (C-4a), 30.9 (C-8), 32.6 (C-10), 34.3 (C-9), 36.7 (C-4), 37.6 (C-9a), 38.8 (C-3), 45.7 (C-2), 67.2 and 67.3 (CH_2OH), 72.6 and 72.9 (CH_2-bipy), 76.8 (C-7), 77.5 (C-6), 118.4 (C-3′ of 6-bipy and 7-bipy), 119.7 and 119.8 (C-3 of 6-bipy and 7-bipy), 121.4 and 121.5 (C-5 of 6-bipy and 7-bipy), 123.7 (C-5′ of 6-bipy and 7-bipy), 137.5 (C-4′ of 6-bipy and 7-bipy), 137.8 and 137.8 (C-4 of 6-bipy and 7-bipy), 156.2, 158.4, 159.7, and 159.7 (C-2,2′,6,6′ of 6-bipy and 7-bipy); HRMS ($C_{40}H_{48}N_4O_4$): *m*/*z* calcd for $[M]^+$ 648.3676; found 648.3672.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-4-oxa-3-oxo-hex-1-en-1-yl]-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene (14)**

Swern oxidation: In a Schlenk flask, oxalyl chloride (40.7 μL, 0.47 mmol) was dissolved in CH_2Cl_2 (3 mL) and the solution was cooled to −78 °C. DMSO (66.0 μL, 0.94 mmol) in CH_2Cl_2 (1 mL) was then added dropwise. Over a period of 15 min, the temperature of the cooling bath was allowed to rise to −50 °C. After cooling to −78 °C once more, a solution of the diol **13** (102 mg, 157 μmol) in CH_2Cl_2 (1 mL) was added. The temperature of the cooling bath was again allowed to reach −50 °C. EtN*i*Pr$_2$ (0.38 mL, 2.20 mmol) was then added at −78 °C. Thereafter, the temperature was allowed to rise to −40 °C (30 min) and then the reaction mixture was kept for a further 30 min at 0 °C. The reaction was eventually quenched by the addition of saturated aqueous $NaHCO_3$ solution (5 mL). After separation of the layers, the aqueous layer was extracted with CH_2Cl_2 (5 × 5 mL), and the combined organic layers were washed with saturated NaCl solution (20 mL) and dried with Na_2SO_4. The solvent was removed in vacuo. Traces of water were removed by azeotropic distillation with toluene (2 × 5 mL). The aldehyde was used in the next step without further purification.

Wittig reaction: The aldehyde and $Ph_3P{=}CHCOOEt$ (440 mg, 1.26 mmol) were dissolved in toluene (5 mL) and the mixture was heated for 15 h at 90 °C. The solvent was then removed in vacuo and the residue was purified by flash chromatography on silica (10 g; PE/AcOEt/MeOH, 10:10:5) to furnish the ester **14** (97 mg, 124 μmol) in 79 % yield over the two steps as a colorless oil. $R_f = 0.51$ (hexane/AcOEt/MeOH, 10:10:1); ^1H NMR (300 MHz, $CDCl_3$): $\delta = 1.00$–2.34 (m, 17H; 1α,1β,2,3,4α,4β,4a,5α,5β,8α,8-β,8a,9β,9a,10α,10β,10a-H), 1.24 (t, $J = 7.1$ Hz, 3H; CH_3CH$_2$), 1.24 (t, $J = 7.1$ Hz, 3H; CH$_2$CH_3), 2.42 (ddd, $J = 13.2$, 12.9, 3.4 Hz, 1H; 9α-H), 2.59 (s, 6H; CH_3), 3.77 (br q, $J = 2.5$ Hz, 1H; 7-H), 3.90 (br s, 1H; 6-H), 4.13 (q, $J = 7.1$ Hz, 2H; CH_2CH$_3$), 4.15 (q, $J = 7.2$ Hz, 2H; CH_2CH$_3$), 4.65, 4.68, 4.76, and 4.78 (AB systems, 4d, $J = 13.6$ Hz, 4H; CH_2-bipy), 5.73 (d, $J = 15.6$ Hz, 2H; C=CH–COO), 6.70 (dd, $J = 15.7$, 8.2 Hz, 1H; HC=C–COO), 6.77 (dd, $J = 15.6$, 8.1 Hz, 1H; HC=C–COO), 7.11 (d, $J = 7.5$ Hz, 2H; 5′-H of 6-bipy and 7-bipy), 7.40 (d, $J = 7.7$ Hz, 1H) and 7.46 (d, $J = 7.2$ Hz) (5-H of 6-bipy and 7-bipy), 7.63 (t, $J = 7.7$ Hz, 1H) and 7.63 (t, $J = 7.7$ Hz, 1H) (4′-H of 6-bipy and 7-bipy), 7.75 (t, $J = 7.8$ Hz, 1H) and 7.76 (t, $J = 7.8$ Hz, 1H) (4-H of 6-bipy and 7-bipy), 8.12 (d, $J = 7.7$ Hz, 2H; 3′-H of 6-bipy and 7-bipy), 8.25 (d, $J = 7.9$ Hz, 2H; 3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 14.5$ (CH_2CH_3), 24.6 (CH_3-bipy), 25.5 (C-10), 28.3 (C-10a), 29.2 and 29.7 (C-4a,8a), 29.7 (C-8), 30.7 and 31.2 (C-1,5), 32.7 (C-9), 35.2 (C-9a), 37.2 (C-4), 39.2 (C-3), 45.3 (C-2), 60.2 (*C*H$_2$CH$_3$), 71.7 and 71.9 (CH_2-bipy), 75.6 (C-7), 76.4 (C-6), 118.1 (C-3′ of 6-bipy and 7-bipy), 119.5 and 119.6 (C-3 of 6-bipy and 7-bipy), 120.6 and 120.7 (C-5 of 6-bipy and 7-bipy), 120.9 and 121.4 (*C*=C–COO) 123.1 (C-5′ of 6-bipy and 7-bipy), 136.9 (C-4′ of 6-bipy and 7-bipy), 137.2 (C-4 of 6-bipy and 7-bipy), 151.6 and 151.9 (C=*C*–COO), 155.5, 155.6, 157.8, 158.5, and 158.5 (C-2,2′,6,6′ of 6-bipy and 7-bipy), 166.5 and 166.5 (COO); HRMS ($C_{48}H_{56}N_4O_6$): *m*/*z* calcd for $[M]^+$ 784.4200; found 784.4191.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-3-hydroxyprop-1-en-1-yl]-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene (15)**: The ester **14** (95 mg, 121 μmol) was dissolved in CH_2Cl_2 (5 mL) and the solution was cooled to −78 °C. DIBAH (1 M in CH_2Cl_2, 0.73 mL, 0.73 mmol) was then added dropwise. The temperature of the cooling bath was allowed to reach 0 °C over a period of 5 h. The reaction was then quenched by the addition of a solution of Rochelle's salt (5 mL, 1 M in water). Stirring was continued overnight in order to destroy the aluminum complex of the product. The phases were then separated. The aqueous layer was extracted with CH_2Cl_2 (5 × 5 mL) and AcOEt (2 × 5 mL). The combined organic layers were dried with $MgSO_4$. After removal of the solvents in vacuo, column chromatography of the residue on silica (8 g; PE/AcOEt/MeOH, 10:10:1) afforded the diol **15** (58 mg, 83 μmol, 69 %) as a

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colorless glassy oil. $R_f = 0.20$ (hexane/AcOEt/MeOH, 10:10:1); ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.96-2.26$ (m, 19H; 1α,1β,2,3,4α,4β,4a,5α,5β,8α,8-β,8a,9β,9a,10α,10β,10a-H, 2OH), 2.39 (ddd, $J = 14.0$, 12.4, 4.1 Hz, 1H; 9α-H), 2.60 (s, 6H; CH_3), 3.77 (br q, $J = 2.4$ Hz, 1H; 7-H), 3.90 (br s, 1H; 6-H), 3.94–4.09 (m, 4H; CH_2OH), 4.65, 4.67, 4.77, and 4.78 (AB systems, 4d, $J = 13.7$ Hz, 4H; CH_2-bipy), 5.33–5.57 (m, 4H; C=CH), 7.12 (d, $J = 7.3$ Hz, 2H; 5′-H of 6-bipy and 7-bipy), 7.41 (d, $J = 7.9$ Hz, 1H) and 7.44 (d, $J = 7.7$ Hz) (5-H of 6-bipy and 7-bipy), 7.64 (t, $J = 7.8$ Hz, 1H) and 7.64 (t, $J = 7.8$ Hz, 1H) (4′-H, 6-bipy and 7-bipy), 7.76 (t, $J = 7.7$ Hz, 1H) and 7.77 (t, $J = 7.7$ Hz, 1H) (4-H of 6-bipy and 7-bipy), 8.12 (d, $J = 7.7$ Hz, 2H; 3′-H of 6-bipy and 7-bipy), 8.24 (d, $J = 7.9$ Hz, 2H; 3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 24.6$ (CH_3), 25.6 (C-10), 28.4 (C-10a), 29.2 and 29.6 (C-4a,8a), 29.9 (C-8), 31.5 and 31.7 (C-1,5), 33.0 (C-9), 35.7 (C-9a), 38.2 (C-4), 39.7 (C-3), 46.1 (C-2), 63.8 (CH_2OH), 71.7 and 71.9 (CH_2-bipy), 75.7 (C-6,7), 118.2 (C-3′ of 6-bipy and 7-bipy), 119.6 and 119.6 (C-3 of 6-bipy and 7-bipy), 120.6 and 120.8 (C-5 of 6-bipy and 7-bipy), 123.2 (C-5′ of 6-bipy and 7-bipy), 128.4 and 128.6 (*C*=C–CH_2OH), 137.0 (C-4′ of 6-bipy and 7-bipy), 137.6 (C-4 of 6-bipy and 7-bipy), 137.8 and 137.9 (C=*C*–CH_2OH), 155.6, 157.9, and 158.7 (C-2,2′,6,6′ of 6-bipy and 7-bipy); UV/Vis (MeCN/$CHCl_3$, 1:1): λ_{max} (ε) = 290 nm (33889); HRMS ($C_{44}H_{52}N_4O_4$): *m*/*z* calcd for $[M]^+$ 700.3989; found 700.3973.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis(hydroxymethyl)-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene zinc bis(triflate) complex (17)**: A solution of $Zn(OTf)_2$ (7.3 mg, 20 μmol) in CD_3CN (0.7 mL) was added to the ligand **16** (13 mg, 20 μmol) and the mixture was heated for 2 min at about 50 °C. The colorless complex **17** was formed quantitatively. IR (neat): $\tilde{\nu} = 3464$, 2911, 2870, 1638, 1600, 1575, 1440, 1261, 1176, 1033, 789, 643, 518 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.02-1.10$ (m, 2H; 1,4α-H), 1.13 (d, $J = 12.9$ Hz, 1H; 10β-H), 1.16–1.31 (m, 3H; 5β,9α,8α-H), 1.38 (td, $J = 12.7$, 4.6 Hz, 1H; 10α-H), 1.43–1.50 (m, 1H; 2-H), 1.55 (td, $J = 11.9$, 5.3 Hz, 1H; 9β-H), 1.56–1.69 (m, 5H; 1,3,4β,8a,9a-H), 1.69–1.76 (m, 1H; 4a-H), 1.81–1.88 (m, 7H; CH_3-bipy and 10a-H), 1.88–1.94 (m, 1H; 8β-H), 2.01 (dt, $J = 13.1$, 4.5 Hz, 1H; 5α-H), 2.71 (brs, 2H; OH), 3.05 (ddd, $J = 11.0$, 9.5, 4.3 Hz, 1H; 7-H), 3.16 (td, $J = 9.9$, 5.2 Hz, 1H; 6-H), 3.38 (dd, $J = 10.6$, 4.9 Hz, 1H; 2-,3-CH_2), 3.42–3.52 (m, 3H; 2-,3-CH_2), 4.51 (d, $J = 15.6$ Hz, 1H), 4.52 (d, $J = 15.6$ Hz, 1H), 4.87 (d, $J = 15.7$ Hz, 1H) and 4.91 (d, $J = 15.7$ Hz, 1H) (AB systems, CH_2-bipy), 7.60 (d, $J = 7.7$ Hz, 1H) and 7.61 (d, $J = 7.7$ Hz, 1H) (5′-H of 6-bipy and 7-bipy), 7.88 (d, $J = 7.5$ Hz, 2H; 5-H of 6-bipy and 7-bipy), 8.25 (t, $J = 7.9$ Hz, 1H) and 8.25 (t, $J = 7.9$ Hz, 1H) (4′-H of 6-bipy and 7-bipy), 8.47 (t, $J = 7.9$ Hz, 1H) and 8.47 (t, $J = 8.0$ Hz, 1H) (4-H of 6-bipy and 7-bipy), 8.52 (d, $J = 7.7$ Hz, 1H) and 8.53 (d, $J = 7.7$ Hz, 1H) (3′-H of 6-bipy and 7-bipy), 8.62 (d, $J = 8.1$ Hz, 1H) and 8.63 (d, $J = 8.2$ Hz, 1H) (3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 23.7$ and 23.8 (CH_3), 25.0 (C-1 or C-4), 29.0 (C-8), 29.8 (C-10a), 30.0 (C-9a), 30.4 (C-4a), 30.8 (C-1 or C-4), 31.3 (C-10), 33.2 (C-5), 33.7 (C-8a), 34.6 (C-9), 38.6 and 38.7 (C-2,3), 65.7, 67.1, 67.1, and 67.4 (CH_2), 77.5 (C-6), 81.0 (C-7), 122.5 (C-3′ of 6-bipy and 7-bipy), 124.3 and 124.3 (C-3 of 6-bipy and 7-bipy), 128.3 and 128.6 (C-5 of 6-bipy and 7-bipy), 130.5 and 130.5 (C-5′ of 6-bipy and 7-bipy), 143.8 and 143.8 (C-4′ of 6-bipy and 7-bipy), 145.1 and 145.3 (C-4 of 6-bipy and 7-bipy), 149.1, 150.1, 150.2, 156.9, 157.0, 161.7, and 161.7 (C-2,2′,6,6′ of 6-bipy and 7-bipy); FAB-MS: *m*/*z* calcd for [**16**-Zn-OTf]$^+$ 863; found 863 (isotope pattern for one zinc).

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-3-hydroxyprop-1-en-1-yl]-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene zinc bis(triflate) complex (19)**

NMR titration: Incremental amounts (0 → 1.1 equiv.) of $Zn(OTf)_2$ solution ($CDCl_3/CD_3CN$, 1:1; $c = 0.4$ mol L^{-1}) were added to a solution of the ligand **18** (14 mg, 20 μmol) in $CDCl_3/CD_3CN$ (1:1, 0.7 mL) and NMR spectra were recorded after each addition. Removal of the solvent left complex **19** as a colorless oil. IR (neat): $\tilde{\nu} = 3451$, 2913, 2857, 1643, 1601, 1575, 1440, 1261, 1229, 1176, 1033, 788, 642, 519 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3/CD_3CN$, 1:1): $\delta = 1.05-1.34$ (m, 8H), 1.59–2.11 (m, 16H) (1,2,3,4,4a,5,8,8a,9,9a, 10,10a-H, CH_3-bipy), 2.51–2.62 (m, 2H; OH), 3.01 (ddd, $J = 10.3$, 9.6, 4.0 Hz, 1H), 3.09 (td, $J = 9.6$, 5.4 Hz, 1H) (6,7-H), 3.90–3.96 (m, 4H; CH_2O), 4.46 (d, $J = 15.7$ Hz, 1H), 4.47 (d, $J = 15.7$ Hz, 1H), 4.83 (d, $J = 15.7$ Hz, 1H), 4.87 (d, $J = 15.7$ Hz, 1H) (AB systems, CH_2-bipy), 5.43–5.52 (m, 2H) and 5.57–5.67 (m, 2H) (C=CH), 7.58 (d, $J = 7.7$ Hz, 1H) and 7.59 (d, $J = 7.7$ Hz, 1H) (5′-H of 6-bipy and 7-bipy), 7.88 (d, $J = 7.5$ Hz, 2H; 5-H of 6-bipy and 7-bipy), 8.24 (t, $J = 7.9$ Hz, 1H) and 8.25 (t, $J = 7.9$ Hz, 1H) (4′-H of 6-bipy and 7-bipy), 8.46 (t, $J = 7.9$ Hz, 1H) and 8.47 (t, $J = 7.9$ Hz, 1H) (4-H of 6-bipy and 7-bipy), 8.52 (d, $J = 7.8$ Hz, 1H) and 8.53 (d, $J = 7.8$ Hz, 1H) (3′-H of 6-bipy and 7-bipy), 8.61 (d, $J = 7.8$ Hz, 1H) and 8.62 (d, $J = 7.8$ Hz, 1H) (3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, CD_3CN): $\delta = 23.7$ (CH_3), 28.0, 29.0, 29.1, 29.8, 29.9, 30.4, 31.4, 32.0, 32.1, 33.8 (C-1,4,4a,5,8,8a,9,9a,10,10a), 40.1 and 40.6 (C-2,3), 63.4 and 63.4 (2-,3-CH_2) 67.1 and 67.1 (CH_2-bipy), 77.5 (C-6), 80.8 (C-7), 122.5 (C-3′ of 6-bipy and 7-bipy), 124.2 and 124.3 (C-3 of 6-bipy and 7-bipy), 128.3 and 128.6 (C-5 of 6-bipy and 7-bipy), 130.5 and 130.5 (C-5′ of 6-bipy and 7-bipy), 143.8 and 143.8 (C-4′ of 6-bipy and 7-bipy), 145.1 and 145.2 (C-4 of 6-bipy and 7-bipy), 149.1, 150.0, 150.2, 156.9, 157.0, 161.7, and 161.7 (C-2,2′,6,6′ of 6-bipy and 7-bipy); UV/Vis (MeCN/$CHCl_3$, 1:1): λ_{max} (ε) = 311 (38106), 323 nm (35599); FAB-MS: *m*/*z* calcd for [**18**-Zn-OTf]$^+$ 915; found 915 (isotope pattern for one zinc).

1,4-Bis[1′-oxa-2′-oxo-3′-(pyren-1-yl)-prop-1′-yl]butane (25): Butane-1,4-diol (50 mg, 555 μmol) was dissolved in CH_2Cl_2 (10 mL). At 0 °C, a solution of pyren-1-yl acetic acid (318 mg, 1.22 mmol), DMAP (542 mg, 4.44 mmol), and EDC (425 mg, 2.22 mmol) in CH_2Cl_2 (10 mL) was added. The resulting mixture was stirred for 3 h at 0 °C, and then saturated NH_4Cl solution (10 mL) was added. The aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL), and the combined organic layers were washed with saturated NaCl solution (15 mL) and dried with Na_2SO_4. After concentration in vacuo, the residue was purified by column chromatography on silica gel (10 g, PE/AcOEt, 4:1) to give diester **25** (223 mg, 389 μmol, 70%) as a yellow solid. M.p. 128 °C ($CHCl_3$); $R_f = 0.22$ (PE/AcOEt, 4:1); IR (KBr): $\tilde{\nu} = 3042$, 2963, 1723 (C=O), 1602, 1464, 1236, 1136, 839, 740 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.47-1.49$ (m, 4H; 2,3-H), 3.97–4.00 (m, 4H; 1,4-H), 4.23 (s, 4H; 3′-H), 7.86 (d, $J = 7.8$ Hz, 2H), 7.95–8.19 (m, 16H; Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 25.0$ (C-2,3), 39.4 (C-1,4), 64.3 (C-3′), 123.1, 124.6, 124.8, 124.9, 125.0, 125.2, 125.9, 127.2, 127.3, 127.8, 128.0, 128.2, 129.3, 130.7, 131.2 (C-Ar), 171.4 (C-3′); elemental analysis calcd (%) for $C_{40}H_{30}O_4$ (574.66): C 83.60, H 5.26; found C 83.84, H 5.39.

(1*R,2*R**)-1,2-Bis[2′-oxa-3′-oxo-4′-(pyren-1-yl)but-1′-yl]cyclohexane (26)**: Diol **32** (50 mg, 347 μmol) was dissolved in CH_2Cl_2 (5 mL). At 0 °C, a solution of pyren-1-yl acetic acid (199 mg, 763 μmol), DMAP (254 mg, 2.08 mmol), and EDC (266 mg, 1.39 mmol) in CH_2Cl_2 (15 mL) was added. The resulting mixture was stirred for 3 h at 0 °C and then saturated NH_4Cl solution (10 mL) was added. The aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL), and the combined organic layers were washed with saturated NaCl solution (15 mL) and dried with Na_2SO_4. After concentration in vacuo, the residue was purified by column chromatography on silica gel (10 g; PE/AcOEt, 4:1) to give diester **26** (164 mg, 260 μmol, 75%) as a yellow solid. M.p. 120 °C ($CHCl_3$); $R_f = 0.36$ (PE/AcOEt, 4:1); IR (KBr): $\tilde{\nu} = 2928$ (CH), 1730 (C=O), 1603, 1447, 1263, 1146, 981, 845, 736 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.77-0.85$ (m, 4H; 3,4,5,6-H), 1.16–1.22 (m, 2H; 1,2-H), 1.37–1.44 (m, 4H; 3,4,5,6-H), 3.86–3.92 (m, 4H; 1′-H), 4.19 (s, 4H; 4′-H), 7.84 (d, $J = 7.5$ Hz, 2H), 7.94–8.18 (m, 16H; Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 25.2$ (C-4,5), 29.2 (C-3,6), 38.6 (C-1,2), 39.4 (C-4′), 67.5 (C-1′), 123.3, 124.6, 124.8, 124.9, 125.0, 125.2, 125.9, 127.2, 127.3, 127.8, 128.2, 128.3, 129.3, 130.7, 131.2 (C-Ar), 171.4 (C-3′); HRMS: *m*/*z* calcd for ($C_{44}H_{36}O_4$) $[M]^+$ 628.2614; found 628.2618.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[2″-oxa-3″-oxo-4″-(pyren-1-yl)but-1″-yl]-6,7-*O*-(2′,3′-dimethoxybutan-2′,3′-diyl)perhydroanthracene-6,7-diol (27)**: Diol **8** (25 mg, 63 μmol) was dissolved in CH_2Cl_2 (2 mL). At 0 °C, a solution of pyren-1-yl acetic acid (163 mg, 627 μmol), DMAP (115 mg, 940 μmol), and EDC (120 mg, 626 μmol) in CH_2Cl_2 (3 mL) was added. The resulting mixture was stirred for 2 h at 0 °C. Saturated NH_4Cl solution (5 mL) was then added. After separation of the layers, the aqueous layer was extracted with CH_2Cl_2 (3 × 5 mL), and the combined organic layers were washed with saturated NaCl solution and dried with Na_2SO_4. After concentration in vacuo, the residue was purified by column chromatography on silica gel (5 g; PE/AcOEt, 4:1) to give diester **27** (49 mg, 55 μmol, 88%) as a yellow solid. M.p. 140 °C ($CHCl_3$); $R_f = 0.18$ (PE/AcOEt, 4:1); IR (KBr): $\tilde{\nu} = 2931$ (CH), 1726 (C=O), 1639, 1126, 1043, 845, 754 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 0.42-0.78$ (m, 3H), 1.00–1.65 (m, 15H) (1,2,3,4,4a,5,8,8a,9,9a,10,10a-H), 1.28 (s, 6H; 1′,4′-H), 3.22 (s, 3H; OCH_3), 3.25 (s, 3H; OCH_3), 3.28–3.35 (m, 1H; 7-H), 3.42–3.50 (m, 1H; 6-H), 3.72–3.81 (m, 1H; 1″-H), 3.86–3.99 (m, 3H; 1″-H), 4.16 (s, 4H; 4″-H), 7.78–8.19 (m, 18H; Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 17.9$ (C-1′,4′), 24.1, 25.5, 28.8, 29.1, 29.2, 31.9, 34.1, 34.2, 34.3, 34.5 (C-1,2,3,4,4a,5,8,8a,9,9a,10,10a), 39.6 (C-4″), 47.7 (OCH_3), 47.8 (OCH_3), 66.4 (3-CH_2), 67.2 (C-6), 67.9 (2-CH_2), 72.0 (C-7), 99.3, 99.4 (C-2′,3′), 123.2,

124.6, 124.7, 124.9, 125.0, 125.2, 125.3, 125.9, 127.2, 127.3, 127.8, 128.1, 128.3, 129.3, 130.7, 131.2 (C-Ar), 171.3 (C-3″), 171.4 (C-3‴); HRMS ($C_{58}H_{58}O_8$): m/z calcd for $[M]^+$ 882.4132; found 882.4139.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-4″-oxa-5″-oxo-6″-(pyren-1-yl)hex-1″-en-1″-yl]-6,7-*O*-(2′,3′-dimethoxybutan-2′,3′-diyl)perhydroanthracene-6,7-diol (28)**: Diol **31** (8.5 mg, 19 μmol) was dissolved in CH_2Cl_2 (2 mL). At room temperature, a solution of pyrene acetic acid (49 mg, 188 μmol), DMAP (34 mg, 283 μmol), and EDC (36 mg, 188 μmol) in CH_2Cl_2 (3 mL) was added. The resulting mixture was stirred for 2 h at room temperature and then saturated NH_4Cl solution (5 mL) was added. After separation of the layers, the aqueous layer was extracted with CH_2Cl_2 (3×5 mL), and the combined organic layers were washed with saturated NaCl solution (5 mL) and dried with Na_2SO_4. After concentration in vacuo, the residue was purified by column chromatography on silica gel (5 g; PE/AcOEt, 4:1) to give diester **28** (12.4 mg, 13.3 μmol, 70 %) as a yellow glassy oil. $R_f = 0.14$ (PE/AcOEt, 4:1); IR (neat): $\tilde{\nu} = 2925, 1732, 1648, 1442, 1378, 1262, 1126, 1043, 969, 846, 736\ cm^{-1}$; ^1H NMR (300 MHz, $CDCl_3$): $\delta =$ 0.50 – 0.72 (m, 1H), 0.73 – 1.99 (m, 17H) (1,2,3,4,4a,5,8,8a,9,9a,10,10a-H), 1.27 (s, 6H; 1′,4′-H), 3.27 (s, 3H; OCH_3), 3.28 (s, 3H; OCH_3), 3.42 – 3.53 (m, 1H; 7-H), 3.59 – 3.70 (m, 1H; 6-H), 4.32 (s, 2H; 6″-H), 4.33 (s, 2H; 6‴-H), 4.47 – 4.51 (m, 4H; 3″-H), 5.22 – 5.29 (m, 2H; 2″-H), 5.35 – 5.40 (m, 2H; 1″-H), 7.89 – 8.27 (m, 18H; Ar-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 17.9$, 18.0 (C-1′,4′), 25.5, 29.3, 29.4, 29.7, 31.9, 32.8, 33.5, 34.1, 34.2, 34.7, 34.8, 39.6 (C-1,2,3,4,4a,5,8,8a,9,9a,10,10a), 39.7 (C-6″), 39.8 (C-6‴), 47.7 (OCH_3), 47.8 (OCH_3), 65.1 (C-3″), 65.4 (C-3‴), 67.5 (C-6), 72.1 (C-7), 99.4, 99.6 (C-2′,3′), 121.7 (C-2″), 122.7, 123.3, 124.8, 125.1, 125.3, 125.4, 126.0, 126.1, 127.3, 127.9, 128.3, 128.4, 129.4 (C-Ar), 138.5 (C-1″), 171.1 (C-5″), 171.2 (C-5‴); HRMS ($C_{62}H_{62}O_8$): m/z calcd for $[M + Na]^+$ 957.4342; found 957.4358.

***trans*-1,2-Bis[(*E*)-4′-oxa-5′-oxo-6′-(pyren-1-yl)hex-1′-en-1′-yl]cyclohexane (29)**

Swern oxidation: In a Schlenk flask, oxalyl chloride (45.0 μL, 0.52 mmol) was dissolved in CH_2Cl_2 (0.5 mL) and the solution was cooled to $-78\,^\circ C$. DMSO (66.0 μL, 0.94 mmol) in CH_2Cl_2 (0.5 mL) was then added dropwise. The temperature of the cooling bath was allowed to rise to $-50\,^\circ C$ over a period of 20 min. After cooling to $-78\,^\circ C$ once more, a solution of the diol **32** (25 mg, 173 μmol) in CH_2Cl_2 (1 mL) was added. Again, the temperature of the cooling bath was allowed to reach $-50\,^\circ C$. EtN*i*Pr$_2$ (0.42 mL, 2.43 mmol) was then added at $-78\,^\circ C$. The temperature was allowed to rise to $-50\,^\circ C$ once more (30 min) and thereafter the reaction mixture was kept for 10 min at $0\,^\circ C$. The reaction was quenched by the addition of saturated aqueous $NaHCO_3$ solution (5 mL). After separation of the phases, the aqueous layer was extracted with dichloromethane (5×5 mL). The combined organic layers were washed with brine (20 mL) and dried with Na_2SO_4. The solvent was removed in vacuo. The aldehyde was used in the next step without further purification.

Wittig reaction: The aldehyde and $Ph_3P{=}CHCOOEt$ (482 mg, 1.38 mmol) were dissolved in toluene (3 mL) and the mixture was heated for 15 h at $100\,^\circ C$. The reaction was then quenched by the addition of saturated aqueous $NaHCO_3$ solution (5 mL) and $CHCl_3$ (5 mL). The phases were separated, and the aqueous layer was extracted with $CHCl_3$ (3×5 mL). The combined organic phases were washed with saturated NaCl solution and dried with $MgSO_4$. The solvent was removed in vacuo, and the residue was purified by flash chromatography on silica (7 g; PE/AcOEt, 1:1) to furnish the ester (47 mg, 168 μmol) in 97 % yield over the two steps as a colorless oil. $R_f = 0.42$ (hexane/AcOEt, 1:1); ^1H NMR (300 MHz, $CDCl_3$): $\delta =$ 1.06 – 1.35 (m, 10H), 1.62 – 1.80 (m, 4H), 1.94 – 2.08 (m, 2H) (CH_3, 1,2,3,4,5,6-H and H_2), 4.10 (q, $J = 7.2$ Hz, 4H; CH_2O), 5.69 (d, $J = 15.6$ Hz, 2H; 2′,2″-H), 6.69 (dd, $J = 15.7$, 8.2 Hz, 2H; 1′,1″-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta =$ 14.2 (CH_3), 25.1 (C-5,4), 31.7 (C-3,6), 45.0 (C-1,2), 60.2 (CO), 121.1 (C-2′,2″), 151.6 (C-1′,1″), 166.6 (C=O).

Reduction: The ester (95 mg, 121 μmol) was dissolved in CH_2Cl_2 (1 mL), and this solution was cooled to $-78\,^\circ C$. DIBAH (1 M in CH_2Cl_2, 0.71 mL, 0.71 mmol) was then added dropwise. The temperature of the cooling bath was allowed to reach $0\,^\circ C$ over a period of 6 h. Thereafter, the reaction was quenched by the addition of a solution of Rochelle's salt (5 mL, 1 M in water). Stirring was continued overnight in order to destroy the aluminum complex of the product. After separation of the phases, the aqueous layer was extracted with CH_2Cl_2 (5×3 mL). The combined organic layers were washed with saturated NaCl solution (5 mL) and dried with $MgSO_4$. After removal of the solvent in vacuo and column chromatography of the residue on silica (5 g; $CHCl_3$/MeOH, 95:5) the diol (12 mg, 56 μmol, 35 %) was obtained as a colorless oil. $R_f = 0.16$ ($CHCl_3$/MeOH, 95:5); ^1H NMR (300 MHz, $CDCl_3$): $\delta =$ 1.01 – 1.36 (m, 4H; 3,4,5,6-H_{ax}), 1.59 – 1.87 (m, 6H; 1,2-H, 3,4,5,6-H_{eq}), 2.14 (brs, 2H; OH), 3.92 – 4.12 (m, 4H; CH_2O), 5.34 – 5.64 (m, 4H; HC=C); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 26.1$ (C-4,5), 33.1 (C-3,6), 46.2 (C-1,2), 64.2 (CH_2O), 128.8 (C-2′,2″), 138.3 (C-1′,1″).

The diol (11 mg, 56 μmol) was dissolved in CH_2Cl_2 (2 mL). DMAP (55 mg, 0.45 mmol), EDC (86 mg, 0.45 mmol), and pyren-1-yl acetic acid (117 mg, 0.45 mmol) were added. After 3 h at room temperature, the solvent was removed in vacuo. The residue was purified by column chromatography on silica (3×6 g, PE/AcOEt, 2:1) to yield the yellowish glassy ester **29** (20 mg, 29 μmol, 53 %), $R_f = 0.39$ (hexane/AcOEt); HPLC: $t_R = 10.1$ min (Rainin Si 60, 7 % B, hexane/AcOEt, 1 mL min^{-1}); ^1H NMR (300 MHz, $CDCl_3$): $\delta =$ 0.67 – 1.60 (m, 10H; 1,2,3,4,5,6-H and H_2), 4.22 – 4.31 (m, 4H; CH_2-pyr), 4.32 – 4.49 (m, 4H; CH_2O), 5.10 – 5.22 (m, 4H; HC=C), 7.80 – 8.26 (m, 18H; pyr-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 25.4$ (C-4,5), 32.2 (C-3,6), 39.6 (CH_2-pyr), 45.1 (C-1,2), 65.4 (CH_2O), 122.7, 123.3, 124.8, 125.0, 125.2, 125.9, 127.2, 127.3, 127.8, 128.2, 128.3, 130.7, 131.3, 139.7 (pyr), 171.2 (C=O); HRMS ($C_{48}H_{40}O_4$): m/z calcd for $[M]^+$ 680.2927; found 680.2927.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-4″-oxa-3‴-oxo-hex-1″-en-1″-yl]-6,7-*O*-(2′,3′-dimethoxybutan-2′,3′-diyl)perhydroanthracene-6,7-diol (30)**

Swern oxidation: Oxalyl chloride (0.04 mL, 492 μmol) was dissolved in CH_2Cl_2 (5 mL), and the solution was cooled to $-78\,^\circ C$. DMSO (0.07 mL, 984 μmol) was then added, followed, after stirring for 10 min, by a solution of diol **8** (49 mg, 123 μmol) in CH_2Cl_2 (5 mL). The resulting mixture was stirred for a further 15 min and then Et_3N (0.27 mL, 1.97 mmol) was added. The reaction mixture was allowed to warm to $0\,^\circ C$ and stirred for 30 min. The reaction was then quenched with H_2O (10 mL). After separation of the phases, the aqueous layer was extracted with CH_2Cl_2 (3×10 mL). The combined organic layers were washed with saturated NaCl solution (20 mL) and dried with Na_2SO_4. After evaporation of the solvent, the residual crude aldehyde was subjected to the Wittig reaction without further purification. $R_f = 0.69$ (SiO_2, $CHCl_3$/MeOH, 20:1); ^1H NMR (300 MHz, $CDCl_3$): $\delta =$ 1.10 – 2.15 (m, 18H; 1,2,3,4,4a,5,8,8a,9,9a,10,10a-H), 1.15 and 1.16 (s, 3H; 1′,4′-H), 3.11 (s, 3H; OCH_3), 3.13 (s, 3H; OCH_3), 3.32 – 3.42 (m, 1H; 7-H), 3.48 – 3.59 (m, 1H; 6-H), 9.61 (d, $J = 9.2$ Hz, 2H; 1″-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 17.3$ (C-1′,4′), 25.5, 27.3, 27.9, 28.5, 28.9, 29.3, 31.6, 31.7, 34.1, 34.2, 34.7, 39.2 (C-1,2,3,4,4a,5,8,8a,9,9a,10,10a), 47.1 ($2 \times OCH_3$), 66.7 (C-6), 71.3 (C-7), 98.7, 98.8 (C-2′,3′), 203.4 (C-1″).

Wittig reaction: The crude bis-aldehyde was dissolved in CH_2Cl_2 (5 mL), and ethoxycarbonylmethylene triphenylphosphorane (257 mg, 738 μmol) was added. The mixture was stirred for 14 h at room temperature. The solvent was then removed in vacuo and the residue was purified by column chromatography on silica gel (10 g; PE/Et_2O, 1:1) to yield diester **30** (48 mg, 90 μmol, 73 %) as a colorless oil. $R_f = 0.21$ (SiO_2; PE/Et_2O, 1:1); IR (neat): $\tilde{\nu} = 2931$ (CH), 1718 (C=O), 1648, 1448, 1369, 1266, 1177, 1124, 1041, 732 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$): $\delta =$ 1.15 – 2.10 (m, 16H; 1,4,4a,5,8,8a,9,9a,10,10a-H), 1.27 (s, 6H; 1′,4′-H), 1.28 (t, $J = 7.1$ Hz, 6H; $2 \times CH_3CH_2$), 2.48 (brs, 1H; 3-H), 2.68 (brs, 1H; 2-H), 3.23 (s, 6H; $2 \times OCH_3$), 3.44 – 3.58 (m, 1H; 7-H), 3.61 – 3.75 (m, 1H; 6-H), 4.15 (q, $J =$ 7.2 Hz, 2H; CH_3CH_2), 4.20 (s, 2H; CH_3CH_2), 5.80 (d, $J = 15.8$ Hz, 1H; 2″-H), 5.83 (d, $J = 15.8$ Hz, 1H; 2‴-H), 6.96 – 7.11 (m, 2H; 1‴-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 14.2$ ($2 \times$ C-6″), 17.9 (C-1′,4′), 24.5, 29.7, 29.8, 31.8, 32.8, 33.5 (C-1,4,5,8,9,10), 29.5, 30.0, 30.1, 35.1 (C-4a,8a,9a,10a), 39.0, 39.1 (C-2,3), 47.8 ($2 \times OCH_3$), 60.3, 60.4 (C-6″), 67.4 (C-6), 72.0 (C-7), 99.4, 99.5 (C-2′,3′), 119.8, 121.3 (C-1″), 151.6, 153.5 (C-2″), 166.7 (C-3‴); HRMS ($C_{29}H_{43}O_7$): m/z calcd for $[M - OCH_3]^+$ 503.3008; found 503.3001.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-3″-hydroxyprop-1″-en-1″-yl]-6,7-*O*-(2′,3′-dimethoxybutan-2′,3′-diyl)perhydroanthracene-6,7-diol (31)**: Diester **30** (14 mg, 26 μmol) was dissolved in CH_2Cl_2 (2 mL). At $-78\,^\circ C$, a solution of DIBAH (0.3 mL, 300 μmol) in hexane was added. The mixture was then allowed to warm to $0\,^\circ C$ over a period of 4 h. After the addition of saturated NH_4Cl solution (5 mL), the aqueous layer was extracted with CH_2Cl_2 (3×5 mL). The combined organic layers were washed with saturated NaCl solution (5 mL) and dried with Na_2SO_4. Evaporation of the solvent in vacuo and purification of the residue by column chromatography on silica gel (1 g; PE/AcOEt, 1:1) afforded diol **31** (7.5 mg, 17 μmol, 64 %) as a colorless oil. $R_f = 0.11$ (SiO_2; PE/AcOEt, 1:1); IR (neat): $\tilde{\nu} = 3413$ (OH), 2915 (CH), 1665, 1443, 1375, 1218, 1122, 1040,

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971, 845 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta = 1.10-2.02$ (m, 18H), 2.15–2.22 (m, 1H), 2.31–2.41 (m, 1H) (1,2,3,4,4a,5,8,8a,9,9a,10,10a-H, OH), 3.23 (s, 3H; OCH_3), 3.24 (s, 3H; OCH_3), 3.46–3.58 (m, 1H; 7-H), 3.62–3.74 (m, 1H; 6-H), 4.04–4.13 (m, 4H; 3″-H), 5.53–5.64 (m, 2H; 2″-H), 5.65–5.79 (m, 2H; 1″-H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 17.9$ (C-1′,4′), 24.9, 29.7, 30.1, 30.4, 31.2, 32.3, 33.4, 34.1, 34.2, 34.8, 40.0, 41.5 (C-1,2,3,4,4a,5,8,8a,9,9a,10,10a), 47.8 (OCH_3), 63.8, 63.9 (C-3″), 67.5 (C-6), 72.2 (C-7), 99.4, 99.5 (C-2′,3′), 127.3, 128.4 (C-2″), 136.9, 138.7 (C-1″); HRMS ($C_{25}H_{39}O_5$): m/z calcd for $[M - OCH_3]^+$ 419.2797; found 419.2793.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-4′-oxa-5′-oxo-6′-(pyren-1-yl)hex-1′-en-1′-yl]-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]perhydroanthracene (33)**: The diol **15** (35 mg, 50 μmol) was dissolved in CH_2Cl_2 (1.5 mL). DMAP (92 mg, 0.75 mmol), EDC (96 mg, 0.50 mmol), and pyren-1-yl acetic acid (130 mg, 0.50 mmol) were then added. After 2 h at 20 °C, the reaction was quenched by the addition of saturated aqueous $NaHCO_3$ solution (5 mL) and CH_2Cl_2 (5 mL). After separation of the phases, the aqueous layer was extracted with CH_2Cl_2 (5 × 5 mL). The combined organic layers were washed with saturated NaCl solution and dried with Na_2SO_4. After removal of the solvent, the residue was purified by column chromatography on silica (25 g; PE/AcOEt, 4:1 → PE/AcOEt/MeOH, 10:10:1) to yield the yellowish glassy ester **33** (56 mg, 47 μmol, 94%), $R_f = 0.25$ (hexane/AcOEt/MeOH); IR (neat): $\tilde{\nu} = 3042$, 2914, 2856, 1731, 1574, 1440, 1251, 1162, 1149, 1131, 1116, 1099, 1080, 967, 845, 785, 756, 712, 667, 635 cm^{-1}; ^{1}H NMR (600 MHz, $CDCl_3$): $\delta = 0.85$ (ddd, $J = 12.9$, 2.2, 1.0 Hz, 1H; 5β-H), 0.93 (dddd, $J = 13.1$, 3.5, 3.2, $J = 0.4$ Hz, 1H; 1α-H), 1.03 (ddd, $J = 12.8$, 9.9, 4.2 Hz, 1H; 4α-H), 1.11 (dddd, $J = 13.4$, 2.8, 2.0, 0.8 Hz, 1H; 9β-H) 1.16 (dddd, $J = 13.1$, 3.0, 2.7, 0.9 Hz, 1H; 4β-H), 1.20 (q, $J = 12.4$ Hz, 1H; 1β-H), 1.36 (dddddd, $J = 12.9$, 12.0, 7.5, 3.6, 2.1, 1.0 Hz, 1H; 2-H), 1.45 (br d, $J = 11.0$ Hz, 1H; 9a-H), 1.47–1.56 (m, 3H; 3,5α,10β-H), 1.60–1.76 (m, 2H; 8a,10a-H), 1.72 (d, $J = 14.6$ Hz, 1H; 8α-H), 1.94 (ddd, $J = 14.2$, 4.9, 3.4 Hz, 1H; 8β-H), 2.08–2.18 (m, 2H; 4a,10α-H), 2.28 (br s, 1H; 9α-H), 2.63 (s, 6H; CH_3), 3.78 (td, $J = 2.8$, 2.4 Hz, 1H; 7-H), 3.91 (br s, 1H; 6-H), 4.29–4.31 (m, 4H; CH_2-pyr), 4.39–4.46 (m, 4H; CH_2-bipy), 4.68 (d, $J = 13.6$ Hz, 1H), 4.73 (d, $J = 13.6$ Hz, 1H), 4.80 (d, $J = 13.6$ Hz, 1H), 4.83 (d, $J = 13.6$ Hz, 1H) (AB systems, CH_2OOC), 5.09–5.22 (m, 4H; C=CH), 7.15 (d, $J = 7.5$ Hz, 2H; 5′-H of 6-bipy and 7-bipy), 7.45 (d, $J = 7.6$ Hz, 1H) and 7.51 (d, $J = 7.6$ Hz) (5-H of 6-bipy and 7-bipy), 7.67 (t, $J = 7.7$ Hz, 1H) and 7.67 (t, $J = 7.7$ Hz, 1H) (4′-H of 6-bipy and 7-bipy), 7.81 (t, $J = 7.7$ Hz, 1H) and 7.82 (t, $J = 7.6$ Hz, 1H) (4-H of 6-bipy and 7-bipy), 7.90 (d, $J = 7.6$ Hz, 1H; pyr-H), 7.90 (d, $J = 7.9$ Hz, 1H; pyr-H), 7.93–7.99 (m, 6H; pyr-H), 8.06–8.14 (m, 8H; pyr-H), 8.16 (d, $J = 7.5$ Hz, 1H) and 8.17 (d, $J = 7.5$ Hz, 1H) (3′-H of 6-bipy and 7-bipy), 8.22 (d, $J = 9.1$ Hz, 2H; pyr-H), 8.28 (d, $J = 7.7$ Hz, 1H) and 8.29 (d, $J = 7.7$ Hz, 1H) (3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta = 24.7$ (CH_3), 25.6 (C-10), 28.2 (C-10a), 28.9 (C-8a), 29.2 (C-4a), 29.8 (C-8), 31.2 and 31.2 (C-1,5), 32.8 (C-9), 35.3 (C-9a), 37.6 (br., C-4), 39.2 (C-3), 39.6 and 39.6 (CH_2-pyr), 45.5 (C-2), 65.2 and 65.4 (CH_2OOC), 71.7 and 71.9 (CH_2-bipy), 75.7 (C-7), 75.8 (C-6), 118.1 (C-3′ of 6-bipy and 7-bipy), 119.6 and 119.6 (C-3 of 6-bipy and 7-bipy), 120.6 and 120.8 (C-5 of 6-bipy and 7-bipy), 122.6 and 122.8 (C=C), 123.2 (C-5′ of 6-bipy and 7-bipy), 123.3, 124.7, 124.8, 125.0, 125.2, 125.2, 125.9, 127.2, 127.3, 127.3, 127.8, 127.8, 128.4, 129.4, and 131.3 (C-pyr), 137.0 and 137.0 (C-4′ of 6-bipy and 7-bipy), 137.3 and 137.4 (C-4 of 6-bipy and 7-bipy), 139.2 and 139.8 (C=C), 155.7, 155.7, 157.9, and 158.7 (C-2,2′,6,6′ of 6-bipy and 7-bipy), 171.2 and 171.2 (COO); HRMS ($C_{80}H_{72}N_4O_6$): m/z calcd for $[M]^+$ 1184.5452; found 1184.5433.

(2*R,3*R**,4a*R**,6*R**,7*R**,8a*S**,9a*S**,10a*R**)-2,3-Bis[(*E*)-4′-oxa-5′-oxo-6′-(pyren-1-yl)hex-1′-en-1′-yl]-6,7-bis[6′-methyl-(2,2′)bipyridin-6-yloxymethyl]-perhydroanthracene zinc bis(triflate) complex (35)**: A solution of $Zn(OTf)_2$ (7.4 mg, 20.3 μmol) in CD_3CN (0.7 mL) was added to the diester **34** (24 mg, 20.3 μmol). The mixture was heated for 2 min at 50 °C and subsequently analysed by NMR spectroscopy. Removal of the solvent left a quantitative yield of complex **35** as a yellowish glassy oil. IR (neat): $\tilde{\nu} = 3039$, 2909, 2859, 1727, 1601, 1575, 1441, 1251, 1162, 1031, 966, 848, 790, 713, 638, 518 cm^{-1}; ^{1}H NMR (600 MHz, CD_{3CN}): $\delta = 0.03$ (br d, $J = 13.4$ Hz, 1H; 4α-H), 0.15 (br s, 1H; 9a-H), 0.25 (br d, $J = 11.2$ Hz, 1H; 10β-H), 0.30–0.42 (m, 4H; 1,4a,9α,10α-H), 0.60 (dt, $J = 14.2$, 5.6 Hz, 1H; 1-H), 0.63 (q, $J = 12.3$ Hz, 1H; 8α-H), 0.74 (ddd, $J = 13.2$, 10.5, 4.5 Hz, 1H; 5β-H), 0.83 (ddd, $J = 14.0$, 11.8, 4.9 Hz, 1H; 4β-H), 0.93–1.06 (m, 2H; 10a,8a-H), 0.99 (td, $J = 12.8$, 4.8 Hz, 1H; 9β-H), 1.30 (br s, 1H; 2-H), 1.45 (br d, $J = 10.9$ Hz, 1H; 8β-H), 1.51 (br s, 1H; 3-H), 1.57 (dt, $J = 12.8$, 4.0 Hz, 1H; 5α-H), 1.86 (s, 3H; CH_3), 1.87 (s, 3H; CH_3), 2.81 (ddd, $J = 11.0$, 9.6, 4.4 Hz, 1H; 7-H), 2.89 (ddd, $J = 10.3$, 9.6, 5.1 Hz, 1H; 6-H), 4.28 (d, $J = 24.6$ Hz, 2H; CH_2-pyr), 4.29 (d, $J = 22.5$ Hz, 2H; CH_2-pyr), 4.37 (d, $J = 4.5$ Hz, 1H), 4.42 (d, $J = 4.5$ Hz, 1H) (CH_2OOC), 4.52 (d, $J = 15.2$ Hz, 1H), 4.63 (d, $J = 15.8$ Hz, 1H), 4.78 (d, $J = 16.0$ Hz, 1H), 4.87 (d, $J = 15.7$ Hz, 1H) (AB systems, CH_2-bipy), 4.87–5.09 (m, 4H; C=CH), 7.62 (d, $J = 7.9$ Hz, 1H), 7.64 (d, $J = 7.7$ Hz, 1H) (5′-H of 6-bipy and 7-bipy), 7.69–8.24 (m, 20H; 5-H of 6-bipy and 7-bipy and pyr-H), 8.26 (t, $J = 8.0$ Hz, 1H), 8.26 (t, $J = 7.9$ Hz) (4′-H of 6-bipy and 7-bipy), 8.47 (t, $J = 8.0$ Hz, 1H; 4-H of 6-bipy or 7-bipy), 8.23 (d, $J = 8.5$ Hz, 1H), 8.54 (d, $J = 8.5$ Hz, 1H), (3′-H of 6-bipy and 7-bipy), 8.60 (t, $J = 8.0$ Hz, 1H; 4-H of 6-bipy or 7-bipy), 8.62 (d, $J = 8.1$ Hz, 1H), 8.69 (d, $J = 8.2$ Hz, 1H) (3-H of 6-bipy and 7-bipy); ^{13}C NMR (75 MHz, CD_{3CN}): $\delta = 23.6$ (CH_3), 27.8 (C-4), 28.3 (C-8), 29.0 (C-10a), 29.2 (C-9a), 29.3 (C-4a), 30.7 (C-10), 32.7 (C-5), 32.8 (C-1), 33.1 (C-9), 33.2 (C-8a), 39.8 (C-3), 40.0 (CH_2-pyr), 40.0 and 40.0 (C-2,3), 64.7 and 65.3 (CH_2OOC), 66.8 and 66.9 (CH_2-bipy), 77.2 (C-6), 80.6 (C-7), 122.3 and 122.4 (C-3′ of 6-bipy and 7-bipy), 122.6 and 123.6 (C=C), 124.1, 124.3, 124.4, 125.1, 125.3, 125.6, 125.7, 125.8, 125.9, 126.1, 126.1, 126.9, 127.0, 127.8, 127.9, 128.1, 128.3, 128.4, 129.4, 129.6, 129.8, 129.9, and 130.0 (C-pyr, C-3,5 of 6-bipy and 7-bipy), 130.3 and 130.5 (C-5′ of 6-bipy and 7-bipy), 131.3, 131.4, 131.4, 131.5, 131.9, 132.0 (C-pyr), 136.8 and 139.9 (C=C), 143.6 (C-4 of 6-bipy and 7-bipy), 145.0 and 145.3 (C-4′ of 6-bipy and 7-bipy), 148.8, 148.9, 149.9, 150.2, 156.8, 157.0, 161.5, and 161.7 (C-2,2′,6,6′ of 6-bipy and 7-bipy), 171.4 and 171.7 (COO); FAB-MS: m/z calcd for [**33**-Zn-OTf]$^+$ 1400; found 1400 (isotope pattern for one zinc).

Fluorescence measurements: Fluorescence spectra were measured on an MPF-2A fluorescence spectrometer (Hitachi–Perkin–Elmer) equipped with a temperature control, correction, and digitalization unit. Argon-flushed (5 min) solutions of the compounds under investigation were placed in quartz cuvettes with a path length of 1 cm and excited in a perpendicular arrangement. The fluorescence quantum yields were determined at 298 K by the relative method using quinine sulfate as a standard ($\varphi_f = 0.545$ in 0.1 N H_2SO_4). At the excitation wavelength (345 nm), the absorbance values of the solutions of the standard and the investigated compounds were identical. The different refractive indices of the solutions were taken into account. Time-resolved fluorescence decay measurements (pulse sampling method) were performed using a nitrogen laser ($\lambda =$ 337 nm) as the excitation source and a transient recorder to monitor the decay. The wavelengths for fluorescence detection were $\lambda = 475$ nm (pyrene excimer) and $\lambda = 380$ nm (pyrene monomer). Details of the equipment and the deconvolution procedure of the experimental decay curve are described in ref. [29]. The time resolution achieved was about 250 ps.

Acknowledgements

This work was supported by the Deutsche Forschungsgemeinschaft, the Fonds der Chemischen Industrie, and the Volkswagenstiftung. Support from the NMR group of Dr. C. Mügge is gratefully acknowledged.

[1] a) J.-M. Lehn, *Supramolecular Chemistry*, VCH, Weinheim, **1995**; b) T. Shimidzu, K. Honda, in *Functionality of Molecular Systems, Vol. 2* (Ed.: K. Honda), Springer, Tokyo, **1999**, pp. 1–4.

[2] a) G. Krauss, *Biochemistry of Signal Transduction and Regulation*, Wiley-VCH, Weinheim, **1999**; b) L. B. Ray, *Science* **1999**, *284*, 755–756.

[3] K. Hinterding, D. Alonso-Díaz, H. Waldmann, *Angew. Chem.* **1998**, *110*, 716–780; *Angew. Chem. Int. Ed.* **1998**, *37*, 688–749.

[4] D. H. R. Barton, *Science* **1970**, *169*, 539–544.

[5] a) J. Berninger, R. Krauss, H.-G. Weinig, U. Koert, B. Ziemer, K. Harms, *Eur. J. Org. Chem.* **1999**, 875–884; b) R. W. Hoffmann, I. Münster, *Liebigs Ann./Recueil* **1997**, 1143–1150; c) A. G. De Oliveira Santos, W. Klute, J. Torode, V. P. W. Böhm, E. Cabrita, J. Runsink, R. W. Hoffmann, *New. J. Chem.* **1998**, 993–997.

[6] For an excellent review on conformational design, see: R. W. Hoffmann, *Angew. Chem.* **2000**, *120*, 2134–2150; *Angew. Chem. Int. Ed.* **2000**, *39*, 2054–2070.

[7] Leading references on conformational switching: a) H. Yuasa, H. Hashimoto, *J. Am. Chem. Soc.* **1999**, *121*, 5089–5090; b) S. E. O'Connor, B. Imperiali, *J. Am. Chem. Soc.* **1997**, *119*, 2295–2296;

c) H. J. Schneider, F. Werner, *J. Chem. Soc. Chem. Commun.* **1992**, 490 – 491; d) V. A. Palyulin, S. V. Emets, V. A. Chertkov, C. Kasper, H.-J. Schneider, *Eur. J. Org. Chem.* **1999**, 3479 – 3482; e) J. N. H. Reek, H. Engelkamp, A. E. Rowan, J. A. A. W. Elemans, R. J. M. Nolte, *Chem. Eur. J.* **1998**, *4*, 716 – 722.

[8] Examples of switching between *cyclo*/*seco* isomers: a) M. Irie, *Chem. Rev.* **2000**, *100*, 1685 – 1716; b) S. H. Kawai, S. L. Gilat, J.-M. Lehn, *J. Chem. Soc. Chem. Commun.* **1994**, 1011 – 1013; *E*/*Z* isomers: c) L. Gobbi, P. Seiler, F. Diederich, *Angew. Chem.* **1999**, *111*, 737 – 740; *Angew. Chem. Int. Ed.* **1999**, *38*, 674 – 678; d) M. Bauer, F. Vögtle, *Chem. Ber.* **1992**, *125*, 1675 – 1686; switchable rotaxanes e) R. A. Bissel, E. Córdova, A. E. Kaifer, J. F. Stoddart, *Nature* **1994**, *369*, 133 – 137; f) P. R. Ashton, V. Balzani, J. Becher, A. Credi, M. C. T. Fyfe, G. Mattersteig, S. Menzer, M. B. Nielsen, F. M. Raymo, J. F. Stoddart, M. Venturi, D. J. Williams, *J. Am. Chem. Soc.* **1999**, *121*, 3951 – 3957.

[9] R. Krauss, H.-G. Weinig, M. Seydack, J. Bendig, U. Koert, *Angew. Chem.* **2000**, *112*, 1905 – 1908; *Angew. Chem. Int. Ed.* **2000**, *39*, 1835 – 1837.

[10] P. Vanhee, B. van de Graaf, D. Tavernier, J. M. A. Baas, *J. Org. Chem.* **1983**, *48*, 648 – 652.

[11] U. Koert, R. Krauss, H.-G. Weinig, C. Heumann, B. Ziemer, C. Mügge, M. Seydack, J. Bendig, *Eur. J. Org. Chem.* **2001**, 575 – 586.

[12] a) M. Raban, D. L. Burch, E. R. Hortelano, D. Durocher, D. Kost, *J. Org. Chem.* **1994**, *59*, 1283 – 1287; b) V. V. Samoshin, O. A. Zelenkina, I. V. Yartseva, N. S. Zefirov, *Zh. Org. Khim.* **1987**, *23*, 2244 – 2245; c) V. V. Samoshin, V. A. Chertkov, L. P. Vaatlina, E. K. Dobretsova, N. A. Simonov, L. P. Katorsky, D. E. Gremyachinsky, H.-J. Schneider, *Tetrahedron Lett.* **1996**, *37*, 3981 – 3984; G. W. Buchanan, K. Bourque, *Tetrahedron Lett.* **1984**, *25*, 3963 – 3966.

[13] E. L. Eliel, S. H. Wilen, L. N. Mander, *Stereochemistry of Organic Compounds*, Wiley, New York, **1994**, p. 686 ff.

[14] All perhydroanthracene derivatives were prepared in the racemic series.

[15] The assignments of the ^{1}H and ^{13}C NMR signals of all perhydroanthracene derivatives were based on two-dimensional correlation spectroscopy. The assigned spectra are given in the Experimental Section.

[16] In order to shift the >99:1 equilibrium ($\Delta G^{0} = 3$ kcal mol^{-1}) to >1:99, an energy input for the conformational switch of $3+3=6$ kcal mol^{-1} can be estimated.

[17] a) S. V. Ley, H. W. M. Priepke, S. L. Warriner, *Angew. Chem.* **1994**, *106*, 2410 – 2412; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2290 – 2292; b) J.-L. Montchamp, F. Tian, M. E. Hart, J. W. Frost, *J. Org. Chem.* **1996**, *61*, 3897 – 3899.

[18] K. Kalyanasundaram, *Coord. Chem. Rev.* **1982**, *46*, 159 – 244.

[19] A. Bilyk, M. M. Harding, P. Turner, T. W. Hambley, *J. Chem. Soc. Dalton Trans.* **1994**, 2783 – 2790.

[20] M. M. Harding, U. Koert, J.-M. Lehn, C. Piguet, A. Marquis-Rigault, J. Siegel, *Helv. Chim. Acta* **1991**, *74*, 594 – 610.

[21] H. Braatz, S. Hecht, H. Seifert, S. Helm, J. Bendig, W. Rettig, *J. Photochem. Photobiol. A* **1999**, *123*, 99 – 108.

[22] a) R. Foster, *Organic Charge-Transfer Complexes*, Academic Press, London, **1969**, p. 128; b) H.-H. Perkampus, *UV/Vis-Spektroskopie und ihre Anwendungen*, Springer, Berlin, **1986**, p. 130.

[23] Reviews concerning the use of pyrene as a reporter molecule: a) A. P. de Silva, H. Q. N. Gunaratne, T. Gunnlaugsson, A. J. M. Huxley, C. P. McCoy, J. T. Rademacher, T. E. Rice, *Chem. Rev.* **1997**, *97*, 1515 – 1566; b) M. Sisido, in *Advances in Photochemistry*, *Vol. 22* (Eds.: D. C. Neckers, D. V. Volman, G. v. Bünau), Wiley, New York, **1997**.

[24] Representative examples of the use of pyrene excimers: a) I. Aoki, T. Harada, T. Sakaki, Y. Kawahara, S. Shinkai, *J. Chem. Soc. Chem. Commun.* **1992**, 1341 – 1345; b) A. Ueno, I. Suzuki, T. Osa, *J. Am. Chem. Soc.* **1989**, *111*, 6391 – 6397; c) M. A. Hossain, K. Hamasaki, H. Mihara, A. Ueno, *Chem. Lett.* **2000**, 252 – 253.

[25] J. B. Birks, *Photophysics of Aromatic Molecules*, Wiley, London, **1970**.

[26] F. C. De Schryver, P. Collart, J. Vandendriessche, R. Goedeweeck, A. Swinnen, M. v. d. Auweraer, *Acc. Chem. Res.* **1987**, *20*, 159 – 166.

[27] B. Stevens, *Adv. Photochem.* **1971**, *8*, 161 – 228.

[28] A. Tsuchida, T. Ikawa, T. Tomie, M. Yamamoto, *J. Phys. Chem.* **1995**, *99*, 8196 – 8199.

[29] C. Grewer, H.-D. Brauer, *J. Phys. Chem.* **1993**, *97*, 5001 – 5006.

[30] For reviews, see ref. [1] and a) V. Balzani, M. Gomez-Lopez, J.-F. Stoddart, *Acc. Chem. Res.* **1998**, *31*, 405 – 414; for representative examples, see: b) T. R. Kelly, H. De Silva, R. A. Silva, *Nature* **1999**, *401*, 150 – 152; c) N. Koumura, R. W. J. Zijlstra, R. A. van Delde, N. Harada, B. L. Feringa, *Nature* **1999**, *401*, 152 – 154; d) A. P. de Silva, N. D. McClenaghan, *J. Am. Chem. Soc.* **2000**, *122*, 3965 – 3966.

Received: October 4, 2000 [F2778]

  0947-6539/01/0710-2088 $ 17.50+.50/0