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Generation and Reactivity of 1,2-Cyclohexadiene under Mild Reaction Conditions

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Dedicated to Professor Luis Castedo on the occasion of his 70th birthday

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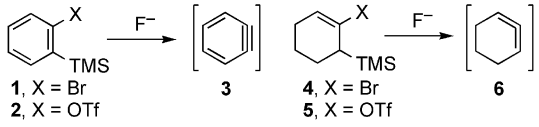
An improved method to generate 1,2-cyclohexadienes by fluoride-induced β-elimination of 6-(trimethylsilyl)cyclohexenyl triflates is presented. This method allows the generation of these highly strained cyclic allenes in good yields and under mild reaction conditions, as demonstrated by trapping experiments based on cycloaddition reactions.

Introduction

In the last few decades fluoride-induced elimination of β-substituted organosilanes has emerged as a powerful method for the generation of unstable short-lived intermediates.[1,2] For example, (*o*-bromophenyl)trimethylsilane (**1**, Scheme 1) has been used as a benzyne precursor and avoids the use of strong bases.[3a] The key advance in the development of this methodology was the introduction of *o*-(trimethylsilyl)phenyl triflate (**2**), as the better leaving group character of the triflate allows the generation of benzyne in higher yields and under milder conditions.[3b] This approach has led to a remarkable revival in the use of benzyne (**3**) over the past few years[4,2d] and has also been used for the efficient generation of other strained molecules such as cyclohexyne[5] and 1,2,3-cyclohexatriene.[6a]



Scheme 1. Fluoride-induced generation of benzyne (**3**) and 1,2-cyclohexadiene (**6**).

Cyclic allenes containing fewer than eight carbon atoms are strained molecules that are closely related to arynes and small cycloalkynes.[1,2] These intermediates are potent electrophiles and undergo pericyclic reactions such as [2+2] and [4+2] cycloadditions with alkenes and dienes, respectively. 1,2-Cyclohexadiene (**6**, Scheme 1) is a highly reactive cyclic allene.[7] The two most general methods for the generation of this molecule have for many years involved the base-induced elimination of HX from alkenyl halides and the decomposition of *gem*-dihalocyclopropanes by organolithium reagents (Doering–Moore–Skattebøl reaction).[1] Both methods are hampered by the use of strong bases and highly nucleophilic reagents, and this limits their scope. Fluoride-induced decomposition of compound **4** to generate **6** was introduced by Shakespeare and Johnson in 1990,[6a] albeit since then, this method has been sporadically used.[8] Herein, we introduce 6-(trimethylsilyl)cyclohexenyl triflate (**5**), which allows the generation of 1,2-cyclohexadiene (**6**) in good yields and under mild reaction conditions as a result of the excellent leaving group character of the triflate group.

Results and Discussion

Vinyl triflate **5** was prepared from 2-(trimethylsilyl)cyclohexenone **7** (Scheme 2).[6] Hydride conjugate addition to this enone with the use of L-Selectride followed by aqueous workup afforded cyclohexanone **8a**. Treatment of this compound with LDA at –78 °C and trapping of the resulting kinetic enolate with *N*-phenyltrifluoromethanesulfonimide led to cycloallene precursor **5** in 48% yield. Remarkably, alkyl-substituted cycloallene precursors such as **9** can be prepared in good yield by minor modifications of this procedure.

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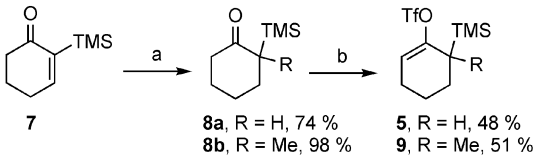
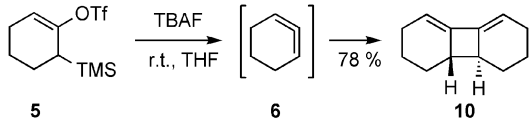


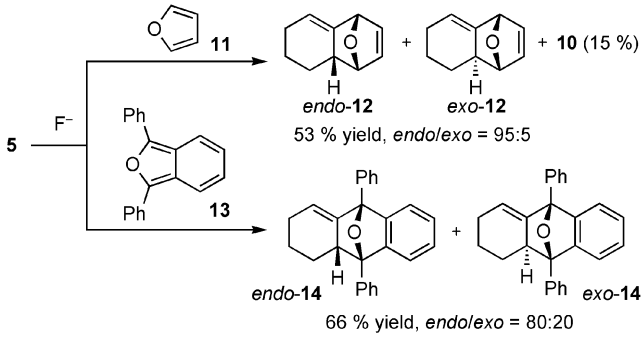
Scheme 2. Synthesis of 1,2-cyclohexadiene precursors. Reagents and conditions: (a) i. L-Selectride, ii. NH_4Cl (aq.) for **8a** or MeI for **8b**; (b) i. LDA ii. $PhNTf_2$.

The ability of triflate **5** to form cycloallene **6** was confirmed when treatment of **5** with tetrabutylammonium fluoride (TBAF) in THF at room temperature afforded 1,2-cyclohexadiene dimer (**10**) in 78% yield through a [2+2] cycloaddition of intermediate **6** (Scheme 3).[9]



Scheme 3. Dimerization of 1,2-cyclohexadiene (**6**).

Compound **6** was also trapped in Diels–Alder reactions. The generation of cyclic allene **6** in the presence of furan (**11**) led to the isolation of a 95:5 mixture of the *endo*- and *exo*- [4+2] cycloaddition adducts **12**, respectively, in 53% yield (Scheme 4).[10] In the presence of 1,3-diphenylisobenzofuran (**13**) a mixture of *endo*- and *exo*-**14** was obtained in 66% yield (ratio *endo*/*exo* = 80:20). It should be mentioned that the generation of **6** by treatment of 1-bromocyclohexene with KO*t*Bu in the presence of **13** afforded *endo*/*exo*-**14** with the same ratio but in 38% yield.[7a] The structure of *endo*-**14** was confirmed by X-ray diffraction studies (Figure 1).



Scheme 4. [4+2] Cycloaddition reactions of 1,2-cyclohexadiene.

These results prompted us to study the reactivity of cycloallene **6** in the presence of other unsaturated compounds as reaction partners. In this context, the reaction with tropone (**15**) would be of special interest due to the vast number of possible peri-, regio- and stereoisomers. It is known that the reaction of benzyne with tropone affords periselectively the [4+2] cycloaddition adduct as the major product, together with small amounts of the [6+2] cycloaddition product.[11] By contrast, the reaction of tropone with acyclic allenes usually leads to mixtures of [8+2] and [4+2] cycloaddition adducts.[12] Treatment of triflate **5** with CsF

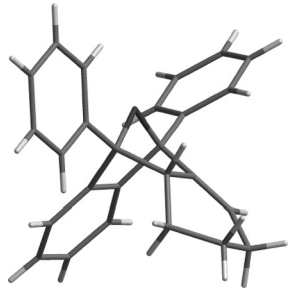
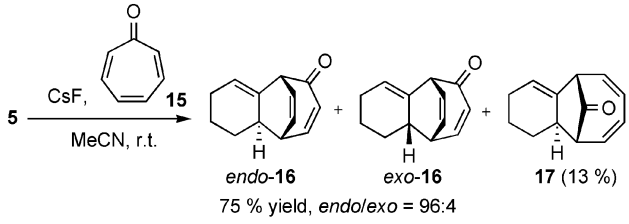


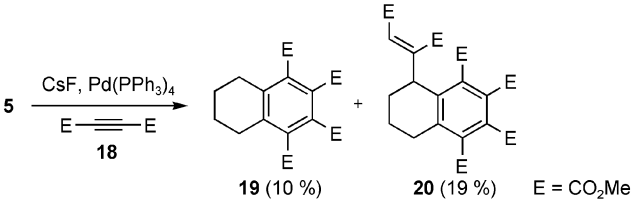
Figure 1. X-ray structure of compound *endo*-**14**.

in the presence of tropone (**15**) selectively afforded a 96:4 mixture of the *endo*- and *exo*- [4+2] cycloaddition adducts **16**, respectively, in good yield (75%, Scheme 5). The relative stereochemistry of compounds *endo*- and *exo*-**16** was established on the basis of 2D NMR spectra (COSY and NOESY).[13] In a similar way to the reaction with benzyne,[11b] [6+2] cycloaddition product **17** was also isolated in 13% yield.



Scheme 5. Cycloadditions of 1,2-cyclohexadiene with tropone.

Analogously to arynes, cyclic allenes can be stabilized by complexation with a transition metal.[14] This opens the possibility of employing cyclic allenes in transition-metal-catalyzed reactions.[15] We therefore decided to study the reactivity of 1,2-cyclohexadiene (**6**) in the presence of catalytic amounts of a palladium complex. In particular, treatment of triflate **5** with CsF in the presence of dimethyl acetylenedicarboxylate (**18**) and 5 mol-% of $Pd(PPh_3)_4$ in MeCN at room temperature resulted in the formation of compounds **19** and **20** in 10 and 19% yield, respectively (Scheme 6). In the absence of the palladium catalyst these products were not detected by GC–MS, whereas in the absence of fluoride the starting material was untouched. The structure of compound **20** was unambiguously determined by single-crystal X-ray diffraction studies (Figure 2).



Scheme 6. Pd-promoted reaction of 1,2-cyclohexadiene with dimethyl acetylenedicarboxylate.

Presumably, a Pd^0 complex promotes the [2+2+2] cycloaddition of one molecule of cycloallene **6** with two molecules of alkyne **18** to give intermediate **21** (Scheme 7). Sub-

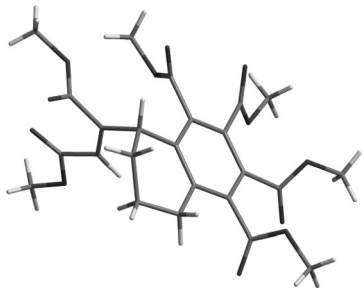


Figure 2. X-ray structure of compound **20**.

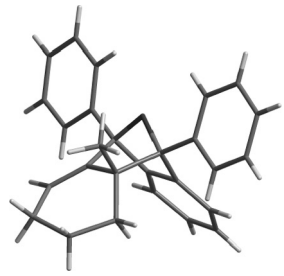
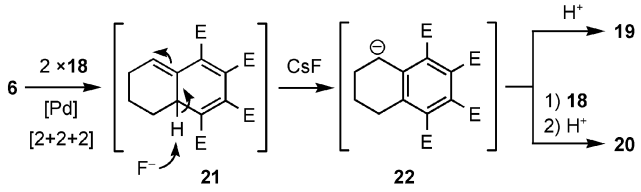


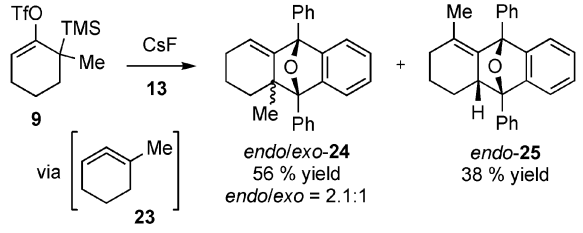
Figure 3. X-ray structure of compound *endo*-**24**.

sequent fluoride-induced deprotonation/rearomatization would give anion **22**, which could evolve in two ways: either by protonation to afford tetrahydronaphthalene **19** or by conjugate addition to alkyne **18** followed by protonation to form compound **20**. Alternatively, this compound could be produced through an ene reaction of intermediate **21** and alkyne **18**. Remarkably, this is the first example of the participation of strained cyclic allenes in a metal-catalyzed reaction.



Scheme 7. Proposed mechanism for the formation of **19** and **20**.

We next planned to confirm the ability of triflate **9** to form 1-methyl-1,2-cyclohexadiene (**23**, Scheme 8). Indeed, treatment of triflate **9** with CsF in the presence of diphenylisobenzofuran (**13**) afforded a mixture of three Diels–Alder adducts: *endo*/*exo*-**24** in 56% yield (ratio *endo*/*exo* = 68:32), resulting from the reaction of the methyl-substituted double bond of the allene with diene **13**,[16] and *endo*-**25**, resulting from the reaction of the less-substituted double bond of cycloallene **23**. Remarkably, the other possible [4+2] cycloaddition product *exo*-**25** was not detected in the reaction mixture. As expected, the corresponding dimer of cyclic allene **23** was obtained in the absence of diene **13**.[17]



Scheme 8. [4+2] Cycloaddition reaction of cyclic allene **23**.

The stereochemistry of compound *endo*-**24** was confirmed by X-ray diffraction studies (Figure 3).

Conclusions

1,2-Cyclohexadienes can be generated and trapped under mild reaction conditions by means of fluoride-induced β-elimination of the corresponding 6-(trimethylsilyl)cyclohexenyl triflates. This method allows the generation of highly strained cyclohexallenes with higher efficiencies than classical approaches. Significantly, cyclic allenes generated by this method can participate not only in [4+2] cycloadditions with furan or tropone but also in palladium-promoted [2+2+2] cycloadditions with alkynes.

Experimental Section

General: All reactions were performed under an argon atmosphere by using oven-dried glassware and standard Schlenk techniques. Solvents were dried by distillation from a drying agent before use: MeCN from CaH_2, THF and toluene from Na. TLC was performed on Merck silica gel 60 F_{254}; chromatograms were visualized with UV light (254 and 360 nm). Flash column chromatography was performed on Merck silica gel 60 (ASTM 230–400 mesh). ^1H and ^{13}C NMR spectra were recorded at 250.13 and 62.83 MHz (Bruker DPX-250 instrument), 300 and 75 MHz (Varian Mercury-300 instrument) or 400 and 100 MHz (Varian Mercury-400 instrument), respectively. NOE, NOESY and COSY were recorded with a Bruker WM-500 instrument. Low-resolution mass spectra [LRMS (electron impact, EI)] were determined at 70 eV with an HP-5988A instrument. High-resolution mass spectra (HRMS) were obtained with a Micromass Autospec spectrometer. IR spectra were recorded with a Mattson Cygnus 100 spectrophotometer. GC–MS analyses were performed with an Agilent 6890N/5973inert instrument with a HP-5MS capillary column. Compound **7** was prepared from 2-cyclohexenone following a previously published procedure.[6] Commercial reagents were used without further purification. CCDC-729036 (for *endo*-**14**), -729037 (for **20**) and -729038 (for *endo*-**24**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Synthesis of 1,2-Cyclohexadiene Precursors

2-(Trimethylsilyl)cyclohexanone (8a): L-Selectride (1.0 M in THF, 3.60 mL, 3.60 mmol) was added dropwise to a solution of **7** (600 mg, 3.57 mmol) in THF (18 mL) at –78 °C. The mixture was stirred under an argon atmosphere at this temperature for 2 h. Then, saturated aqueous NH_4Cl solution (45 mL) and Et_2O (30 mL) were added, the phases were separated and the aqueous

layer was extracted with Et_2O (2 × 40 mL). The combined organic layer was dried with Na_2SO_4, filtered and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2; Et_2O/hexane, 1:20) to afford **8a** (450 mg, 74%) as a colourless oil: ^1H NMR (400 MHz, $CDCl_3$): δ = 2.36 (m, 1 H), 2.26–2.11 (m, 2 H), 2.01–1.92 (m, 3 H), 1.75–1.60 (m, 3 H), 0.10 (s, 9 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 212.5 (C), 45.4 (CH), 41.3 (CH_2), 26.5 (CH_2), 25.3 (CH_2), 23.4 (CH_2), –1.6 (3 CH_3) ppm. MS (EI): *m*/*z* (%) = 170 (98), 155 (100). HRMS: calcd for $C_9H_{18}OSi$ 170.1127; found 170.1120.

6-(Trimethylsilyl)-1-cyclohexenyl 1-Trifluoromethanesulfonate (5): *n*BuLi (2.25 M in hexane, 1.65 mL, 3.63 mmol) was added dropwise to *i*Pr_2NH (0.50 mL, 3.80 mmol) at –78 °C, leading to a gel that was dissolved in THF (6 mL). The mixture was stirred at –78 °C for 10 min and at room temperature for 20 min. Then, a solution of **8a** (588 mg, 3.46 mmol) in THF (5 mL) was added at –78 °C. After stirring at –78 °C for 35 min, a solution of $PhNTf_2$ (1.30 g, 3.63 mmol) in THF (5 mL) was added, and the mixture was stirred at room temperature for 12 h. Then, 5% aqueous $NaHCO_3$ solution (35 mL) was added, the phases were separated and the aqueous layer was extracted with Et_2O (2 × 35 mL). The combined organic layer was dried with Na_2SO_4, filtered and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, pentane) to afford **5** (500 mg, 48%) as a colourless oil. ^1H NMR (400 MHz, $CDCl_3$): δ = 5.65 (ddd, *J* = 5.0, 3.6, 1.7 Hz, 1 H), 2.26–2.02 (m, 2 H), 2.00–1.90 (m, 2 H), 1.70–1.40 (m, 3 H), 0.10 (s, 9 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 152.8 (C), 118.6 (*J* = 320 Hz, CF_3) 115.2 (CH), 28.9 (CH), 25.5 (CH_2), 24.1 (CH_2), 21.0 (CH_2), –2.1 (3 CH_3) ppm. IR (CsI): $\tilde{\nu}$ = 2925 cm^{-1}. MS (EI): *m*/*z* (%) = 302 (2), 79 (100). HRMS: calcd. for $C_{10}H_{17}F_3O_3SiS$ 302.0620; found 302.0620.

2-Methyl-2-(trimethylsilyl)cyclohexanone (8b): L-Selectride (1.0 M in THF, 2.86 mL, 2.86 mmol) was added dropwise to a solution of **7** (400 mg, 2.38 mmol) in THF (12 mL) at –78 °C, and the mixture was stirred at this temperature for 2 h. Then, MeI (0.770 mL, 11.9 mmol) was added, and the mixture was stirred at room temperature for 5 h. Cold saturated NH_4Cl solution (30 mL) was added, the phases were separated and the aqueous layer was extracted with Et_2O (3 × 20 mL). The combined organic layer was dried with Na_2SO_4, filtered and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2; Et_2O/hexane, 1:20) to afford **8b** (430 mg, 98%) as a colourless oil. ^1H NMR (500 MHz, $CDCl_3$): δ = 2.44–1.89 (m, 4 H), 1.73–1.64 (m, 3 H), 1.53 (m, 1 H), 1.13 (s, 3 H), 0.07 (s, 9 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 214.7 (C), 44.1 (C), 40.9 (CH_2), 35.7 (CH_2), 25.5 (CH_2), 22.5 (CH_2), 20.8 (CH_3), –2.4 (3CH_3) ppm. IR (CsI): $\tilde{\nu}$ = 1680 cm^{-1}. MS (EI): *m*/*z* (%) = 184 (42), 169 (100). HRMS: calcd. for $C_{10}H_{20}OSi$ 184.1283; found 184.1282.

6-Methyl-6-(trimethylsilyl)-1-cyclohexenyl 1-Trifluoromethanesulfonate (9): *n*BuLi (2.25 M in hexane, 1.01 mL, 2.28 mmol) was added dropwise to *i*Pr_2NH (0.31 mL, 2.39 mmol) at –78 °C, leading to a gel that was dissolved in THF (4 mL). The mixture was stirred at –78 °C for 10 min and at room temperature for 20 min. Then, a solution of **8b** (400 mg, 2.17 mmol) in THF (4 mL) was added at –78 °C. After stirring at –78 °C for 40 min, a solution of $PhNTf_2$ (820 mg, 2.28 mmol) in THF (5 mL) was added, and the mixture was stirred at room temperature for 18 h. Then, 5% aqueous $NaHCO_3$ solution (30 mL) was added, the phases were separated and the aqueous layer was extracted with Et_2O (2 × 25 mL). The combined organic layer was dried with Na_2SO_4, filtered and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, hexane) to afford **9** (350 mg, 51%) as a colourless oil. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.68 (dd, *J* = 5.4, 2.9 Hz, 1 H), 2.28–1.98 (m, 2 H), 1.76–1.45 (m, 4 H), 1.18 (s, 3 H) 0.06 (s, 9 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 156.8 (C), 118.3 (*J* = 320 Hz, CF_3), 114.3 (CH), 33.3 (CH_2), 27.7 (C), 24.8 (CH_2), 19.5 (CH_3), 17.3 (CH_2), –3.5 (3 CH_3) ppm. MS (EI): *m*/*z* (%) = 183 (6) [M – Tf], 79 (100). HRMS: calcd. for $C_{10}H_{18}OSi$ [M – Tf] 183.1160; found 183.1162.

Cycloaddition Reactions of 1,2-Cyclohexadienes

[2+2] Cycloaddition of 1,2-Cyclohexadiene (6): Tetrabutylammonium fluoride (TBAF; 1.0 M in THF, 280 μL, 0.28 mmol) was added dropwise to a solution of **5** (44 mg, 0.14 mmol) in MeCN (5 mL) at room temperature, and the mixture was stirred at this temperature for 1 h. Then, H_2O (5 mL) and Et_2O (5 mL) were added, the phases were separated and the aqueous layer was extracted with Et_2O (3 × 5 mL). The combined organic layer was dried with anhydrous Na_2SO_4, filtered and concentrated under reduced pressure. The residue was purified by column chromatography (SiO_2, hexane) to afford *trans*-1,2,3,6,7,8,8a,8b-octahydrobiphenylene[9,18] (**10**; 9 mg, 78%) as a colourless oil. ^1H NMR (300 MHz, $CDCl_3$): δ = 5.39 (s, 2 H), 2.35–2.22 (m, 2 H), 2.16–2.03 (m, 4 H), 2.01–1.90 (m, 2 H), 1.83–1.72 (m, 2 H), 1.52–1.30 (m, 2 H), 1.23–1.04 (m, 2 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 143.0 (C), 111.1 (CH), 46.8 (CH), 27.5 (CH_2), 24.5 (CH_2), 21.7 (CH_2) ppm. MS (EI): *m*/*z* (%) = 160 (73), 117 (100). HRMS: calcd. for $C_{12}H_{16}$ 160.1252; found 160.1246.

[4+2] Cycloaddition of 1,2-Cyclohexadiene (6) with Furan (11): TBAF (1.0 M in THF, 0.38 mL, 0.38 mmol) was added dropwise to a solution of **5** (97 mg, 0.32 mmol) in furan (**11**, 2.0 mL) at room temperature, and the mixture was stirred at this temperature for 24 h. Then, the mixture was concentrated under reduced pressure and the residue was purified by column chromatography (SiO_2, hexane) to afford a mixture of *endo*/*exo*-1,4,4a,5,6,7-hexahydro-1,4-epoxynaphthalene[7d] (*endo*/*exo*-**12**; 25 mg, 53%; 95:5 *endo*/*exo*) and dimer **10** (4 mg, 15%). Data for *endo*-**12**: ^1H NMR (300 MHz, $CDCl_3$): δ = 6.34 (dd, *J* = 5.5, 1.0 Hz, 1 H), 6.02 (dd, *J* = 5.6, 1.1 Hz, 1 H), 5.57 (s, 1 H), 5.01 (s, 2 H), 2.34 (m, 1 H), 2.16 (m, 1 H), 1.99–1.74 (m, 3 H), 1.52 (m, 1 H), 0.35 (m, 1 H) ppm. MS (EI): *m*/*z* (%) = 148 (19), 91 (100).

[4+2] Cycloaddition of 1,2-Cyclohexadiene (6) with 1,3-Diphenylisobenzofuran (13): Finely powdered anhydrous CsF (76 mg, 0.50 mmol) was added to a solution of **5** (60 mg, 0.20 mmol) and 1,3-diphenylisobenzofuran (**13**; 81 mg, 0.30 mmol) in MeCN/THF (1:1, 2 mL), and the mixture was stirred at room temperature for 24 h. Then, the mixture was concentrated under reduced pressure and the residue was purified by column chromatography (SiO_2; hexane/CH_2Cl_2, 9:1) to afford *endo*/*exo*-9,10-diphenyl-1,2,3,9,9a,10-hexahydro-9,10-epoxyanthracene[7a] (*endo*/*exo*-**14**; 46 mg, 66%; 80:20 *endo*/*exo*) as a colourless oil. Data for *endo*-**14**: ^1H NMR (250 MHz, $CDCl_3$): δ = 7.91–7.82 (m, 2 H), 7.77–7.66 (m, 2 H), 7.53–7.33 (m, 6 H), 7.24–7.16 (m, 2 H), 7.15–7.07 (m, 2 H), 5.68 (dd, *J* = 3.3, 3.2 Hz, 1 H), 3.05 (m, 1 H), 1.69–1.52 (m, 2 H), 0.55–0.35 (m, 2 H), 1.82 (m, 1 H), 2.19 (m, 1 H) ppm. ^{13}C NMR (62.8 MHz, $CDCl_3$): δ = 148.3 (C), 144.4 (C), 144.2 (C), 138.0 (C), 134.8 (C), 128.6 (2 CH), 128.5 (CH), 128.4 (2 CH), 128.2 (2 CH), 127.9 (CH), 127.0 (CH), 126.7 (2 CH), 125.8 (CH), 121.3 (CH), 120.2 (CH), 117.8 (CH), 90.2 (C), 89.8 (C), 48.2 (CH), 26.2 (CH_2), 24.9 (CH_2), 21.9 (CH_2) ppm. MS (CI): *m*/*z* (%) = 351 (40), 333 (100). Data for *exo*-**14**: ^1H NMR (250 MHz, $CDCl_3$): δ = 7.87–7.61 (m, 4 H), 7.43 (m, 6 H), 7.31–7.22 (m, 2 H), 7.20–6.98 (m, 2 H), 5.62 (m, 1 H), 2.52 (m, 1 H), 2.11 (m, 1 H), 1.92 (m, 1 H), 1.82–1.64 (m, 2 H), 1.39 (m, 1 H), 0.80 (m, 1 H) ppm. MS (CI): *m*/*z* (%) = 351 (38), 333 (100).

Cycloaddition of 1,2-Cyclohexadiene (6) with Tropone (15): Finely powdered anhydrous CsF (74 mg, 0.48 mmol) was added to a solution of **5** (74 mg, 0.24 mmol) and tropone (**15**; 24 μL, 0.24 mmol) in MeCN (2.5 mL), and the mixture was stirred at room temperature for 14 h. Then, the mixture was concentrated under reduced pressure and the residue was purified by column chromatography (SiO_2; AcOEt/hexane, 1:20) to afford *endo*/*exo*-**16** (34 mg, 75%; 96:4 *endo*/*exo*) and **17** (6.0 mg, 13%). Data for *endo*-**16**: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 6.75 (dd, J = 11.1, 8.5 Hz, 1 H), 6.62 (ddd, J = 8.2, 7.2, 1.0 Hz, 1 H), 6.00 (ddd, J = 8.3, 7.1, 1.1 Hz, 1 H), 5.83–5.70 (m, 2 H), 3.94 (d, J = 6.6 Hz, 1 H), 3.25 (m, 1 H), 2.35 (m, 1 H), 2.25–1.96 (m, 2 H), 1.91–1.75 (m, 2 H), 1.55 (m, 1 H), 1.08 (m, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 193.0 (C), 148.7 (CH), 139.4 (CH), 132.3 (C), 130.4 (CH), 128.1 (CH), 124.0 (CH), 60.0 (CH), 41.9 (CH), 41.4 (CH), 28.9 (CH_2), 25.5 (CH_2), 22.5 (CH_2) ppm. MS (EI): *m*/*z* (%) = 186 (62), 131 (100). HRMS: calcd. for $C_{13}H_{14}O$ 186.1044; found 186.1046. Data for **17**: ^{1}H NMR (250 MHz, $CDCl_3$): δ = 6.01–5.83 (m, 2 H), 5.73 (m, 1 H), 5.56 (m, 1 H), 5.37 (m, 1 H), 3.39 (m, 1 H), 3.02–2.84 (m, 2 H), 2.17–2.03 (m, 2 H), 1.85–1.72 (m, 3 H), 0.88 (m, 1 H) ppm. ^{13}C NMR (125 MHz, $CDCl_3$): δ = 214.0 (C), 144.1 (C), 128.9 (CH), 125.8 (2 CH), 125.6 (CH), 123.6 (CH), 57.0 (CH), 51.9 (CH), 51.7 (CH), 25.2 (CH_2), 22.0 (CH_2), 21.8 (CH_2) ppm. MS (EI): *m*/*z* (%) = 186 (70), 131 (100). HRMS: calcd. for $C_{13}H_{14}O$ 186.1044; found 186.1040.

Pd-Promoted Reaction of 1,2-Cyclohexadiene (6) with Dimethyl Acetylenedicarboxylate (18): Finely powdered anhydrous CsF (94 mg, 0.61 mmol) was added to a solution of **5** (93 mg, 0.31 mmol), $Pd(PPh_3)_4$ (18 mg, 0.015 mmol) and dimethyl acetylenedicarboxylate (DMAD, **18**; 94 μL, 0.76 mmol) in MeCN (3 mL), and the mixture was stirred at room temperature for 22 h. Then, the mixture was concentrated under reduced pressure, and the residue was purified by column chromatography (SiO_2; Et_2O/hexane, 1:9 to 8:2) to afford **19**[19] (11 mg, 10%) as a colourless oil and **20** (28 mg, 19%) as a white solid. Data for **19**: ^{1}H NMR (250 MHz, $CDCl_3$): δ = 3.88 (s, 6 H), 3.83 (s, 6 H), 2.85–2.73 (m, 4 H), 1.85–1.71 (m, 4 H) ppm. MS (EI): *m*/*z* (%) = 332 (100). HRMS: calcd. for $C_{18}H_{20}O_8$ 322.0896; found 332.0895. Data for **20**: ^{1}H NMR (250 MHz, $CDCl_3$): δ = 5.14 (d, J = 1.4 Hz, 1 H), 4.39 (m, 1 H), 3.90 (s, 3 H), 3.87–3.81 (m, 12 H), 3.67 (s, 3 H), 3.02 (m, 1 H), 2.70 (m, 1 H), 2.02 (m, 1 H), 1.88–1.71 (m, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 168.0 (C), 167.2 (C), 166.8 (C), 166.3 (C), 166.2 (C), 165.0 (C), 150.9 (C), 139.2 (C), 136.4 (C), 135.5 (C), 135.1 (C), 129.8 (C), 129.4 (C), 123.9 (CH), 53.0 (CH_3), 53.0 (CH_3), 52.9 (CH_3), 52.8 (CH_3), 52.5 (CH_3), 51.8 (CH_3), 39.4 (CH), 26.3 (CH_2), 25.2 (CH_2), 16.4 (CH_2) ppm. MS (EI): *m*/*z* (%) = 474 (8), 207 (100). HRMS: calcd. for $C_{24}H_{26}O_{12}$ 474.1162; found 474.1171.

[4+2] Cycloaddition of 1-Methyl-1,2-Cyclohexadiene (23) with 1,3-Diphenylisobenzofuran (13): Finely powdered anhydrous CsF (67 mg, 0.44 mmol) was added to a solution of **9** (54 mg, 0.17 mmol) and 1,3-diphenylisobenzofuran (**13**; 70 mg, 0.26 mmol) in MeCN/THF (2:1, 2 mL), and the mixture was stirred at room temperature for 24 h. Then, the mixture was concentrated under reduced pressure, and the residue was purified by column chromatography (SiO_2; hexane/CH_2Cl_2, 9:1) to afford *endo*/*exo*-9a-methyl-9,10-diphenyl-1,2,3,9,9a,10-hexahydro-9,10-epoxyanthracene (*endo*/*exo*-**24**; 35.6 mg, 56%; 2.1:1 *endo*/*exo*) as white solids and *endo*-4-methyl-9,10-diphenyl-1,2,3,9,9a,10-hexahydro-9,10-epoxyanthracene (*endo*-**25**; 24.2 mg, 38%) as a pale-brown solid. Data for *endo*-**24**: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.94–7.84 (m, 2 H), 7.72–7.63 (m, 2 H), 7.56–7.40 (m, 5 H), 7.34 (m, 1 H), 7.25 (m, 1 H), 7.21–7.03 (m, 3 H), 5.59 (dd, J = 4.2, 2.8 Hz, 1 H), 2.18 (m, 1 H), 1.99 (m, 1 H), 1.91–1.62 (m, 2 H), 1.08 (s, 3 H), 0.95–0.72 (m, 2 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 148.5 (C), 148.2 (C), 145.2 (C), 137.8 (C), 135.2 (C), 128.8 (2 CH), 128.6 (CH), 128.4 (2 CH), 128.1 (2 CH), 127.1 (CH), 127.0 (CH), 125.6 (2 CH), 125.3 (CH), 121.5 (CH), 120.4 (CH), 117.7 (CH), 93.1 (C), 89.6 (C), 46.8 (C), 32.7 (CH_2), 23.4 (CH_2), 21.4 (CH_3), 18.2 (CH_2) ppm. MS (EI): *m*/*z* (%) = 364 (31), 346 (100). HRMS: calcd. for $C_{27}H_{24}O$ 364.1827; found 364.1819. Data for *exo*-**24**: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.87–7.61 (m, 4 H), 7.56–7.45 (m, 4 H), 7.43–7.31 (m, 3 H), 7.27 (m, 1 H), 7.21–7.02 (m, 2 H), 5.57 (dd, J = 6.2, 3.0 Hz, 1 H), 2.15–1.92 (m, 2 H), 1.70 (m, 1 H), 1.37–1.09 (m, 3 H), 0.88 (s, 3 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 147.7 (C), 147.6 (C), 144.9 (C), 137.5 (C), 136.4 (C), 128.3 (2 CH), 128.2 (2 CH), 127.2 (CH), 127.1 (CH), 126.5 (CH), 126.3 (CH), 125.6 (2 CH), 125.4 (2 CH), 120.3 (CH), 119.8 (CH), 117.1 (CH), 91.8 (C), 89.4 (C), 46.3 (C), 31.9 (CH_2), 20.9 (CH_3), 20.7 (CH_2), 17.0 (CH_2) ppm. MS (EI): *m*/*z* (%) = 364 (40), 346 (100). HRMS: calcd. for $C_{27}H_{24}O$ 364.1827; found 364.1821. Data for *endo*-**25**. ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.81 (dd, J = 7.9, 1.5 Hz, 2 H), 7.68 (dd, J = 8.2, 1.3 Hz, 2 H), 7.50–7.22 (m, 8 H), 7.20–7.11 (m, 2 H), 3.11 (m, 1 H), 2.26–1.98 (m, 2 H), 1.84–1.56 (m, 3 H), 1.33 (d, J = 1.7 Hz, 3 H), 0.33 (m, 1 H) ppm. ^{13}C NMR (75 MHz, $CDCl_3$): δ = 146.6 (C), 144.7 (C), 138.0 (C), 137.3 (C), 135.6 (C), 129.8 (2 CH), 128.7 (CH), 128.4 (2 CH), 128.2 (2 CH), 127.9 (CH), 127.8 (C), 127.0 (2 CH), 126.8 (CH), 125.5 (CH), 121.9 (CH), 117.6 (CH), 90.4 (C), 90.1 (C), 48.6 (CH), 31.6 (CH_2), 26.2 (CH_2), 22.6 (CH_2), 19.7 (CH_3) ppm. MS (EI): *m*/*z* (%) = 364 (33), 346 (100). HRMS: calcd. for $C_{27}H_{24}O$ 364.1827; found 364.1818.

Supporting Information (see footnote on the first page of this article): Determination of the relative stereochemistry of *endo*-**16** and **17**; copies of the ^{1}H and ^{13}C NMR spectra.

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