Spin-Delocalization in a Helical Open-Shell Hydrocarbon

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Supporting Information

ABSTRACT: Neutral open-shell molecules, in which spin density is delocalized through a helical conjugated backbone, hold promise as models for investigating phenomena arising from the interplay of magnetism and chirality. Apart from a handful of examples, however, the chemistry of these compounds remains largely unexplored. Here, we examine the prospect of extending spin-delocalization over a helical backbone in a model compound naphtho[3,2,1-ff]tetraphene, the first helically chiral open-shell hydrocarbon, in which one benzene ring is fused to [5]helicene, forming a phenalenyl subunit. The unpaired electron in this molecule is delocalized over the entire helical core composed of six rings, albeit in a nonuniform fashion, unlike in phenalenyl. In the case of a monosubstituted derivative, the uneven spin-distribution results in a selective σ-dimer formation in solution, as confirmed by 2D NMR spectroscopy. In contrast, the dimerization process is suppressed entirely when four substituents are installed to sterically hinder all reactive positions. The persistent nature of the tetrasubstituted derivative allowed its characterization by EPR, UV−vis, and CD spectroscopies, validating spin-delocalization through a chiral backbone, in accord with DFT calculations. The nonuniform spin-distribution, which dictates the selectivity of the σ-dimer formation, is rationalized by evaluating the aromaticity of the resonance structures that contribute to spin-delocalization.

INTRODUCTION

Spin-delocalization is an intrinsic feature of π-conjugated open-shell molecules that contain one or more unpaired π-electrons. A prototypical example of neutral spin-delocalized systems is phenalenyl (1, Figure 1), a three-ring triangular hydrocarbon (HC), in which one of the 13 π-electrons is unpaired and uniformly delocalized between six positions. The spin-delocalized nature of planar systems such as 1 determines their propensity to self-assemble via formation of multicenter bonds and hence dictates their magnetic and conducting properties in the solid state. Extending spin-delocalization through a nonplanar, helically twisted backbone brings an additional element, that of chirality, and links it in a unique manner with the properties arising from nonzero spin. Such union of spin and chirality can provide useful model systems for investigating effects arising from the interplay of magnetism and chirality, which have recently gained considerable fundamental interest as they create a broad spectrum of technological opportunities. These phenomena emerge on account of the simultaneous breaking of parity and time-reversal symmetries in magnetized chiral systems, and cause nonreciprocal dependence of (1) absorption/emission of unpolarized light and (2) electrical resistance on the direction of magnetization.

Whereas numerous examples of planar open-shell systems based on 1 are known, the chemistry of related helical HC systems remains, with an exception of two examples that contain heteroatoms, unexplored. The only nonplanar HC featuring the phenalenyl subunit that has been described to date is a bowl-shaped corannulene derivative 2 (Figure 1). The parent neutral radical compound could not, however, be detected and only its anionic closed-shell species were characterized. This seminal contribution was shortly followed by a report describing the first helical phenalenyl-based radical, featuring a hetero-[4]helicene backbone. Compound 3 displayed spin-delocalization over the entire π-conjugated twisted path and could be resolved into its enantiomers that showed complementary CD spectra. Most recently, one more example of a nonplanar phenalenyl derivative comprising a hetero-[4]helicene backbone, compound 4, was described. In both cases, the spin density was delocalized over the phenalenyl subunit to a greater extent compared with other rings of the π-conjugated path. This intriguing feature inspired us to investigate whether spin-delocalization can be extended over larger helical systems and what structural elements affect it.

Here, we describe the synthesis and properties of two substituted derivatives of naphtho[3,2,1-ff]tetraphene (5a, Figure 1), and demonstrate that spin-delocalization can be extended over a [5]helicene backbone (in red), which ensures nonplanarity and inherent chirality of the system. In this helically chiral HC, the spin density is delocalized over the entire core composed of six rings, albeit in a nonuniform fashion, with the largest spin densities displayed by the peripheral carbon atoms of the phenalenyl unit, similarly to 3 and 4. In the case of monosubstituted derivative 5b, the nonsymmetric electronic structure results in the selective σ-dimer-formation process, as confirmed by 2D NMR spectroscopy in solution. In contrast, this dimerization process is...
suppressed in the case of tetrasubstituted derivative 5c, on account of steric hindrance introduced around all of the reactive positions. The persistent nature of 5c allowed its characterization by variable-temperature (VT) EPR and NMR, and UV−vis spectroscopies, MALDI-ToF spectrometry, as well as CD spectroscopy of its two enantiomers that displayed mirror-like Cotton effects in their CD spectra. In addition, we show that the nonuniformity of the spin-density distribution as well as the selectivity of the σ-dimer-formation process can be rationalized by evaluating the aromaticity of the resonance structures that contribute to spin-delocalization, and support our conclusions with the aid of DFT calculations.

Results and Discussion

Synthesis. Initially, the preparation of the parent compound 5a starting from 3-bromodibenzo[c,g]phenanthrene was attempted, following a modified synthetic strategy for 5b outlined in Scheme 1. The required keto-intermediate (an unsubstituted analogue of 8) did not, however, form over the course of the Friedel−Crafts acylation (see Experimental

Figure 1. (A) Structural formulas of the resonance forms of phenalenyl (1). (B) Structural formulas and SOMOs (obtained from Hückel molecular orbital analysis) of nonplanar derivatives of 1: bowl-shaped anion 2 (HOMO shown), hetero-[4]helicene-based radicals 3 and 4, and [5]helicene-based radical 5 described in this work (5a: R1, R2 = H; 5b: R1, R2 = H, R3 = Ph; 5c: R1, R3 = Ph, R2 = tBu). Color code: phenalenyl subunits/purple, corannulene and helicene subunits/red.

Scheme 1. Synthesis of Precursors 9a, 9b, and 15, and Target Compound 5c.

A reaction conditions: (a) methyl acrylate, Pd(OAc)2, PPh3, K2CO3, Bu4NBr, DMF, 110 °C, 88%; (b) H2, Pd/C, CH2Cl2/EtOH, room temperature, 98%; (c) (i) LiI, 2,4,6-collidine, 185 °C, (ii) C2O2Cl2, 65 °C, (iii) AlCl3, CH2Cl2, −78 to −10 °C, 55% (8)/62% (14); (d) (i) NaBH4, CH2Cl2/EtOH, room temperature, (ii) p-TSA, toluene, 90 °C, 64% (9a)/59% (15); (e) TFA, CH2Cl2, room temperature, 85%; (f) O2, ambient light, quantitative; (g) MeMgBr, Ni(dppe)Cl2, Et2O, 0 to 45 °C, 98%; (h) (i) Br2, CH2Cl2, −78 °C to room temperature, (ii) phenylboronic acid, Pd(PPh3)4, K2CO3, toluene/EtOH/H2O, 85 °C, 86%; (i) (i) NBS, dibenzoyl peroxide, CCl4, 87 °C, (ii) methyl 3,3-dimethylbutanoate, LDA, THF, −78 °C to room temperature, 60%; (j) p-chloranil, C6H6, 65 °C. The aromatic rings of 6, 9a, 9b, and 15 are highlighted in red. The open-shell core of 5c is highlighted in purple.
Section and Section S2 for details) and it was necessary to block the 4-position next to the bromo-substituent. Compound 6 bearing a phenyl substituent at this position was therefore employed as the starting material to successfully synthesize the mono- and tetrasubstituted derivatives of 5a (5b and 5c, respectively, Scheme 1).

Compound 9a, the precursor of the monosubstituted derivative 5b, was prepared in seven steps from the racemic starting material 6 (Scheme 1, top) that was obtained by the Suzuki coupling of 3,4-dibromodibenzo[e,g]phenanthrene.28,29 The Heck coupling of 6, which afforded 7 in 88% yield, was followed by reduction, demethylation, and acid chloride formation before the Friedel–Crafts acylation step, which this time yielded exclusively intermediate 8 in 54% yield over the four steps. After reduction of 8 and subsequent dehydration, the hydro-precursor 9a was obtained in 64% yield over the two steps, as a solid material that in the presence of an acid isomerizes to its more stable isomer 9b.

This isomerization process occurs spontaneously in deuterated solvents that contain trace amounts of acids, such as CD3Cl2, during an NMR experiment (see Figure S1), or it can be performed on a larger scale by using trifluoroacetic acid, which instantly converts 9a to 9b that can be purified by column chromatography and isolated. The observed isomerization process is in accord with the results from DFT calculations at the B3LYP/6-31G(d,p) level of theory, which predict that 9b is lower in energy compared to 9a by 4.6 kcal mol−1. This energy difference is most likely the result of either (1) different strain energies, as the calculated distance between two “fjord” hydrogen atoms, 1-H and 15-H (see Figure 3B), is 2.7 Å in 9a and 2.9 Å in 9b, (2) different degrees of aromaticity, as all 24 π-electrons of 9b are part of either a six-π-ε− or an 18-π-ε− aromatic system, while two π-electrons of 9a form a double bond that is conjugated to a 22-π-ε− aromatic system (highlighted in red in Scheme 1), or (3) the combination of the two effects.

It is of interest to note that while 9b is stable in the dark or in the absence of oxygen, it undergoes a clean transformation to form endoperoxide 10 in the presence of oxygen and ambient light at room temperature (Scheme 1). Such a reaction is not unusual, and it has been observed30 previously for analogous systems containing a twisted tetrathene moiety. The driving force of this transformation, or at least a part of it, seems to be the release of strain energy upon formation of the 2,3-dioxabicyclo[2.2.2]octane subunit during this reaction. The strain release is reflected by the change in the chemical shift of proton 15-H (8.90 ppm in 9b and 7.14 ppm in 10) in the fjord region of the [5]helicene unit, when the distance between protons 1-H and 15-H is increased from 2.9 Å in 9b to 3.1 Å in 10 (DFT/B3LYP/6-31G(d,p)).

The precursor of the tetrasubstituted derivative 5c, compound 15, was prepared in ten steps from the racemic starting material 6 (Scheme 1, bottom). In this case, the synthetic strategy was slightly altered, as two additional phenyl substituents had to be introduced in 11 that was obtained by the Kumada coupling of 6 in 98% yield. The two phenyl groups were installed by a selective bromination of 11 followed by the Suzuki coupling to afford intermediate 12, bearing three phenyl and one methyl substituents, in 86% yield. The methyl group of 12 was brominated with NBS and then reacted with a lithium salt of methyl 3,3-dimethylbutanoate to afford 13 in 60% yield over the two steps. To build the remaining six-membered ring, the same reaction sequence as for 8, namely, demethylation, acyl chloride formation, and the Friedel–Crafts acylation, was employed to form intermediate 14 in 62% yield over the three steps. The subsequent reduction and dehydration yielded the hydro-precursor 15, bearing three phenyl and one tert-butyl substituents, in 59% yield over the two steps. In contrast to 9a, compound 15 does not isomerize in CD3Cl2 either because 15 represents the most stable isomer or the energy barrier for the isomerization process is higher than that for 9a.

All compounds were characterized by 1H and 13C NMR spectroscopy, and MALDI-ToF mass spectrometry. The key intermediates and the hydro-precursors 9a, 9b, and 15, as well as the endoperoxide 10 were additionally characterized by 2D NMR spectroscopic techniques (COSY, NOESY, HMQC, and HMBC), which allowed a full assignment of their 1H and 13C resonances to the corresponding hydrogen and carbon atoms, respectively (see the SI). The structure of 15 was additionally confirmed by a single-crystal X-ray diffraction analysis (Figure 2). The target compounds 5b and 5c were generated in situ from the hydro-precursors 9 and 15 by using oxidant p-chloranil in argon-saturated benzene or toluene, and their properties are discussed below.

DFT Analysis. The DFT calculations at the UB3LYP/6-31G(d,p) level of theory were performed on the parent compound 5a to gain insight into the electronic structure of the target molecules (Figure 3A). These results show that the distribution of the singly occupied (SOMO) and the lowest unoccupied (LUMO) molecular orbitals, as well as the spin density of 5a are largely delocalized over the entire helically twisted backbone. In contrast to phenalenyl (Figure 3A, top), where the spin density is distributed uniformly, however, 5a displays (Figure 3A, bottom) a nonuniform spin-density distribution over the six rings. A more quantitative picture can be obtained by comparing the values of positive Mulliken spin densities of the corresponding atoms (Figure 3B, bottom right), which are distinctly higher (0.27–0.35) in the case of peripheral carbon atoms of the phenalenyl unit (positions 5, 6, 8, and 9) than those (0.05–0.12) of the remaining peripheral.

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positions (2, 4, 10, 13, and 15) of the [5]helicene unit (for numbering, see Figure 3B, top left).

To understand and rationalize the nonuniform spin-density distribution, we evaluated the aromaticity of the resonance structures (Figure 3B) that contribute to spin-delocalization. The resonance structures with the highest degree of aromaticity, that is, structures with the highest number of aromatic rings, were assumed to be the most stable ones and thus contribute to spin-delocalization to a greater extent than those with a lower number of aromatic rings. Accordingly, the resonance structures with the unpaired electron at positions 5, 6, 8, and 9, which all contain the maximum number (five) of aromatic rings (highlighted in red, Figure 3B, top), contribute to spin-delocalization more than structures with the unpaired electron at positions 2 and 4 (four aromatic rings), and these contribute more than those with the unpaired electron at positions 10, 13, and 15 (three aromatic rings, Figure 3B, bottom).

This evaluation is in good qualitative agreement with the positive Mulliken spin densities obtained from DFT calculations (Table S1), which provide values 0.27–0.35 for positions 5, 6, 8, and 9, 0.10–0.12 for positions 2 and 4, and 0.05–0.06 for positions 10, 13, and 15, and can be carried out in a similar fashion also for the nonperipheral positions. This analysis is further supported by the NICS(1) values obtained by the GIAO-UB3LYP/6-31G(d,p) calculations (Table S2), which show that the two outer rings of the [5]helicene unit possess a higher degree of aromatic character than the remaining [5]helicene rings, and the ring that is not part of the [5]helicene unit displays the lowest degree. The same exercise can be carried out to rationalize the nonuniform spin-density distribution of 3 and 4 (Figure 1), and applied to other spin-delocalized structures in general.

Properties of 5b. First, we investigated the effect of the nonuniform spin-delocalized electronic structure of 5a on the σ-dimer-formation process of its monosubstituted derivative 5b. Compound 5b was generated in situ, by oxidation of either 9a or 9b with p-chloranil (CA) in argon-saturated solvents at room temperature (Figure 4), and the reaction was monitored by EPR (toluene) and NMR (C6D6) spectroscopy in solution. Two hours after the addition of two equivalents of CA to 9a, a very weak unresolved signal that diminished within a few hours was observed in the EPR spectrum (Figure S18). When the same reaction was followed (Figure 4) by 1H NMR spectroscopy, all major components that formed over the course of the reaction could be unambiguously identified (Section S3) with the help of high-resolution 2D NMR techniques, HSQC and HMBC. Within 3 h after the addition of

Figure 3. (A) Spin density and the singly occupied (SOMO) and the lowest unoccupied (LUMO) molecular orbitals of phenalenyl (top) and 5a (bottom) and (B) representative examples of the resonance structures of 5a (numbers denote the position of the unpaired electron) and Mulliken spin densities for 5a (bottom right; positive and negative values are denoted in purple and red, respectively). The aromatic rings in the corresponding resonance structures are highlighted in red.
CA, the starting material 9a was almost completely consumed and proton resonances of new species appeared, including two singlets at 4.93 and 4.81 ppm. These species were identified as two 5,5′-σ-dimers of 5b (16a and 16b), most likely diastereomers, which are in dynamic equilibrium with the monomeric species 5b. The observed sharp well-resolved 1H NMR signals and the weak EPR signal indicate that this equilibrium is shifted strongly in favor of the σ-dimers 16. Within 24 h, proton resonances of two additional species were detected and assigned to compounds 17a and 17b, products of oxidation of 5b bearing an oxo group at the 5- and 6-position, respectively. Presumably, the oxidation of 5b occurs on account of trace amounts of oxygen present in the argon-saturated sample and results in slow conversion of the reaction mixture to the final species 17. Assignment of the signals corresponding to 9a (purple) and 17a (red) is shown. The signals at 9.35 and 6.62 ppm (red) correspond to 17b and the signals at 4.93 and 4.81 ppm (gray) correspond to 16a and 16b, respectively. Partial isomerization of 9a to 9b was observed. The signals at ∼5.0–5.5 ppm that broaden as the reaction progresses belong to reduced CA species.
affording 17a and 17b as the major final products. Again, this observation is in agreement with the spin-distribution in 5b (Table S1), which makes the S- and 6-positions more prone toward oxidation than the other positions. The formation of compound 17a was favored over its isomer 17b and according to DFT calculations (DFT/B3LYP/6-31G(d,p)), 17a is lower in energy by 2.9 kcal mol⁻¹ compared with 17b, similarly to the case of 9a and 9b.

Properties of 5c. To increase the kinetic stability of 5b, three additional substituents were introduced in the tetrasubstituted derivative 5c, which protect all of the most reactive positions (5, 6, 8, and 9) and, consequently, suppress the σ-dimer-formation process entirely. Compound 5c was generated from hydro-precursor 15 by using one equivalent of CA in argon-saturated solvents at 65 °C, and proved to be stable under argon-saturated conditions at room temperature and in the presence of light. The persistent nature allowed its characterization by variable-temperature (VT) EPR and UV–vis spectroscopy, as well as MALDI-ToF mass spectrometry (SI, page S104).

The formation of 5c was first monitored by 1H NMR spectroscopy in C₅D₅ at 65 °C, which showed almost complete disappearance of the resonances corresponding to the starting material 15 within 3 h after the addition of CA. No new resonances appeared during this period, and no signals could be detected even when the sample was cooled to 200 K (toluene-de, 8), indicating that the σ-dimer-formation was indeed suppressed. An argon-saturated sample of freshly generated 5c in toluene was subsequently studied by EPR spectroscopy (Figure S5). At room temperature, the sample exhibited a three-broad-line EPR spectrum at a g-value of 2.0036, which is in accord with spin-1/2 hydrocarbons. The two observed proton hyperfine coupling constants (a₁ and a₂) were roughly 7.0 and 7.1 G (Figure S5B).

The proton hyperfine coupling constant, a₁H values for 5c (Figure S5A) were obtained from DFT calculations (UB3LYP/EPR-III) on the optimized geometry (UB3LYP/6-31G(d,p)) and indicate that spin-density is delocalized over the entire hydrocarbon core. The highest absolute a₁H values were obtained for the hydrogen atoms of the phenalenyl moiety (7.57 and 7.02 G, purple), while the hydrogen atoms of the remaining three rings display distinctly lower absolute a₁H values (0.69–2.68 G, red), following the nonuniform distribution of spin density, which is delocalized primarily over the phenalenyl core. Because of the large number of nonequivalent protons displaying similar absolute a₁H values in the range 0.69–2.68 G (red), only the two highest a₁H values (purple) could be elucidated from our experimental data (Figure S5A,B).

The measured EPR spectrum is, however, in a good agreement with the simulated spectrum (Figure S19) obtained by using the calculated a₁H values. In addition, the VT-EPR spectra were recorded for 5c at two different spin concentrations (1.3 × 10⁻⁴ and 1.5 × 10⁻³ M, calibrated with TEMPO) in toluene. In both cases, the EPR signal intensity increased upon decreasing the temperature, in accord with the Curie law (Figure S5C), which further supports 15,16 that 5c does not undergo σ- as well as π-dimer formation in solution.

The UV–vis spectrum of compound 5c in toluene at room temperature displays (Figure 6A) an absorption maximum at 537 nm, a band that corresponds to the SOMO→LUMO transition, as confirmed by TD-DFT calculations (UB3LYP/6-31G(d,p)). As a result of the extended π-conjugation, the LUMO-α energy of 5c (−1.41 eV) is lowered when compared
to that (−0.22 eV) of phenalenyl (DFT/UB3LYP/6-31G(d,p)). Because the nonbonding SOMO−α have similar energies (−4.18 eV for 5c and −4.32 eV for phenalenyl), the SOMO−α−LUMO−α energy gap of 5c (2.77 eV) is significantly lowered compared to phenalenyl (4.18 eV). Consequently, the SOMO−LUMO transition of 5c displays a bathochromic shift compared with phenalenyl.

To confirm the helical character of 5c, the enantiomers of hydro-precursor 15 were separated by HPLC employing a chiral stationary phase and n-heptane/tert-butyl methyl ether (9:1) solvent mixture as the eluent (20 °C). The enantiomers displayed mirror-image CD spectra (Figure S21) and their enantiomeric purity was confirmed by resubjecting the separated fractions to HPLC (Figure S20). The absolute configuration of the enantiomers was determined with the aid of TD-DFT calculations (B3LYP/6-31G(d,p)), and the value of their racemization barrier, obtained by time-dependent CD measurements performed on (P)-15 at 298 K, was determined to be (24.61 ± 0.03) kcal mol⁻¹ (Figure S22), a value marginally higher than that (24.1 kcal mol⁻¹ at 298 K) of [5]helicene. The oxidation of (P)-15 and (M)-15 with an excess of CA afforded the two enantiomers of chiral neutral radical 5c, (P)-5c and (M)-5c, respectively, which displayed complementary CD spectra that were in good agreement with spectra simulated by TD-DFT calculations (UB3LYP/6-31G(d,p); Figure 6B). Each of the enantiomers gave a three-broad-line EPR spectrum identical to that of racemic 5c.

**CONCLUSION**

We have synthesized and studied two substituted derivatives of naphtho[3,2,1-no]tetrathene, the first example of a neutral open-shell hydrocarbon, which is helically chiral. In this spin-1/2 system, the spin density is delocalized over the entire nonplanar core composed of six rings, featuring a [5]helicene subunit. We have shown that the nonuniform spin-density distribution in this hydrocarbon promotes a highly selective σ-dimer formation as well as oxidation of the monosubstituted derivative. The dimerization process was fully suppressed in the case of the tetrasubstituted derivative, in which four substituents sterically hinder all of the reactive positions, and where both magnetic and chiroptical properties were integrated within a single molecule. Additionally, we have demonstrated that evaluation of aromaticity of the resonance structures that contribute to spin-delocalization can be used to qualitatively predict the distribution of spin density in conjugated open-shell molecules. This lesson of principles can be applied in rational design of helical systems, where spin-delocalization is extended beyond one turn of a helicene, for example, by incorporation of multiple phenalenyl units, and ultimately give rise to a new type of model systems for investigating phenomena arising from the interplay of chirality and magnetism.
**EXPERIMENTAL SECTION**

**Materials and Instrumentation.** All chemicals and solvents were purchased from commercial sources and were used without further purification unless stated otherwise. The reactions and experiments that were sensitive to oxygen were performed using Schlenk techniques and argon-saturated solvents. The solvents were saturated with argon by either passing argon gas through the solvent or using the freeze–pump–thaw technique in three cycles. The NMR experiments were performed on NMR spectrometers operating at 400, 500, 600, or 700 MHz proton frequencies. The instruments were equipped with a direct-observe 5 mm BBFO smart probe (400 and 600 MHz), an indirect-detection 5 mm BBI probe (500 MHz), a five-channel cryogenic 5 mm QCI probe (600 MHz), or a four-channel cryogenic 5 mm TCI probe (700 MHz). All probes were equipped with actively shielded z-gradients (10 A). The experiments were performed at 295 or 298 K unless indicated otherwise and the temperatures were calibrated using a methanol standard showing accuracy within ±0.2 K. Standard pulse sequences were used and the data was processed using 2-fold zero-filling in the indirect dimension for all 2D experiments. The highly deuterium-enriched benzene (C6D6, > 99.96% D) was used were calibrated using a methanol standard showing accuracy within ±0.2 K. 

**Synthesis.** The synthesis of the parent compound 5a was attempted starting from racemic 3-bromodibenzo[c,g]phenanthrene18 (Scheme S1). The Friedel–Crafts acylation step did not, however, afford the desired intermediate 22a. Instead, the planar byproducts 23 and 24 formed and were isolated. A similar result was obtained in an attempt to synthesize a monosubstituted derivative of 5a starting from 18. Instead of the expected product 22b, the Friedel–Crafts acylation step yielded planar byproduct 29. In both cases, the intramolecular acylation occurred mainly (22a) or exclusively (22b) at the 4+ instead of the 2-position, and was accompanied by an intramolecular cyclization leading to planarization. Compound 6, in which the 4-position is blocked by a phenyl substituent, was therefore used as the starting material in the synthesis of mono- and tetrasubstituted hydrocarbons 9a and 9b (Scheme S2). Compound 6 was synthesized from 3,4-dibromodibenzo[c,g]phenanthrene (30), which was prepared according to the previously described1 procedure. All compounds were characterized by 1H and 13C NMR spectroscopy and MALDI-ToF mass spectrometry (MS). Compounds 7, 8, 9a, 9b, 10, 15, 23, 24, and 34 were additionally characterized by COSY/TOSY, NOESY, HMQC, and HMBC NMR techniques and their structures were confirmed by assigning the 1H and 13C NMR resonances to the corresponding atoms. For the copies of the 1H and 13C NMR spectra, see Section S10. For the copies of MALDI-ToF MS and ESI-HRMS spectra, see Section S11. The solid-state structures of compounds 15 and 29 were confirmed (see Section S8) by X-ray diffraction (XRD) analysis of the corresponding single crystals. The separation of enantiomers of 15 by HPLC is described in Section S5.

(±)-Methyl (E)-3-(dibenzo[c,g]phenanthren-3-yl)acrylate (19). A mixture of 18 (147 mg, 0.406 mmol), methyl acrylate (145 mg, 1.64 mmol), PPh3 (43 mg, 0.16 mmol), Pd(OAc)2 (19 mg, 0.085 mmol), K2CO3 (114 mg, 0.825 mmol), tetrabutylammonium bromide (132 mg, 0.409 mmol), and DMF (10 mL) was heated at 100 °C for 20 h under an argon atmosphere before the reaction mixture was poured into water and extracted with CH2Cl2. The combined organic layers were washed with brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (7:3) as an eluent to afford the desired product (128 mg, 86%) as a yellow solid. 1H NMR (400 MHz, CDCl3, ppm) δ 8.62 (d, J = 15.8 Hz, 1H), 8.40 (ddd, J = 8.6, 1.4, 0.7 Hz, 1H, 1H), 8.35 (ddd, J = 8.6, 1.4, 0.7 Hz, 1H, 1H), 8.24 (d, J = 8.9 Hz, 1H), 8.16 (s, 1H), 8.04 (d, J = 8.6 Hz, 1H), 8.01–7.98 (m, 2H), 7.97 (d, J = 8.7 Hz, 1H), 7.91 (d, J = 8.6 Hz, 1H), 7.56 (ddd, J = 8.0, 6.6, 1.2 Hz, 1H), 7.54 (ddd, J = 8.0, 6.6, 1.2 Hz, 1H), 7.27 (ddd, J = 8.5, 6.9, 1.5 Hz, 1H), 7.26 (ddd, J = 8.6, 6.8, 1.4 Hz, 1H), 6.68 (d, J = 15.7 Hz, 1H), 3.86 (s, 3H), 13C NMR (101 MHz, CDCl3, ppm) δ 167.4, 142.1, 133.4, 132.6, 131.9, 131.2, 131.1, 131.0, 130.3, 129.6, 129.3, 128.4, 128.0, 128.2, 128.0, 127.9, 127.2, 127.1, 126.7, 126.5, 125.2, 125.1, 121.8, 121.7, 52.1. MALDI-ToF MS (m/z) calc’d for C26H20O2 Na+ 385.1199, found 385.1200 (Δm ≈ 0.2 ppm).

(±)-Methyl 3-(dibenzo[c,g]phenanthren-3-yl)propanoate (20). To a mixture of 19 (100 mg, 0.276 mmol) and CuCl (20 mg, 0.21 mmol) in CH2Cl2/EtOH (20 mL, 1:1), NaBH4 (0.21 g, 5.5 mmol) was added in 10 portions at 0 °C over 2 h. The reaction mixture was quenched with aqueous HCl (2 M) and extracted with CH2Cl2. The combined organic layers were washed with saturated NaHCO3, water, and brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (7:3) as an eluent to afford the desired product (60 mg, 59%) as a pale yellow solid. 1H NMR (400 MHz, CDCl3, ppm) δ 8.42 (ddd, J = 8.6, 1.3, 0.7 Hz, 1H), 8.35 (ddd, J = 8.6, 1.3, 0.7 Hz, 1H), 8.12 (d, J = 8.9 Hz, 1H), 8.00 (d, J = 8.5 Hz, 1H), 8.00–7.93 (m, 2H), 7.93 (d, J = 8.6 Hz, 1H), 7.85 (d, J = 8.5 Hz, 1H), 7.77 (s, 1H), 7.53 (ddd, J = 8.1, 6.8, 1.1 Hz, 1H), 7.50 (ddd, J = 8.1, 6.8, 1.1 Hz, 1H), 7.25 (ddd, J = 8.6, 6.9, 1.7 Hz, 1H), 7.25 (ddd, J = 8.6, 6.9, 1.7 Hz, 1H), 7.26 (s, 3H), 3.63–3.46 (m, 2H), 2.95–2.97 (m, 2H), 13C NMR (101 MHz, CDCl3, ppm) δ 173.5, 135.9, 132.8, 132.4, 132.2, 131.4, 131.1, 129.8, 129.2, 128.3, 128.0, 128.0, 127.9, 127.8, 127.5, 126.7, 126.38, 126.36, 126.3, 124.9, 124.8, 121.9, 52.0, 35.2, 28.6. MALDI-ToF MS (m/z) calc’d for C26H21O2 Na+ 364.15, found 364.12 ([M]+). ESI-HRMS (m/z) calc’d for C26H20O2 Na+ 364.1536, found 364.1535 (Δm ≈ 0.4 ppm)

(±)-3-(Dibenzo[c,g]phenanthren-3-yl)propanoic acid (21). A mixture of 20 (60 mg, 0.16 mmol), lithium iodide (155 mg, 1.16 mmol), and 2,4,6-collidine (2.5 mL) was heated at 185 °C for 3 h before the excess of oxalyl chloride was removed under the reduced pressure. The crude product was dissolved in CH2Cl2 (10 mL) and the mixture was cooled to −78 °C. AlCl3 (52 mg, 0.39 mmol) was added and the reaction mixture was allowed to warm to −10 °C over 5 h before it was poured onto ice and acidified with aqueous HCl (2 M). The organic layer was separated and the aqueous layer was extracted with CH2Cl2. The combined organic layers were washed with saturated aqueous NaHCO3, water, and brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (4:1) as an eluent to afford

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byproducts 23 (8 mg, 18%) and 24 (16 mg, 37%) as yellow solids. The desired product 22a was not observed.

**9,10-Dihydro-9H-naphtho[2,1-b:2',1'-pyrene]-8-ones (21)**. 1H NMR (500 MHz, CDCl3, ppm) δ 9.09 (dd, J = 7.8, 1.0 Hz, 1H), 8.94 (dd, J = 7.9, 1.0 Hz, 1H), 8.76 (d, J = 0.6 Hz, 1H), 8.37 (dd, J = 7.8, 0.6 Hz, 1H), 8.29 (d, J = 1.2 Hz, 1H), 8.23 (dd, J = 7.7, 1.0 Hz, 1H), 8.15 (dd, J = 8.2 Hz, 1H), 8.08 (dd, J = 7.8, 7.8 Hz, 1H), 8.04 (dd, J = 7.8, 7.8 Hz, 1H), 3.81-3.77 (m, 2H), 3.20-3.14 (m, 2H). 13C NMR (From HMBC and HMQC, 500 MHz, CDCl3, ppm) δ 198.9, 132.4, 132.1, 131.5, 131.0, 129.7, 129.6, 128.5, 128.1, 127.6, 127.5 (2 ×), 127.2, 126.9, 126.8, 125.9, 125.1, 122.9, 121.5, 139.5, 29.6 (one resonance could not be determined, see page S28). MALDI-ToF MS (m/z) calc for C23H16O+ 308.1196, found 308.1195 ([M+]) and 308.1192 ([M+]).

**23-Dihydro-1H-indene[4,5,6,7]-gipheryl-1-one (24)**. 1H NMR (500 MHz, CDCl3, ppm) δ 9.47 (d, J = 8.9 Hz, 1H), 9.05 (dd, J = 7.8, 1.0 Hz, 1H), 9.04 (dd, J = 7.9, 1.0 Hz, 1H), 8.26 (dd, J = 7.7, 0.8 Hz, 1H), 8.24 (dd, J = 8.9, 0.5 Hz, 1H), 8.24 (dd, J = 8.9 Hz, 1H), 8.24-8.22 (m, 1H), 8.16 (dd, J = 8.8, 0.5 Hz, 1H), 8.10 (dd, J = 8.7, 0.8 Hz, 1H), 8.06 (dd, J = 7.7, 7.7 Hz, 1H), 3.73-3.69 (m, 2H), 3.05-3.01 (m, 2H). 13C NMR (From HMBC and HMQC, 500 MHz, CDCl3, ppm) δ 208.4, 154.6, 133.9, 133.2, 131.6, 130.3, 128.7, 128.8, 127.8 (2 ×), 127.5, 126.9, 126.3, 126.1, 125.6, 125.3, 123.2, 123.1, 121.9, 121.6, 37.5, 24.8. MALDI-ToF MS (m/z) calc for C23H16O 310.10, found 310.17 ([M+] and 310.16 ([M+]). ESI-HRMS (m/z) calc for C23H16O+ 311.1117, found 311.1110 ([M+]).

**7-(3-Bromomethyl) dibenzo[c]giphanethrene (27)**. To a solution of 26 (550 mg, 1.78 mmol) in benzene (50 mL), Pb(OAc)2 (0.25 mL, 2.7 mmol) was added slowly and the resulting solution was heated at 95 °C for 1 h. The reaction mixture was cooled to room temperature, quenched with NaHCO3, and extracted with CH2Cl2. The combined organic layers were washed with water and brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (1:1) as an eluent to afford the desired product (565 mg, 86%) as a pale yellow solid.

**7-(Acetoxymethyl)dibenzo[c]giphanethrene (28)**. To a cooled (−78 °C) solution of methyl tert-butylacetate (0.53 mL, 3.5 mmol) in THF (15 mL), LDA (1.73 mL, 3.47 mmol, 2 M in THF/heptane) was added dropwise and the mixture was stirred at −78 °C for 2 h. While maintaining the temperature, a suspension of 27 (322 mg, 0.52 mmol) in THF (10 mL) was then added and the reaction mixture was allowed to warm to room temperature overnight before it was quenched with saturated aqueous NH4Cl and extracted with CH2Cl2. The combined organic layers were washed with water and brine, and dried over anhydrous Na2SO4. After filtration and evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (7:3) as an eluent to afford the methyl ester intermediate (247 mg, 68%) as a yellow solid. A mixture of this intermediate (220 mg, 0.53 mmol), lithium iodide (350 mg, 2.62 mmol), and 2,4,6-collidine (5 mL) was heated at 185 °C for 1 h under an argon atmosphere before it was cooled to room temperature and concentrated in a vacuum. To the residue, aqueous HCl (10 mL, 2 M) was added, and the precipitate that formed was filtered and washed with water to give the desired product (200 mg, 94%; 64% over two steps) as a brown solid and as an approximately 1:1 mixture of two possible diastereomers, which was used in the next step without further purification.

**Acetylation (29)**. A solution of 28 (180 mg, 0.476 mmol) in benzene (50 mL), acetic anhydride (545 mg, 5.3 mmol) was added. The reaction mixture was allowed to warm to room temperature, a suspension of HCl (10 mL, 2 M) was then added and the reaction mixture was allowed to warm to room temperature overnight before it was quenched with saturated aqueous NH4Cl and extracted with CH2Cl2. The combined organic layers were washed with water and brine, and dried over anhydrous Na2SO4. After filtration and evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (7:3) as an eluent to afford the desired product (94 mg, 47%) as a yellow solid. The desired product 22b was not observed.

**7-(2-(tert-Butyl)-2,3-dihydro-1H-indeno[4,5,6,7-ghi]perylen-1-one (29)**. A solution of 28 (190 mg, 0.467 mmol) in o-xylol chloride (8 mL) was heated at 65 °C for 2 h before the excess of o-xylol chloride was removed under the reduced pressure. The crude acyl chloride intermediate was dissolved in CH2Cl2 (30 mL) and the solution was cooled to −78 °C. AlCl3 (207 mg, 1.55 mmol) was added and the reaction mixture was allowed to warm to −10 °C over 5 h before it was poured onto ice and acidified with aqueous HCl (2 M). The organic layer was separated and the aqueous layer was extracted with CH2Cl2. The combined organic layers were washed with saturated aqueous NaHCO3, water, and brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (7:3) as an eluent to afford product 29 (91 mg, 47%) as a yellow solid. The desired product 22b was not observed.
2H), 8.19−8.16 (m, 2H), 8.11 (d, J = 8.9 Hz, 1H), 8.04 (d, J = 7.6, 7.5 Hz, 1H), 8.01 (d, J = 7.7, 7.5 Hz, 1H), 3.53 (dd, J = 17.3, 3.9 Hz, 1H), 2.80 (dd, J = 7.8, 3.8 Hz, 1H), 1.19 (s, 9H). 1H NMR (From HMQC and HMBC, 500 MHz, CDCl3, ppm) δ 209.7, 152.7, 133.9, 132.4, 131.7, 130.4, 130.0, 129.5, 128.5, 128.0, 127.9, 127.8, 127.5, 127.0, 126.5, 126.2, 126.0, 125.7, 125.6, 125.4, 123.0, 121.7, 53.84, 53.83. MALDI-ToF MS (m/z) calcd for C32H22O2 582.18, found 582.20 ([M]. MALDI-ToF HRMS (m/z) calcd for C32H22O2 582.1866, found 582.1865 ([Δ]/m = 0.1 ppm).

(±)-3-Bromo-4-phenylidbenzoc[g]phenanthrene (30). A mixture of (30) (15 mg, 0.04 mmol), p-benzoilic acid (0.07 mmol) and LiClO4 (0.07 m, 15 mL) was added to the reaction mixture. The reaction mixture was then stirred at room temperature until no more precipitation occurred. The precipitate was filtered and washed with water to afford the desired product (9 mg, 9%) as a white solid. MALDI-ToF HRMS (m/z) calcd for C26H17Br 340.08, found 340.07 ([Δ]/m = 0.2 ppm).

(±)-3-(4-Phenylenidbenzo[c,g]phenanthren-3-yl)propanoic acid (31). A solution of (31) (220 mg, 0.516 mmol) in oxalyl chloride (11 mL) was heated at 80 °C for 2 h. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (7:3) as an eluent to afford the desired product (220 mg, 42%) as a pale yellow solid. MALDI-ToF HRMS (m/z) calcd for C32H22O2 582.1866, found 582.1865 ([Δ]/m = 0.1 ppm).

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(11) A solution of tetraphenemagnesium bromide (11.5 mmol, 34.6 mmol, 3 M in Et2O) was added dropwise to a cooled (0 °C) solution of 6 (2.50 g, 5.77 mmol) and NaCl(d) (0.22 g, 0.40 mmol) in dry EtO (300 mL) under an argon atmosphere. The reaction mixture was then allowed to warm to room temperature over 20 min before it was heated at reflux overnight. After cooling the reaction mixture to 0 °C, aqueous HCl (200 mL, 2 M) was added slowly to quench the reaction. The organic layer was separated and the aqueous layer was washed with EtO (3 × 50 mL). The combined organic layers were washed with brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane as an eluent to afford the desired product (2.08 g, 98%) as a white solid. 1H NMR (400 MHz, CDCl3, ppm) δ 8.36 (d, J = 8.5, 1.3, 0.6, 0.6 Hz, 1H), 8.20 (d, J = 8.9, 0.7, 0.7 Hz, 1H), 7.99 (d, J = 8.0, 1.3, 0.6, 0.6 Hz, 1H), 7.91 (d, J = 8.0, 1.3, 0.6, 0.6 Hz, 1H), 7.76 (d, J = 8.9, 0.7, 0.7 Hz, 1H), 7.90–7.96 (m, 2H), 7.44 (d, J = 8.9, 1.4 Hz, 1H), 7.37–7.32 (m, 2H), 7.25 (d, J = 8.8, 1.4, 1.4 Hz, 1H), 7.24 (d, J = 8.4, 1.4, 1.4 Hz, 1H), 2.54 (s, 3H). 13C NMR (101 MHz, CDCl3, ppm) δ 140.8, 138.4, 132.4, 132.1, 131.9, 131.7, 131.3, 131.3, 130.4, 129.8, 129.7, 128.9, 128.8, 128.0, 127.9, 127.8, 127.6, 127.1, 126.9, 126.5, 126.4, 125.9, 124.9, 124.3, 124.2, 123.5. MALDI-ToF MS (m/z) calcld for C31H20O2 +H + 425.1542, found 425.1536 (Δm = 1.4 ppm). In the IR spectrum of 10, no bands corresponding to the O–H stretches were visible, excluding the possibility of a dihydroxy product.

(12) A solution of 4,4-triphenyl-2-[(phenylmethylene)amino]benzonitrile (11) in CHCl3 (10 mL) was added dropwise to a cooled (−78 °C) solution of 11 (2.08 g, 5.64 mmol) in CHCl3 (120 mL). The reaction mixture was allowed to warm to room temperature overnight and then it was stirred at room temperature for 2 d before saturated aqueous Na2SO4 was added to quench the excess of bromine. The organic layer was separated, washed with water and brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane as an eluent to afford the desired product (2.79 g, 94%) as a pale yellow solid. 1H NMR (500 MHz, CDCl3, ppm) δ 8.51 (s, 1H), 8.41 (d, J = 8.4, 1.4, 0.6 Hz, 1H), 8.33 (d, J = 8.3, 1.3, 0.6 Hz, 1H), 8.28 (d, J = 8.5, 1.2, 0.6, 0.6 Hz, 1H), 8.24 (d, J = 8.5, 1.2, 0.6, 0.6 Hz, 1H), 7.73 (s, 1H), 7.72 (d, J = 8.8, 1.4, 1.4 Hz, 1H), 7.59 (d, J = 8.2, 6.9, 1.3 Hz, 1H), 7.60–7.67 (m, 2H), 7.56–7.51 (m, 1H), 7.35–7.26 (m, 4H), 2.50 (s, 3H). 13C NMR (101 MHz, CDCl3, ppm) δ 139.6, 138.3, 132.3, 132.2, 132.1, 131.6, 131.3, 130.6, 130.3 (two overlapped signals), 130.1, 130.0, 129.2, 129.0, 128.6, 128.1, 127.9, 127.7, 127.1, 126.5, 126.6, 125.9, 125.9, 125.6 (two overlapped signals), 122.8, 122.2, 17.5. MALDI-ToF MS (m/z) calcld for C20H14Br2 +H + 428.9770, found 428.9768 (Δm = 0.3 ppm).

(13) A mixture of bromine (0.67 mL, 13 mmol) in CH2Cl2 (10 mL) was added dropwise to a cooled (−78 °C) solution of 11 (2.08 g, 5.64 mmol) in CHCl3 (120 mL). The reaction mixture was allowed to warm to room temperature overnight and then it was stirred at room temperature for 2 d before saturated aqueous Na2SO4 was added to quench the excess of bromine. The organic layer was separated, washed with water and brine, dried over anhydrous Na2SO4, and filtered. After evaporation of the solvents, the residue was purified by column chromatography over silica gel using cyclohexane as an eluent to afford the desired product (2.79 g, 94%) as a pale yellow solid. 1H NMR (500 MHz, CDCl3, ppm) δ 8.51 (s, 1H), 8.41 (d, J = 8.4, 1.4, 0.6 Hz, 1H), 8.33 (d, J = 8.3, 1.3, 0.6 Hz, 1H), 8.28 (d, J = 8.5, 1.2, 0.6, 0.6 Hz, 1H), 8.24 (d, J = 8.5, 1.2, 0.6, 0.6 Hz, 1H), 7.73 (s, 1H), 7.72 (d, J = 8.8, 1.4, 1.4 Hz, 1H), 7.59 (d, J = 8.2, 6.9, 1.3 Hz, 1H), 7.60–7.67 (m, 2H), 7.56–7.51 (m, 1H), 7.35–7.26 (m, 4H), 2.50 (s, 3H). 13C NMR (101 MHz, CDCl3, ppm) δ 139.6, 138.3, 132.3, 132.2, 132.1, 131.6, 131.3, 130.6, 130.3 (two overlapped signals), 130.1, 130.0, 129.2, 129.0, 128.6, 128.1, 127.9, 127.7, 127.1, 126.5, 126.6, 125.9, 125.9, 125.6 (two overlapped signals), 122.8, 122.2, 17.5. MALDI-ToF MS (m/z) calcld for C20H14Br2 +H + 428.9770, found 428.9768 (Δm = 0.3 ppm).
because of the signal overlap) 141.3, 141.1, 140.6, 139.7, 138.9, 138.7, 138.1, 131.7, 131.4, 131.29, 131.27, 131.1, 130.9, 130.6, 130.5, 130.3, 130.2, 130.1, 129.0, 128.9, 128.7, 127.5, 127.9, 127.7, 126.6, 126.41, 126.26, 126.34, 126.26, 125.4, 125.3, 124.90, 124.88, 123.4, 17.6. MALDI-ToF MS (m/z) calc for C16H18O6 520.2186, found 520.2184 (160 mL). 

δ-(3-Bromomethyl)-1,4,6-triphenyldibenzoc[g]phenanthrene (35). A mixture of 12 (2.50 g, 4.56 mmol), N-bromosuccinimide (1.06 g, 9.39 mmol), dibenzoyl peroxide (55 mg, 0.23 mmol), and CCl4 (160 mL) was heated at reflux overnight under an argon atmosphere before the solvent was evaporated and the residue was purified by column chromatography over silica gel using cyclohexane/CH2Cl2 (95:5 to 9:1) as an eluent to afford the desired product (2.88 g, 84%) as a pale yellow solid. H NMR (400 MHz, CDCl3, ppm) δ 8.54 (d, J = 8.5, 1.3, 0.6, 0.6 Hz, 1H), 8.54 (d, J = 8.5, 1.3, 0.6, 0.6 Hz, 1H), 8.24 (s, 1H), 8.03 (d, J = 8.3, 1.4, 0.6 Hz, 1H), 7.92 (d, J = 8.3, 1.4, 0.6 Hz, 1H), 7.80–7.77 (m, 2H), 7.64–7.39 (m, 16H), 7.30 (d, J = 8.5, 6.9, 1.6 Hz, 1H), 7.29 (d, J = 8.7, 7.0, 1.7 Hz, 1H), 4.88 (d, J = 10.4 Hz, 1H), 4.83 (d, J = 10.5 Hz, 1H). 13C NMR (101 MHz, CDCl3, ppm) δ 175.2, 175.1, 141.3, 141.2, 139.4, 139.3, 138.2, 138.1, 136.4, 134.3, 133.7, 132.6, 132.0, 131.81, 131.75, 131.6, 131.4, 131.0, 131.0, 131.0, 130.97, 130.95, 130.7, 130.6, 130.53, 130.52, 130.49, 130.44, 130.37, 130.29, 130.26, 130.2, 129.4, 129.0, 128.88, 128.85, 128.78, 128.60, 127.9, 127.82, 127.77, 127.70, 126.79, 126.68, 126.66, 126.64, 126.57, 126.5, 126.23, 126.2, 126.1, 125.8, 125.6, 125.2, 125.1, 125.0, 124.9, 124.79, 124.77, 124.1, 123.6, 57.2, 56.4, 50.9, 50.7, 33.5, 33.4, 28.0, 27.4, 27.24, 27.21. MALDI-ToF MS (m/z) calc for C16H18O6 520.2184, found 520.2183. 

δ-(3,3-Dimethyl-2-(1,4,6-triphenyldibenzoc[g]phenanthren-3-ylmethyl)butanoic acid (36). A mixture of 13 (200 mg, 0.308 mmol), lithium iodide (289 mg, 2.16 mmol), and 2,4,6-collidine (5 mL) was heated at 185 °C for 3 h under an argon atmosphere before the reaction mixture was cooled to room temperature and concentrated in vacuo. To the residue, aqueous HCl (15 mL, 2 M) was added, and the precipitate that formed was filtered and washed with water to afford the desired product (158 mg, 81%) as a pale yellow solid and as an approximately 1:0.7 mixture of two possible diastereomers, which was used in the next step without further purification. H NMR (400 MHz, CDCl3, ppm) δ 8.54 (d, J = 8.5, 1.3, 0.6, 0.6 Hz, 1H), 8.54 (d, J = 8.5, 1.3, 0.6, 0.6 Hz, 1H), 8.00 (d, J = 8.3, 0.7 Hz, 0.79 (d, J = 8.1 Hz, 1H), 7.89 (d, J = 7.9 Hz, 0.7H), 7.84–7.79 (m, 1.3H), 7.73–7.69 (m, 2.7H), 7.64–7.37 (m, 25H), 7.35–7.30 (m, 17H), 7.29–7.21 (m, 3.3H), 3.65 (dd, J = 14.2, 12.4 Hz, 1H), 3.51 (dd, J = 13.7, 12.1 Hz, 0.7H), 3.31 (dd, J = 14.0, 3.4 Hz, 0.7H), 2.11 (dd, J = 14.1, 3.5 Hz, 1H), 2.59 (dd, J = 11.6, 3.1 Hz, 0.7H), 2.45 (dd, J = 12.1, 3.4 Hz, 1H). MALDI-ToF MS (m/z) calc for C16H18O6 634.29, found 634.27 (160 mL). DOI: 10.1021/acs.joc.6b02246.
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The dimer-formation process of 5b was followed by 1D and 2D NMR spectroscopy (400, 600, and 700 MHz, C$_{6}$D$_{6}$). The radical species 5b were generated from the hydro-precurors 9a or 9b by oxidation with p-chloranil (CA). The 1D and 2D NMR measurements revealed that 5b is in equilibrium with its σ-dimers 16a and 16b and undergoes slow oxidation to afford keto-compounds 17a and 17b as two major species (Figures S2 and S3). Presumably, the oxidation occurs on account of trace amounts of oxygen present in the argon-saturated sample. Additionally, intermediate species 38 and 39 (Figure S12) that form over the course of the reaction were identified. The use of either 9a or 9b in this reaction gave similar results (Figures S2 and S3), as oxidation with CA generates the same radical species 5b. In the case when 9a was used, small amounts of 9b were observed (Figure S2) as the reaction progressed. The isomerization of 9a to 9b was most likely catalyzed by reduced CA species containing phenolic hydroxyl groups that are acidic. The structures of the final products 17a and 17b were confirmed by 2D NMR spectroscopy once the reaction was completed, that is, when the starting material 9b and the σ-dimers 16 were not present anymore. The combination of TOCSY and NOESY, as well as high-resolution HSQC and HMBC NMR techniques (600 MHz, C$_{6}$D$_{6}$ 25 °C) allowed for unambiguous structural validation of both 17a (Figures S4 and S6–S8) and 17b (Figures S5 and S9–S11). The structures of the relatively short-lived intermediate species 16a, 16b, 38, and 39 were confirmed during an NMR experiment at a lower temperature (15 °C), at which these compounds exhibited a prolonged lifetime of approximately 1 day. The combination of TOCSY, NOESY, and PGFSE, as well as high-resolution HSQC and HMBC NMR techniques (700 MHz, C$_{6}$D$_{6}$, 15 °C) allowed for structural validation of all four compounds that were present in the reaction mixture together with the starting material 9a and/or 9b, the final products 17a and 17b, and small amounts of other unidentified species. The characteristic proton resonances of 16a, 16b, 38, and 39 are highlighted in Figure S12 and all their carbon resonances that could be identified are highlighted in Figure S13. Assignment of the proton and carbon resonances to the corresponding atoms is shown in Figures S14 (16a), S15 (16b), S16 (38), and S17 (39). All acquired spectra used for identification of compounds 16a, 16b, 38, and 39 were submitted as a separate Supporting Information file. Proton and carbon resonances of the phenyl group could not be assigned for compounds 16a, 16b, 17b, 38, and 39 because of signal overlap.

Diffusion coefficients (D) obtained from the PFGE NMR experiments for 9a (1.088 × 10$^{-9}$ m$^{2}$ s$^{-1}$), 16a (8.250 × 10$^{-9}$ m$^{2}$ s$^{-1}$), 16b (8.029 × 10$^{-9}$ m$^{2}$ s$^{-1}$), 38 (1.085 × 10$^{-9}$ m$^{2}$ s$^{-1}$), and 39 (9.222 × 10$^{-9}$ m$^{2}$ s$^{-1}$) were used to estimate the ratio between the molecular weight of 16a, 16b, 38, and 39 and the molecular weight of 9a, which was in all cases in a good qualitative agreement with the calculated value (in the brackets): 16a:2.3 (2), 16b:2.5 (2), 38:1 (1.1), and 39:1.2 (1.5).

Sample Preparation for the σ-Dimer-Formation NMR Experiments. Stock solutions of the starting material, 9a or 9b, and CA were saturated with argon by using the freeze–pump–thaw technique in three cycles. The NMR spectra were acquired before and after the addition of the solution of CA to the solution of 9a or 9b. After the addition of CA, the NMR tube was sealed.

Electron Paramagnetic Resonance (EPR) Spectroscopy. Compound 5b was generated in situ by oxidation of either 9a or 9b with CA in an argon-saturated toluene at 25 °C, and the reaction was monitored by electron paramagnetic resonance (EPR) spectroscopy in solution. Compound 5c was generated in situ by heating a mixture of 15 and 1 equiv of CA in an argon-saturated toluene for 3 h at 65 °C. Subsequently, the EPR spectrum was recorded at variable temperatures. The spin concentration was determined by calibration with TEMPO.

C Circular Dichroism (CD) Spectroscopy. The enantiomers of 15, (P)-15 and (M)-15, obtained from chiral-stationary-phase HPLC (multiple fractions were combined) were each dissolved in tert-butyl methyl ether and the solutions were saturated with argon. To these solutions, an argon-saturated solution of CA (10 equiv with respect to 15) was added and the CD spectra were recorded at 25 °C.
Theoretical Calculations. All DFT calculations were performed in Gaussian 09 (Revision D.01) suite of electronic structure programs. Geometries were optimized using (U)B3LYP functional and 6-31G(d,p) basis set in the gas phase. Chemcraft software was used to analyze the TD-DFT calculated spectra and to generate graphical images of frontier molecular orbitals (FMOs). The nucleus independent chemical shift (NICS) calculations were performed on UB3LYP/6-31G(d,p) optimized geometry at the GIAO-UB3LYP/6-31G(d,p) level. Considering the nonplanarity of the molecule, NICS(1) values were obtained by placing dummy atoms 1 Å above and below each benzenoid ring.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.joc.6b02246.

Detailed synthetic schemes, spectroscopic (NMR, EPR), kinetic (CD), computational (DFT), and crystallographic data, copies of 1H and 13C NMR, and MALDI-ToF MS spectra, and Cartesian coordinates for all optimized geometries (PDF)

Crystal data (CIF)

Crystal data (CIF)

NMR data (ZIP)

MOL2 data (ZIP)

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Notes

The authors declare no competing financial interest.

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**REFERENCES**


