Supporting Information for

Trapping of hexadehydro-Diels-Alder benzenes with exocyclic, conjugated enals as a route to fused spirocyclic benzopyran motifs

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I. General Experimental Protocols

NMR spectra were recorded on either a Bruker Avance 500 MHz spectrometer in CDCl₃ or C₆D₅CD₃. ¹H NMR data are reported according to the following format: chemical shift in ppm [multiplicity, coupling constant(s) in Hz, integral value (to one significant figure), and assignment]. Coupling constant analysis has been guided by protocols we have previously described.¹ Chemical shifts for ¹H spectra are referenced to TMS (δ 0.00 ppm) or the C₆D₅CD₂H resonance (δ 2.09 ppm). Non-first order multiplets are identified as "nfom". Chemical shifts for ¹³C spectra are referenced to CHCl₃ (δ 77.23 ppm) or C₆D₅CD₃ (δ 137.86 ppm). TMS is observable in some of the ¹³C NMR spectra (δ ca. 0.0 ppm).

Infrared spectra were obtained with a Midac Corporation Prospect 4000 FT-IR spectrometer. Thin film samples in attenuated total reflectance (ATR) mode on a germanium window was used.

Electrospray ionization (ESI) mass spec data were collected using a Bruker BioTOF II (ESI-TOF) instrument. PEG was added to analyte samples as an internal calibrant for high-resolution mass spectral (HRMS) measurements. The samples were introduced as solution in methanol.

Flash chromatography was carried out on E. Merck silica gel (230-400 mesh). Thin layer chromatography (TLC) was done on plastic-backed plates of silica gel. Material was visualized by UV irradiation or with a solution of ceric ammonium molybdate followed by heating.

MPLC refers to medium pressure liquid chromatography (50-200 psi) performed on hand-packed silica gel columns (25-35 µm, 60 Å pores). A Fluid Metering Incorporation (FMI) pump and a Waters R401 differential refractive index detector were used.

Reactions done under anhydrous conditions were carried out in flame- or oven-dried glassware under an atmosphere of nitrogen. Anhydrous methylene chloride and THF were passed through a column of activated alumina immediately before use. The reaction temperatures reported are the temperature of the external heating or cooling bath. HDDA-initiated reactions, including many that were carried out at temperatures above the boiling point of the solvent, were typically done in a threaded vial that was closed with an inert, Teflon®-lined screw-cap.

Procedures are given for preparation of all new compounds specifically shown in the manuscript. Copies of their ¹H and ¹³C NMR spectra are also provided. A citation is provided for each known compound that was used; these are not given a unique structure number.
II. Preparation and characterization data for all key compounds

General Procedure for these HDDA cycloisomerization reactions

The indicated triyne (or tetrayne) precursor was added to a glass vial. 1,2-Dichloroethane (DCE) was added to bring the concentration of the multi-yne to 0.02 M. The indicated trapping agent (2 equiv) was then added. The vial was sealed with a Teflon-lined cap and placed in an oil bath held at 100 or 120 °C. After 15 h, the reaction vessel was allowed to cool to room temperature and concentrated, and the residue was then purified by flash column chromatography or medium pressure liquid chromatography (MPLC) on silica gel.

![Diagram of cycloisomerization](image)

Preparation of 5'-methyl-4'-(prop-1-yn-1-yl)-1'-tosyl-2',3'-dihydro-1'H-spiro[cycloheptane-1,7'-pyrano[2,3-g]indole] (17a)

Compound 17a was prepared following the General Procedure using N-(hepta-3,5-diyn-1-yl)-4-methyl-N-(penta-1,3-diyn-1-yl)benzenesulfonamide (15, 30 mg, 93 µmol), 2-cycloheptylideneacetaldehyde (16a, 26 mg, 188 µmol), and DCE (5 mL). After 15 h at 100 °C, the cooled solution was partitioned between EtOAc and 30% aqueous n-butylamine (to remove excess enal, which had a very similar R₁ on silica gel to that of 17a). The EtOAc layer was dried (Na₂SO₄), filtered, and concentrated. Purification of the residue by MPLC (hexanes: ethyl acetate = 5:1) gave the spirocyclic product 5'-methyl-4'-(prop-1-yn-1-yl)-1'-tosyl-2',3'-dihydro-1'H-spiro[cycloheptane-1,7'-pyrano[2,3-g]indole] (17a, 30 mg, 65 µmol, 70%) as a colorless oil.

\[1^H\text{ NMR (500 MHz, CDCl}_3\]: \(\delta 7.39 (d, J = 8.3 \text{ Hz, 2H, SO}_2\text{Ar}_\text{ortho}), 7.17 (d, J = 8.5 \text{ Hz, 2H, SO}_2\text{Ar}_\text{meta}), 6.90 (d, J = 9.9 \text{ Hz, 1H, H1}), 5.73 (d, J = 9.9 \text{ Hz, 1H, H2}), 3.96 (t, J = 7.4 \text{ Hz, CH}_2\text{NTs}), 2.39 (s, 3H, SO₂ArCH₃), 2.26 (s, 3H, ArCH₂H), 2.16 (t, J = 7.4 \text{ Hz, 2H, CH}_2\text{CH}_2\text{NTs}), 2.15–2.08 (nfom, 2H), 2.02 (s, 3H, -C≡CH), 1.82–1.67 (m, 6H), 1.63–1.55 (m, 2H), and 1.53–1.45 (m, 2H).

\[1^C\text{ NMR (125 MHz, CDCl}_3\]: \(\delta 150.4, 144.1, 136.0, 134.6, 131.3, 130.6, 129.8, 127.8, 126.0, 120.0, 119.9, 116.0, 93.1, 80.4, 76.6, 53.1, 39.1, 29.6, 28.7, 22.0, 21.8, 13.8, \text{ and } 4.7\).

IR: 2921, 2856, 1598, 1354, 1164, 1089, 1017, 913 and 814 cm⁻¹.

HRMS (ESI-TOF): Calcd for C₂₈H₂₁NNaO₃S⁺ [M+Na⁺] requires 484.1917; found 484.1920.
Preparation of methyl 5'-methyl-11'-tosyl-11'H-spiro[fluorene-9,3'-pyrano[3,2-a]carbazole]-6'-carboxylate (17b)

Compound 17b was prepared following the General Procedure using methyl 3-(2-((4-methyl-N-(penta-1,3-diyn-1-yl)phenyl)sulfonamido)phenyl)propionate\(^6\) (18, 20 mg, 51 \(\mu\)mol), 2-(9\(H\)-fluoren-9-ylidene)acetaldehyde\(^3\) (16b, 21 mg, 102 \(\mu\)mol), and DCE (2.5 mL). Purification by column chromatography (hexanes: ethyl acetate = 5:1) gave the spirocyclic product methyl 5'-methyl-11'-tosyl-11'H-spiro[fluorene-9,3'-pyrano[3,2-a]carbazole]-6'-carboxylate (17b, 22 mg, 37 \(\mu\)mol, 73%) as a pale yellow oil.

\(^1\)H NMR (500 MHz, CDCl\(_3\)): \(\delta\) 8.18 (d, \(J = 8.8\) Hz, 1H, Ar\(H_5\)), 7.68 (d, \(J = 7.6\) Hz, 2H, H\(_{14}\)), 7.66 (d, \(J = 10.0\) Hz, 1H, H\(_9\)), 7.62 (d, \(J = 7.5\) Hz, 2H, H\(_{11}\)), 7.42 (ddd, \(J = 1.1, 7.5, 7.5\) Hz, 2H, H\(_{13}\)), 7.27–7.33 (m, 2H, H\(_8\) & H\(_6\)), 7.26 (ddd, \(J = 1.0, 7.5, 7.5\) Hz, 2H, H\(_{12}\)), 7.23 (ddd, \(J = 7.7, 7.5, 1.1\) Hz, 1H, H\(_7\)), 7.16 (d, \(J = 8.3\) Hz, 2H, ArSO\(_2\)Ar\(_{ortho}\)), 6.98 (d, \(J = 8.2\) Hz, 2H, ArSO\(_2\)Ar\(_{meta}\)), 5.75 (d, \(J = 10.0\) Hz, 1H, H\(_{10}\)), 3.96 (s, 3H, CO\(_2\)C\(_3\)H\(_3\)), 2.25 (s, 3H, tosyl C\(_3\)H\(_3\)), and 2.05 (s, 3H, Ar carbazole C\(_3\)H\(_3\)).

\(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \(\delta\) 169.1, 152.4, 147.4, 144.8, 141.6, 139.5, 136.2, 132.5, 130.1, 129.2, 128.4, 128.1, 127.22, 127.15, 126.5, 125.8, 125.3, 124.3, 123.7, 122.4, 120.4, 120.3, 119.3, 115.1, 85.4, 52.7, 21.7, and 13.3.

\textbf{IR}: 3064, 1733, 1451, 1372, 1297, 1225, 1187, 1174, 1154, 1085, 1049, 974, and 813 cm\(^{-1}\).

\textbf{HRMS} (ESI-TOF): Calcd for C\(_{37}\)H\(_{27}\)NNaO\(_5\)S\(^+\) [M+Na\(^+\)] requires 620.1502; found 620.1530.
Preparation of (±)-1-benzyl-5'-methyl-4'-(prop-1-yn-1-yl)-1'-tosyl-2',3'-dihydro-1'H-spiro[indoline-3,7'-pyrano[2,3-g]indol]-2-one (17c)

Compound 17c was prepared following the General Procedure using N-(hepta-3,5-diyn-1-yl)-4-methyl-N-(penta-1,3-diyn-1-yl)benzenesulfonamide 4 (15, 30 mg, 93 µmol), 2-(1-benzyl-2-oxoindolin-3-ylidene)acetaldehyde 5 (16c, E:Z = 5:1, 49 mg, 186 µmol), and DCE (5 mL). Purification by MPLC (hexanes:ethyl acetate = 3:1) gave the spirocyclic product (±)-1-benzyl-5'-methyl-4'-(prop-1-yn-1-yl)-1'-tosyl-2',3'-dihydro-1'H-spiro[indoline-3,7'-pyrano[2,3-g]indol]-2-one (17c, 28 mg, 48 µmol, 51%) as a pale yellow solid.

**1H NMR** (500 MHz, CDCl₃): δ 7.56 (d, J = 8.3 Hz, 2H, SO₂ArHortho), 7.45 (ddd, J = 7.4, 1.4, 0.6 Hz, 1H, H6), 7.41 (d, J = 9.9 Hz, 1H, HI), 7.36–7.31 (m, 4H, ArH), 7.30–7.26 (m, 1H, ArH), 7.24–7.22 (m, 1H, ArH), 7.23 (d, J = 8.0 Hz, 2H, SO₂ArHmeta), 7.03 (ddd, J = 7.5, 7.5, 1.0 Hz, 1H, H4), 6.72 (dd, J = 7.9, 0.8 Hz, 1H, H3), 5.63 (d, J = 9.9 Hz, 1H, H2), 4.94 (d, J = 15.8 Hz, 1H, PhCH₃H₅), 4.89 (d, J = 15.8 Hz, 1H, PhCH₃H₅), 4.07 (ddd, J = 13.0, 8.0, 6.5 Hz, CH₃H₃NTs), 3.98 (ddd, J = 13.0, 8.0, 7.5 Hz, CH₃H₃NTs), 2.40 (s, 3H, SO₂ArCH₃), 2.23 (ddd, J = 15.8, 7.9, 6.4 Hz, 1H, CH₃CH₂CH₂NTs), 2.19 (ddd, J = 15.8, 7.8, 7.8 Hz, 1H, CH₃CH₂CH₂NTs), 2.16 (s, 3H, ArCH₂), and 2.01 (s, 3H, -C≡CC₃H₃).

**13C NMR** (125 MHz, CDCl₃): δ 173.8, 150.0, 144.3, 142.4, 136.5, 135.6, 134.4, 132.6, 130.7, 130.1, 129.8, 129.3, 129.1, 128.0, 127.9, 127.6, 127.4, 125.8, 125.7, 125.4, 123.5, 121.1, 119.8, 114.7, 109.8, 94.0, 79.5, 76.4, 53.1, 43.9, 28.8, 21.8, 13.9 and 4.8. (*these two resonances are likely from an impurity present in the sample used to record the 1D ¹³C data).

**IR**: 2918, 2850, 1729, 1613, 1488, 1467, 1353, 1165, 1089, and 995 cm⁻¹.

**HRMS (ESI-TOF)**: Calcd for C₃₆H₃₀N₆NaO₄S⁺ [M+Na]⁺ requires 609.1818; found 609.1808.

**m.p.** 133–134 °C
Preparation of tert-butyl 5'-methyl-11'-tosyl-6'-(trifluoromethyl)-11'H-spiro[piperidine-4,3'-pyrano[3,2-a]carbazole]-1-carboxylate (17d)

Compound 17d was prepared following the General Procedure using 4-methyl-N-(penta-1,3-diyn-1-yl)-N-(2-(3,3,3-trifluoroprop-1-yn-1-yl)phenyl)benzenesulfonamide (10, 15 mg, 37 µmol), tert-butyl 4-(2-oxoethylidene)piperidine-1-carboxylate (7, 17 mg, 0.075 mmol), and DCE (2 mL). Purification by column chromatography (hexanes: ethyl acetate = 5:1) gave the spirocyclic product tert-butyl 5'-methyl-11'-tosyl-6'-(trifluoromethyl)-11'H-spiro[piperidine-4,3'-pyrano[3,2-a]carbazole]-1-carboxylate (17d, 22 mg, 35 µmol, 95%) as a pale yellow oil.

**1H NMR** (500 MHz, CDCl₃): δ 8.14 (ddq, J = 8.2, 1.2, 0.6 Hz, 1H, ArH₅), 7.80 (br d, J = 8.1 Hz, 1H, ArH₈), 7.36 (ddd, J = 8.2, 7.3, 1.2 Hz, 1H, ArH₆), 7.253 (d, J = 9.6 Hz, 1H, ArH₉), 7.252 (ddd, J = 8.2, 7.4, 1.2 Hz, 1H, ArH₇), 6.90 (d, J = 8.5 Hz, 2H, ArSO₂Arortho), 6.86 (d, J = 8.2 Hz, 2H, ArSO₂Armeta), 5.74 (d, J = 9.8 Hz, 1H, H₁₀), 3.98 (br s, 2H, H₁₂a), 3.34 (br app t, J = 10.6 Hz, 2H, H₁₂b), 2.50 (br, J = 13.6 Hz, 2H, H₁₁b), 2.20 (br, J = 13.7 Hz, 2H, H₁₁a), 1.80 (br ddd, J = 13.7, 11.8, 4.8 Hz, 2H, H₁₁b), and 1.50 [s, 9H, NCO₂C(CH₃)₃].

Because this product contains a CF₃ group, the resonances for several carbon atoms in the 13C NMR spectrum of 17d are observed as quartets; for each, the midpoint of the multiplet (i.e., the actual chemical shift) is given in the line listing.

**13C NMR** (125 MHz, CDCl₃): δ 155.0, 150.4, 144.9, 141.8, 137.2, 131.3, 128.9, 128.3, 127.2, 127.1, 126.9, 126.1, 125.1 (q, J = 274.8 Hz), 124.4 (q, J = 1.8 Hz), 123.4 (q, J = 7.5 Hz), 123.3, 122.7 (q, J = 3.3 Hz), 122.0 (q, J = 32.0 Hz), 119.5, 117.6, 80.0, 75.7, 39.9 (v br), 34.9 (br), 28.7, 21.6, and 12.8 (q, J = 4.5 Hz).

**IR**: 2978, 2931, 2875, 1738, 1697, 1374, 1324, 1249, 1223, 1176, 1147, 1117, 1081, 1016, and 965 cm⁻¹.

Preparation of a diastereomeric mixture of 1'-(tert-buty1) 5'-methyl (5'S,7'R)- and (5'S,7S)-5-methyl-4-(prop-1-yn-1-yl)-1-tosyl-2,3-dihydro-1H-spiro[pyrano[2,3-g]indole-7,2'-pyrrolidine]-1',5'-dicarboxylate (17e)

Compound 17e was prepared following the General Procedure using N-(hepta-3,5-diyn-1-yl)-4-methyl-N-(penta-1,3-diyn-1-yl)benzenesulfonyamide (15, 30 mg, 93 µmol), 1-(tert-buty1) 2-methyl (S,E)-5-(2-oxoethylidene)pyrrolidine-1,2-dicarboxylate8 (16e, 50 mg, 186 µmol), and DCE (5 mL). Purification by MPLC (hexanes: ethyl acetate = 3:1) gave a mixture of the diastereomeric spirocyclic products (5'S,7R)- and (5'S,7S)-17e (42 mg, 71 µmol, 76%) as a colorless oil.

**Major diastereomer:**
Data extracted from the proton spectrum of the ca. 3:1 mixture of (coeluting) diastereomers, collected at 360 K in toluene. The proton NMR spectrum recorded at ambient temperature has many broadened resonances because of interconversions (N-Boc rotation and N-tosyl pyramidalization) whose rates are comparable to those of the “NMR time scale.” The configuration of the spirocyclic stereogenic for each of the two diastereomers could not be deduced by NOE experiments.

**1H NMR (500 MHz, toluene-d8, 360 K):** 7.46 (d, J = 8.2 Hz, 2H, SO2Arortho), 7.44 (d, J = 8.1 Hz, 1H, H9), 6.69 (d, J = 10.1 Hz, 1H, H8), 5.87 (d, J = 10.1 Hz, 1H, H5'), 4.61 (br dd, J = 8.9, 1.1 Hz, 1H, H5'), 3.89 (ddd, J = 12.8, 8.1, 4.6 Hz, 1H, CHaHbNTs), 3.67 (ddd, J = 12.8, 8.5, 8.5 Hz, 1H, CHaHbNTs), 3.43 (s, 3H, CO2C2H5), 2.32 (s, 3H, Ts-C2H5), 2.26-2.21 (m, 1H), 2.19–2.10 (m, 3H, CH2CH2NTs and CH2NTs), 1.98 (ddd, J = 12.3, 13.2, 7.1, 0.7 Hz, 1H, H3'b), 1.87 (s, 3H, ArCH2), 1.66 (ddd, J = 12.6, 7.2, 1.4, 1.4 Hz, 1H, H4'b), 1.64 (s, 3H, -C≡CH2), and 1.26 [s, 9H, -C(C2H5)3].

**13C NMR (125 MHz, toluene-d8, 360 K):** δ 173.0, 151.6, 143.70, 136.8, 131.9, 129.65, 128.7, 125.0, 123.9, 121.0, 115.1, 94.5, 93.4, 81.0, 77.7, 61.6, 53.6, 51.7, 42.3, 40.9, 29.5, 28.6, 26.2, 21.3, and 13.8. (two aromatic and two aliphatic resonances could not be observed, likely due to complications from the toluene solvent resonances in the aromatic region).

**Minor diastereomer** (see comments above for the “major diastereomer”)

**1H NMR (500 MHz, toluene-d8, 360 K):** 7.50 (d, J = 10.0 Hz, 1H, H9), 7.49 (d, J = 8.3 Hz, 2H, SO2Arortho), 6.69 (d, J = 8.1 Hz, 2H, SO2Armeta), 5.39 (d, J = 10.1 Hz, 1H, H8), 4.32 (dd, J = 7.6, 7.6 Hz, 1H, H5'), 3.88 (m, 1H, CH2H3NTs), 3.72 (m, 1H, CH2H3NTs), 3.49 (s, 3H, CO2CH3), 2.46 (s, 3H, Ts-CH3), 2.27-2.21 (m, 1H), 2.19–2.10 (m, 3H, CH2CH2NTs and H3'a), 2.01 (ddd, J = 12.4, 9.5, 7.2, 7.2 Hz, 1H, H4'a), 1.87 (s, 3H, ArMe), 1.81 (m, 1H), 1.63 (s, 3H, -C≡CCH3), and 1.25 [s, 9H, -C(CH3)3].

**13C NMR (125 MHz, CDCl3):** δ 172.7, 151.9, 143.70, 136.8, 131.9, 129.65, 128.7, 125.0, 123.9, 121.1, 114.9, 93.6, 93.3, 80.8, 77.8, 61.9, 53.7, 51.6, 42.3, 29.4, 28.8, 26.5, and 13.8. (two aromatic and two aliphatic resonances could not be observed, likely due to complications from the toluene solvent resonances in the aromatic and methyl region and/or coincidental overlap with an aliphatic carbon in the major diastereomer).

**IR:** 2975, 2954, 2921, 1746, 1721, 1698, 1598, 1392, 1355, 1205, 1163, 1084, and 1015 cm−1.

**HRMS (ESI-TOF):** Calcd for C32H36N2NaO7S+ [M+Na]+ requires 615.2135; found 615.2143.
III. References for the Supporting Information

125 MHz
CDCl₃, 298 K

Supporting Information

Spiropyran

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125 MHz
CDCl₃, 298 K

Supporting Information

Spiropyran

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17c

Supporting Information

Spiropyran

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Supporting Information

Spiropyran

500 MHz
CDCl₃, 298 K

17d
Supporting Information

Spiropyran

500 MHz C6D5CD3, 360 K

17e