10.1071/CH14211_AC

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SUPPLEMENTARY MATERIAL

Enantioselective Pd-catalysed deallylative γ-lactonisation of propargyl carbazolones, mechanistic insight into the decarboxylative allylation of carbazolones.

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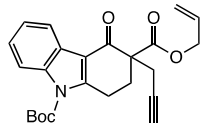
I General Experimental

Proton and carbon nuclear magnetic resonance (^{1}H-NMR, ^{13}C-NMR) spectra were recorded at 30 ˚C using a Bruker DRX400 spectrometer operating at 400 MHz for proton and 100 MHz for carbon nuclei. Chemical shifts (δ) are reported relative to the residual proton peak in the solvent used as specified. Infrared spectra (ν_{max}) were recorded using a Perkin-Elmer RXI FTIR Spectrometer or a Bruker Equinox 55 Infrared Spectrometer fitted with a Specac Diamond ATR source. RXI FTIR samples were analysed as thin films on NaCl plates for oils or as KBr discs for solids and all IR bands are expressed in cm^{-1}. High resolution mass spectrometry (HRMS) was performed using a Agilent series 6500 accurate-mas quadrupole time-of-flight (Q-TOF) LC/Ms system. Analytical chiral HPLC was performed with a Perkin Elmer Series 200 HPLC using Chiralpak OD-H, AD-H or OJ-H columns (4.6 mm x 25 cm) obtained from Daicel Chemical Industries, Ltd. with visualization at 238 nm. Melting points were measured on a Stuart Scientific Melting Point Apparatus in an open capillary. Analytical thin layer chromatography (TLC) was performed using aluminium-backed plates coated with 0.2 mm silica (Merck, DC-Platten, Kieselgel; 60 F_{254} plates). Eluted plates were visualised using a 254 nm UV lamp and/or by treatment with a suitable stain followed by heating. Flash column chromatography was performed on silica gel (Davisil LC60A, 40-63 μm silica media) using compressed air or nitrogen.

Starting materials and reagents were purchased from Sigma-Aldrich, Alfa-Aesar, D-L Chiral or Oakwood chemicals and were used as supplied or, in the case of some liquids, distilled. Tetrahydrofuran (THF) was distilled from sodium benzophenone ketyl. Concentration under reduced pressure was performed on a rotary evaporator with the bath temperature not exceeding 40 °C. All reactions were conducted under an atmosphere of nitrogen unless otherwise specified

II Synthetic Procedures

(±)-3-Allyl 9-(*tert*-butyl) 4-oxo-3-(prop-2-yn-1-yl)-1,2,3,4-tetrahydro-9*H*-carbazole-3,9-dicarboxylate (2a)

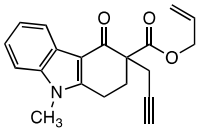


Sodium hydride (30 mg of 60 % dispersion in mineral oil, 0.75 mmol) was added portionwise to a magnetically stirred solution of carbazolone allyl ester (0.60 mmol) in tetrahydrofuran (25 ml) at 0 ˚C and the reaction was stirred at this temperature for 20 min. Propargyl Bromide (111.5 mg of an 80 wt. % solution in toluene, 0.75 mmol) was added and the reaction was allowed to warm to room temperature over 4 hours. The mixture was diluted with diethyl ether (5 ml) and water (5 ml). The layers were separated and the aqueous phase extracted with another portion of diethyl ether (5 ml). The combined organic was washed with brine (10 ml), dried ($MgSO_4$), filtered and concentrated under reduced pressure. The crude material was purified using flash column chromatography to afford the title compound (**2a**) in 89% yield.

M.p. 130.5 – 132.1 ºC. ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.30 – 8.27, (m, 1H), 8.11 – 8.08 (m, 1H), 7.34 – 7.32 (m, 2H), 5.82 (ddt, *J* = 17.2, 10.8, 5.6 Hz, 1H), 5.23 (dd, *J* = 17.2, 1.2 Hz, 1H), 5.16 (dd, *J* = 10.8, 1.2 Hz, 2H), 4.66 – 4.56 (m, 2H), 3.57 – 3.41 (m, 2H), 3.10 (dd, *J* = 17.2, 2.8 Hz, 1H), 2.87 – 2.81 (m, 2H), 2.50 – 2.43 (m, 1H), 2.05 (t, *J* = 2.8 Hz, 1H), 1.71 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ 189.6, 170.0, 151.6, 149.8, 136.3, 131.6, 125.9, 125.3, 124.7, 121.7, 118.5, 116.3, 115.4, 85.9, 79.9, 71.6, 66.2, 56.4, 30.8, 28.3, 24.3, 23.8. IR ν_{max} 2980, 1789, 1651, 1567, 1480, 1450, 1409, 1365, 1299, 1258, 1156, 1113, 916, 668 cm^{-1}. HRMS (ESI) m/z calculated for $C_{24}H_{25}NO_5$ $[M+Na]^+$ requires 430.1625: found 430.1621

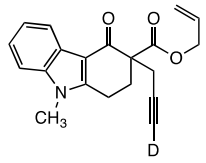
(±)-Allyl 9-methyl-4-oxo-3-(prop-2-yn-1-yl)-2,3,4,9-tetrahydro-1*H*-carbazole-3-carboxylate (**2b**)

The title compound (**2b**) was prepared using the procedure outlined above in >95% isolated yield.



R_f = 0.46 (1:1, v/v EtOAC−Hexanes). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23-8.22 (m, 1H), 7.29-7.26 (m, 3H), 5.84 (m, 1H), 5.20-5.15 (m, 2H), 4.58 (ddt, *J* = 12.4, 5.4, 1.6 Hz, 2H), 3.69 (s, 3H), 3.32-3.23 (m, 1H), 3.22-3.21 (d, *J* = 16.0 Hz, 1H), 3.00-2.87 (m, 2H), 2.80 (d, *J* = 16.0 Hz, 1H), 2.50-2.43 (m, 1H), 2.04 (t, *J* = 2.8 Hz, 1H). ^{13}C NMR (100 MHZ, $CDCl_3$) δ 187.3, 170.4, 151.4, 137.6, 131.7, 125.1, 123.4, 122.8, 121.7, 118.2, 111.3, 109.3, 80.3, 71.4, 65.9, 56.3, 30.5, 29.8, 24.5, 19.9. IR ν_{max} 2925, 1610, 1419, 1402, 1327, 1264, 1041, 923, 895, 756 cm^{-1}. MS (ESI) m/z calculated for $C_{20}H_{19}NO_3$ $[M+Na]^+$ requires 344.1: found 344.1

(±)-Allyl 9-methyl-4-oxo-3-(prop-2-yn-1-yl-3-*d*)-2,3,4,9-tetrahydro-1*H*-carbazole-3-carboxylate (D-2b)



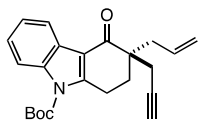
To a magnetically stirred solution of diisopropylamine (0.07 ml, 0.50 mmol) in tetrahydrofuran (10 ml) at –78 ˚C was added *n*-butyl lithium (0.32 ml of a 1.6 M solution in hexanes, 0.50 mmol) dropwise. After 20 minutes at this temperature the mixture was transferred *via* cannula to a second flask containing a suspension of the carbazalone (**2b**) (0.50 mmol) in tetrahydrofuran (10 ml) at –78 ˚C. The mixture was stirred at this temperature for 1.5 hours before the addition of neat deuterium oxide (2mL, 110.5 mmol), the reaction was stirred at –78 ˚C for 0.5 hours. The solvent was then

removed under reduced pressure. The crude material was purified using flash column chromatography (1:1 v/v, EtOAC−Hexanes) to yield the product (**D-2b**) in 99% yield.

R_f = 0.46 (1:1, v/v EtOAC−Hexanes). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23-8.22 (m, 1H), 7.29-7.26 (m, 3H), 5.84 (m, 1H), 5.20-5.15 (m, 2H), 4.58 (ddt, *J* = 12.4, 5.4, 1.6 Hz, 2H), 3.69 (s, 3H), 3.32-3.23 (m, 1H), 3.22-3.21 (d, *J* = 16.0 Hz, 1H), 3.00-2.87(m, 2H), 2.80 (d, *J* = 16.0 Hz, 1H), 2.50-2.43 (m, 1H). ^{13}C NMR (100 MHZ, $CDCl_3$) δ 187.3, 170.4, 151.4, 137.8, 131.7, 125.0, 123.3, 122.8, 121.6, 118.1, 111.2, 109.3, 79.9, 71.4 (t) 65.9, 56.3, 30.4, 29.8, 24.5, 19.9. IR ν_{max} 2925, 1610, 1419, 1402, 1327, 1264, 1041, 923, 895, 756 cm^{-1}.

***tert*-Butyl (*S*)-3-allyl-4-oxo-3-(prop-2-yn-1-yl)-1,2,3,4-tetrahydro-9*H*-carbazole-9-carboxylate (1a)**

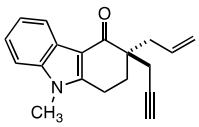
The title compound was prepared in 89% isolated yield using previously reported conditions in which the reaction was conducted for 4 hours.[1]



R_f = 0.53 (1:1, v/v EtOAC−Hexanes). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.33-8.28 (m, 1H), 8.11-8.06 (m, 1H), 7.35-7.30 (m, 2H), 5.82-5.72 (m, 1H), 5.13-5.08 (m, 2H), 3.45-3.29 (m, 2H), 2.58-2.53 (m, 3H), 2.45-2.25 (m, 3H), 2.03 (t, *J* = 2.8Hz, 1H), 1.72 (s, 9H). IR ν_{max} 2938, 1737, 1650, 1413, 1372, 1352, 1303, 1234, 1149, 845, 769, 752, 741 cm^{-1}.

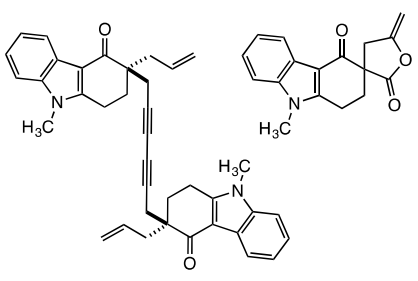
(*S*)-3-Allyl-9-methyl-3-(prop-2-yn-1-yl)-1,2,3,9-tetrahydro-4*H*-carbazol-4-one (1b)

The title compound was prepared in 16% yield using previously reported conditions in which the reaction was conducted for 4 hours.[1]



R_f = 0.63 (1:1, v/v EtOAC−Hexanes). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23-8.25 (m, 1H), 7.32-7.26 (m, 3H), 5.87-5.76 (m, 1H), 5.13-5.67 (m, 2H), 3.71 (s, 3H), 3.03-2.98 (m, 2H), 261-2.54 (m, 3H), 2.43-2.28 (m, 3H), 2.02 (t, *J* = 2.8 Hz, 1H). IR ν_{max} 2925, 1610, 1402, 1327, 1264, 1041, 923, 895, 756 cm^{-1}.

9-Methyl-5'-methylene-1,4',5',9-tetrahydro-2'*H*-spiro[carbazole-3,3'-furan]-2',4(2*H*)-dione (9) and 3,3'-(hexa-2,4-diyne-1,6-diyl)bis(3-allyl-9-methyl-1,2,3,9-tetrahydro-4*H*-carbazol-4-one) (10)



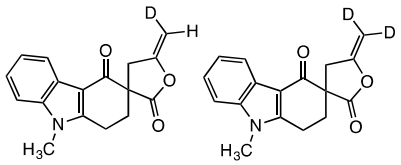
The title compounds were prepared in a combined yield of 98% using previously reported conditions with the reaction conducted for 24 hours.[1] The two materials were separable by column chromatography.

γ-lactone 9: R_f = 0.31 (1:1, v/v EtOAC−Hexanes). HPLC Daicel AD-H, λ = 238 nm, hexane : i-PrOH = 90 : 10, 1.0 ml/min, fraction tr = 32.36 and 39.61, ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.21-8.11 (m, 1H), 7.32-7.26 (m, 3H), 4.83 (dd, *J* = 4.6, 2.0 Hz, 1H), 4.42 (dd, *J* = 4.6, 2.0 Hz, 1H), 3.77-3.70 (m, 4H), 3.47-3.39 (m, 1H), 3.00-2.99 (m, 1H), 2.73-2.63 (m, 2H), 2.42-2.35(m, 1H). IR ν_{max} 2923, 2845, 1780, 1631, 1480, 1456, 1421, 1128, 1043, 864, 754. **Diyne 10**: R_f = 0.39 (1:1, v/v EtOAC−Hexanes). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.23-8.25 (m, 2H), 7.32-7.26 (m, 6H), 5.87-5.76 (m, 2H), 5.13-5.67 (m, 4H), 3.71 (s, 6H), 3.03-2.98 (m, 4H), 261-2.54 (m, 6H), 2.43-2.28 (m,

[1] C. J. Gartshore, D. W. Lupton, *Angew. Chem. Int. Ed.*, **2013**, *52*, 4113.

6H). IR ν_{max} 2927, 1730, 1625, 1482, 1422, 1229, 1184, 966, 951, 892, 760 cm^{-1}. HRMS (ESI) m/z calculated for $C_{20}H_{17}NO_2$ $[M+H]^+$ requires 553.2850: found 553.2852

9-Methyl-5'-(methylene-*d*$_2$)-1,4',5',9-tetrahydro-2'*H*-spiro[carbazole-3,3'-furan]-2',4(2*H*)-dione (D_2-9) and (*E*)-9-methyl-5'-(methylene-*d*)-1,4',5',9-tetrahydro-2'*H*-spiro[carbazole-3,3'-furan]-2',4(2*H*)-dione (**D** *–trans*-**9**)

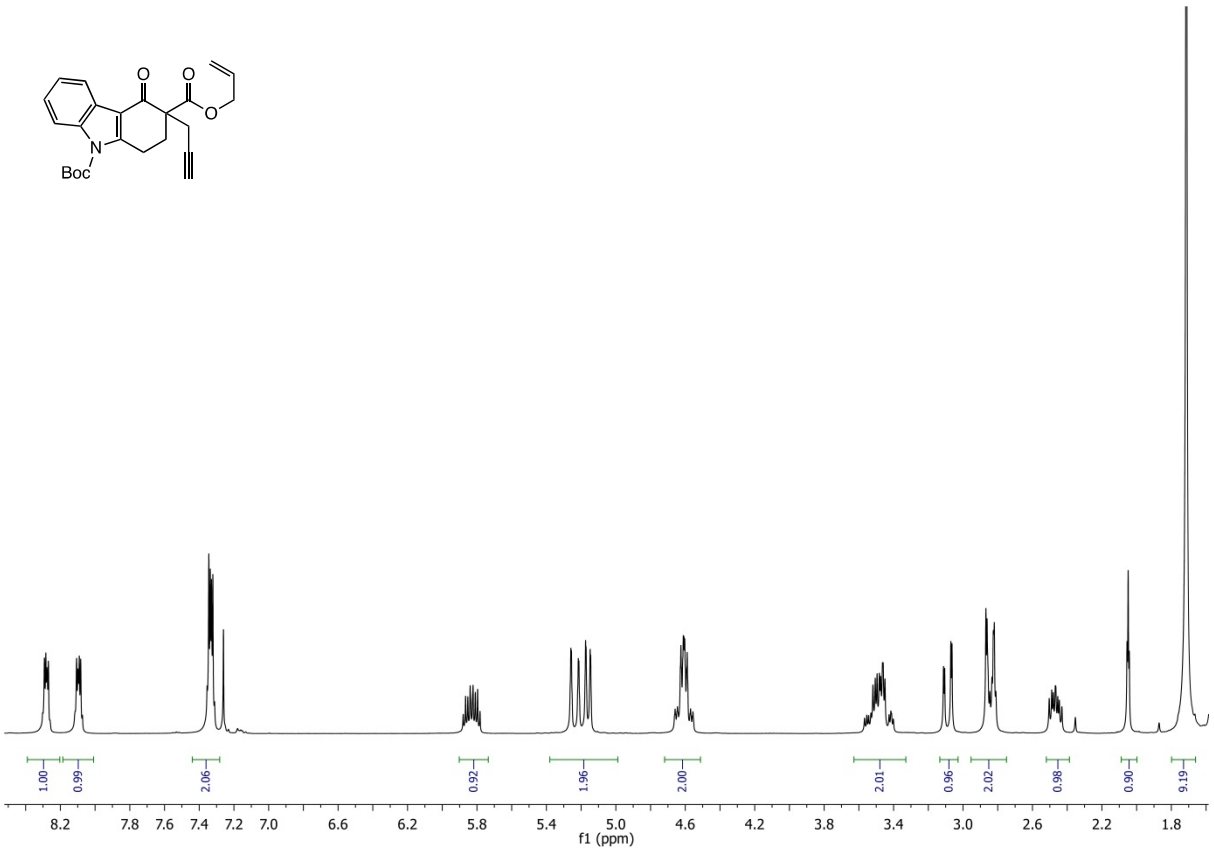


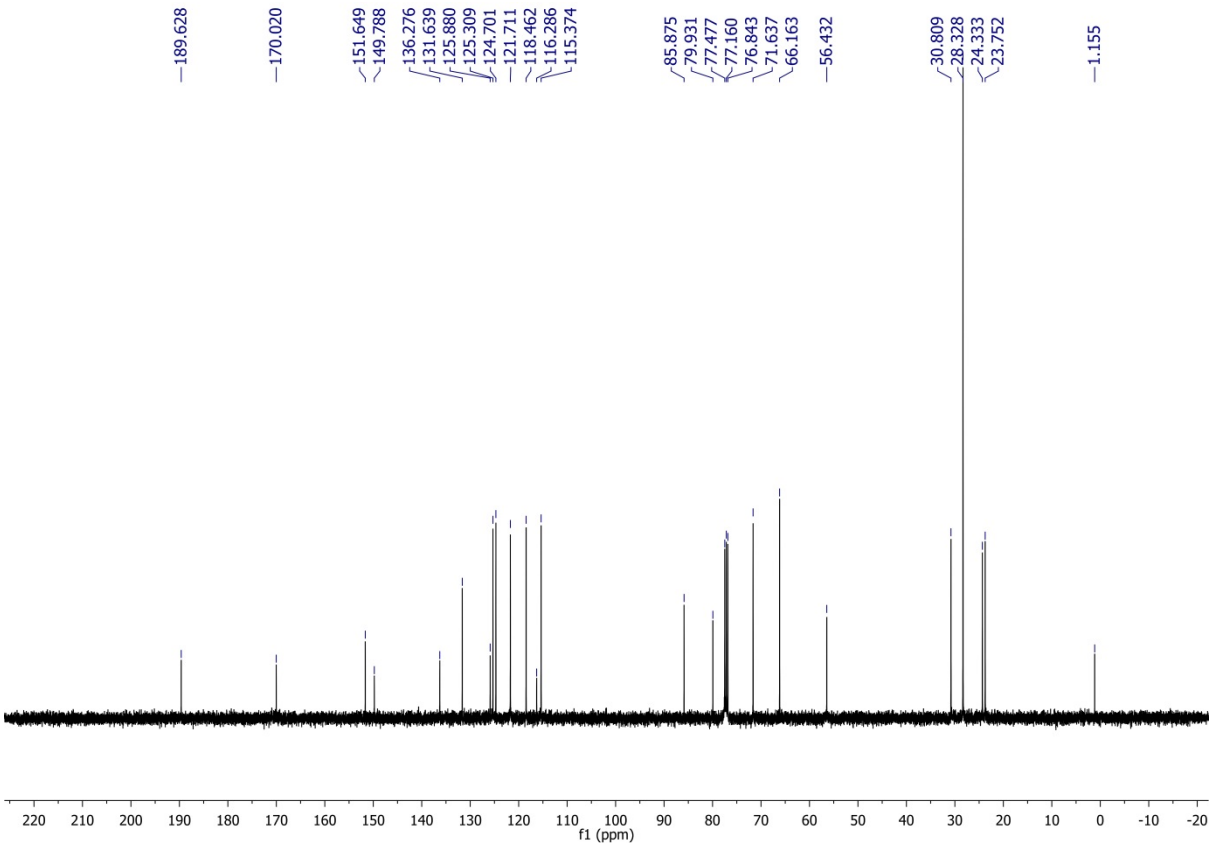
The title compounds were prepared using previously reported conditions with the reaction conducted for 24 hours.[1]

R_f = 0.31 (1:1, v/v EtOAC−Hexanes). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.21-8.11 (m, 1H), 7.32-7.26 (m, 3H), 4.42 (dd, *J* = 4.6, 2.0 Hz, 0.18H), 3.77-3.70 (m, 4H), 3.47-3.39 (m, 1H), 3.00-2.99 (m, 1H), 2.73-2.63 (m, 2H), 2.42-2.35(m, 1H). IR ν_{max} 2923, 2845, 1780, 1631, 1480, 1456, 1421, 1128, 1043, 864, 754 cm^{-1}.

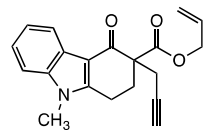
III ^{1}H and ^{13}C NMR spectra

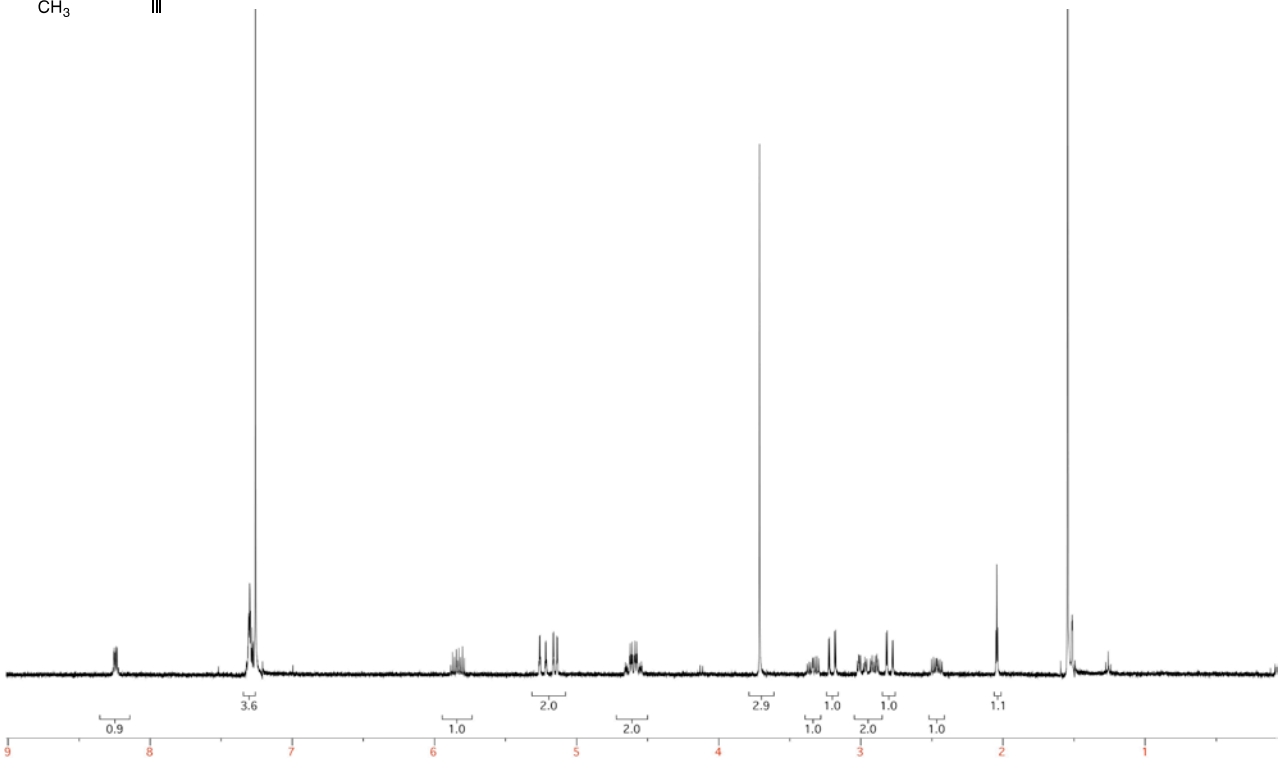
(±)-3-Allyl 9-(*tert*-butyl) 4-oxo-3-(prop-2-yn-1-yl)-1,2,3,4-tetrahydro-9*H*-carbazole-3,9-dicarboxylate (2a)





(±)-Allyl 9-methyl-4-oxo-3-(prop-2-yn-1-yl)-2,3,4,9-tetrahydro-1*H*-carbazole-3-carboxylate (2b)





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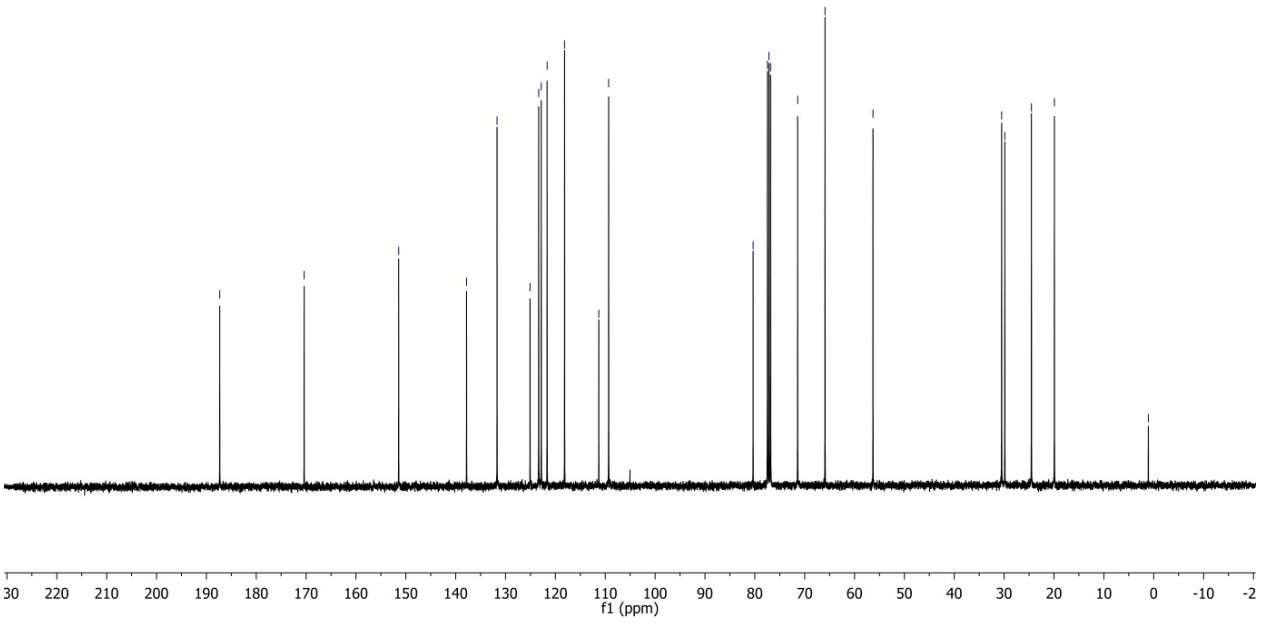
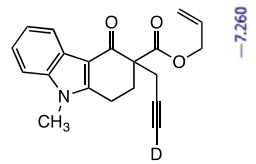
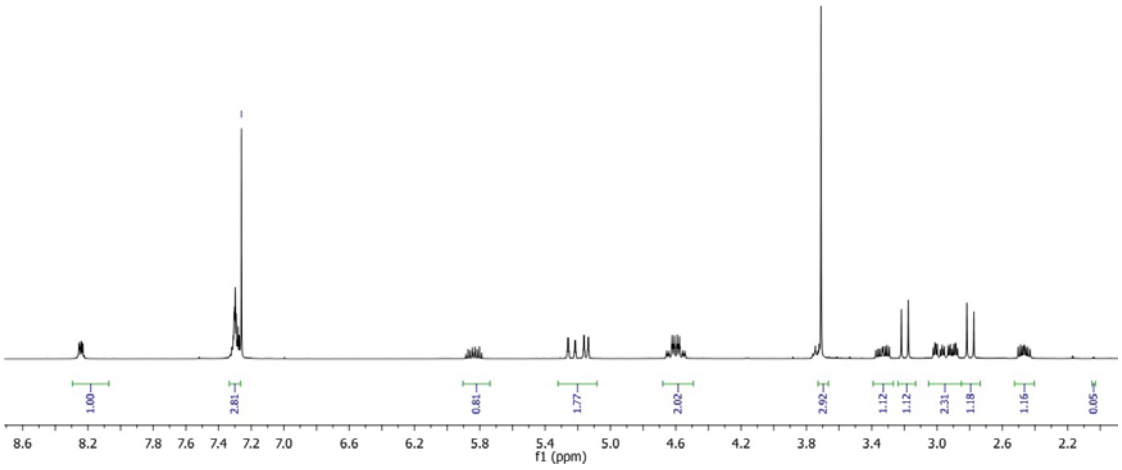
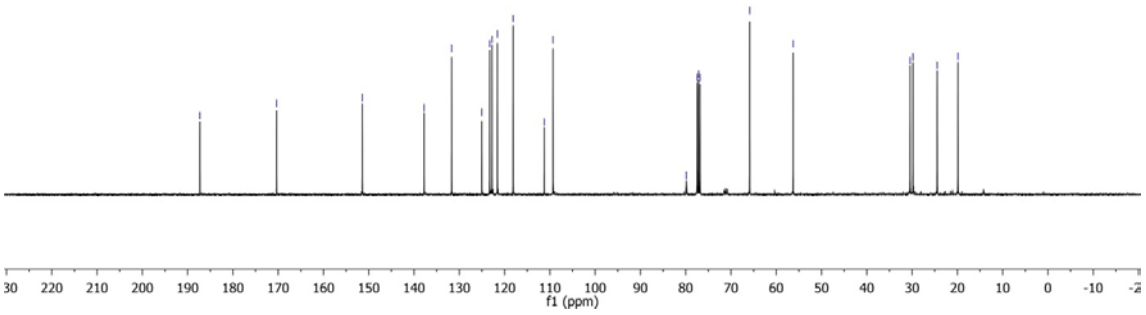


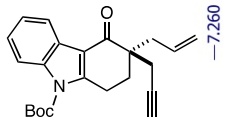
(±)-Allyl 9-methyl-4-oxo-3-(prop-2-yn-1-yl-3-*d*)-2,3,4,9-tetrahydro-1*H*-carbazole-3-carboxylate (D-2b)

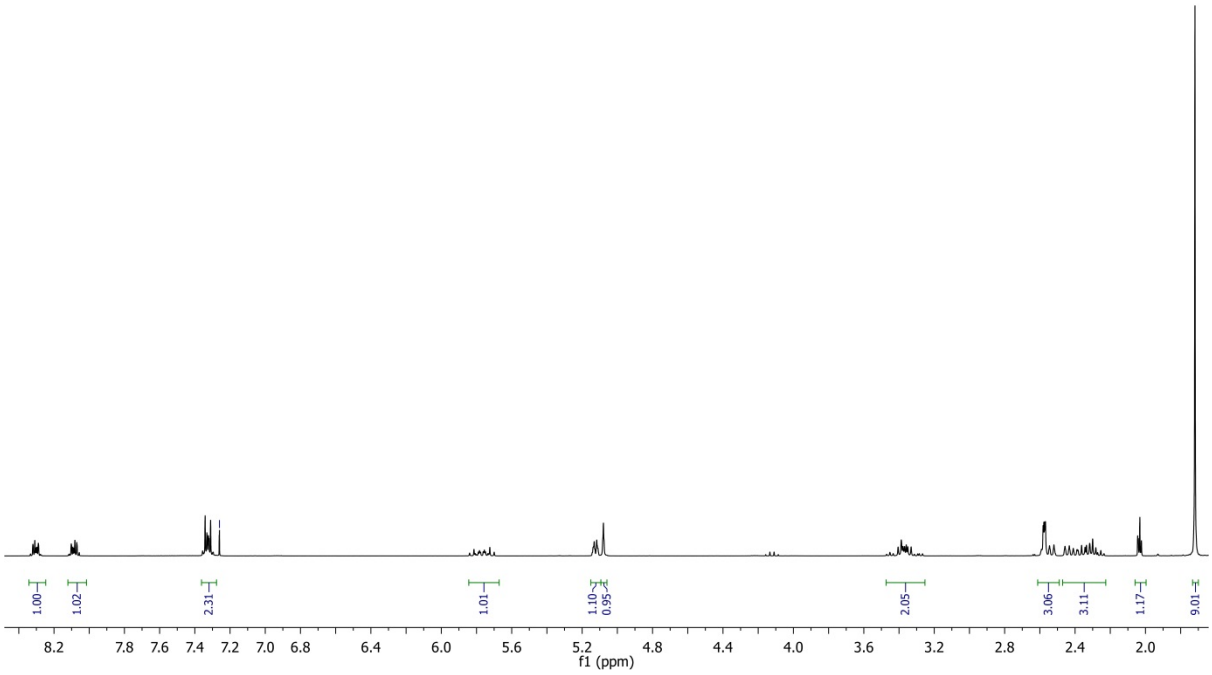




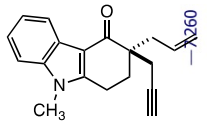


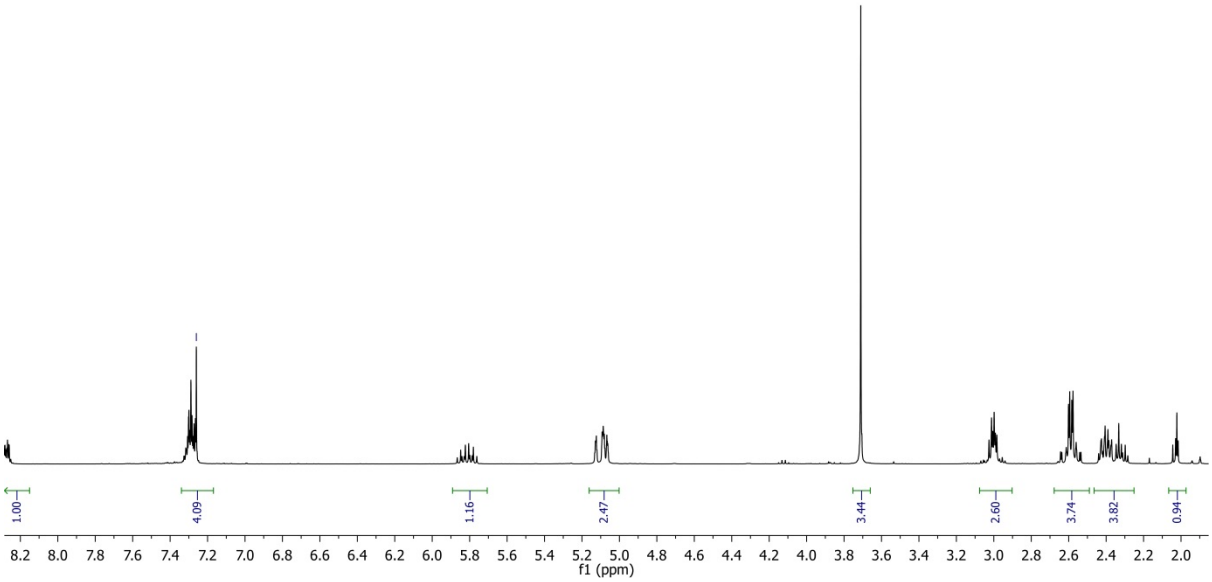
***tert*-Butyl (*S*)-3-allyl-4-oxo-3-(prop-2-yn-1-yl)-1,2,3,4-tetrahydro-9*H*-carbazole-9-carboxylate (1a)**



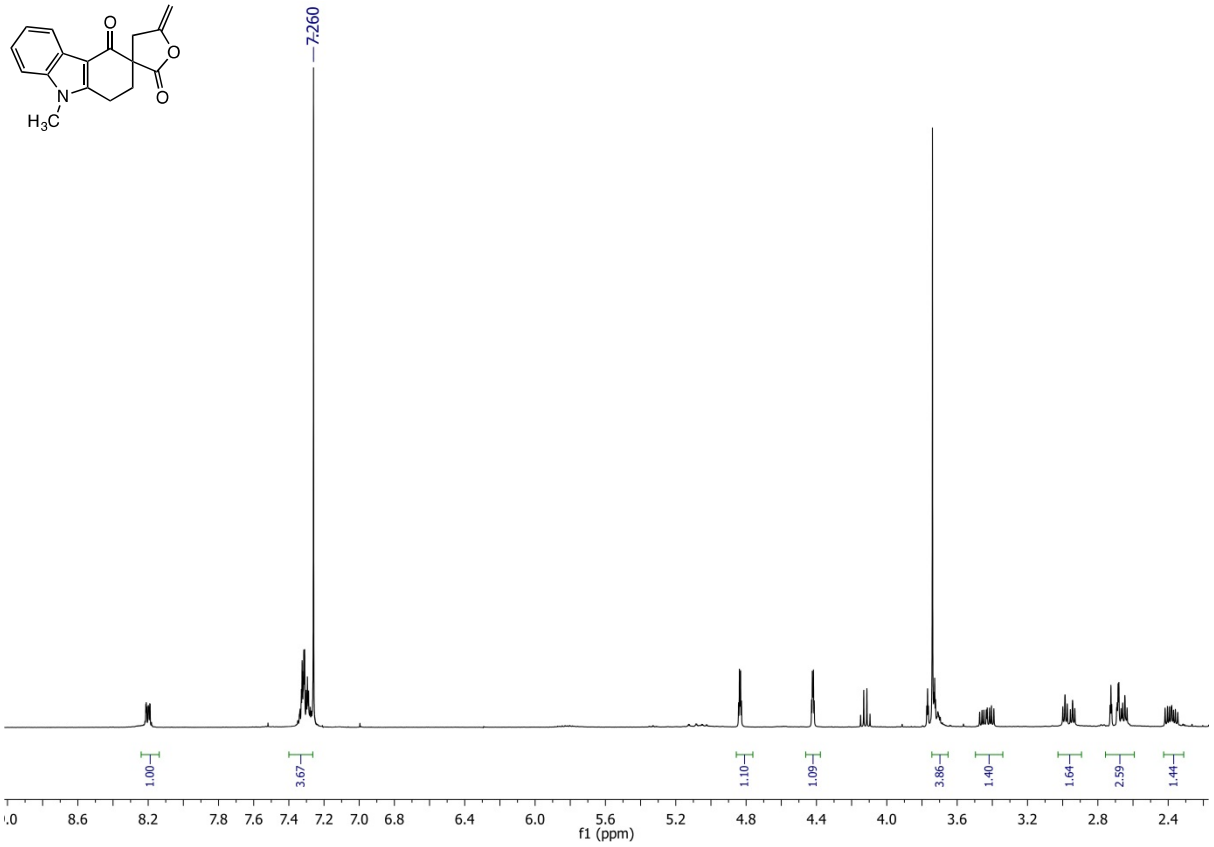


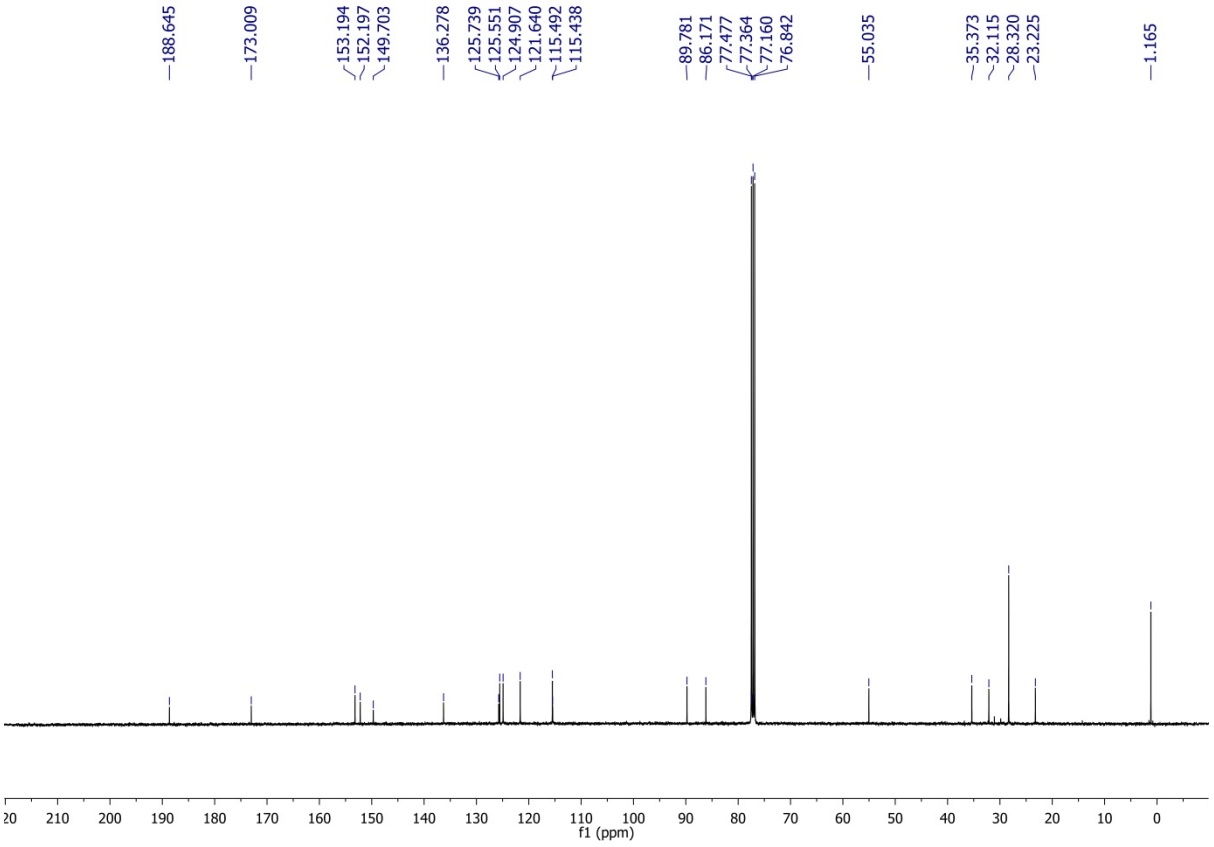
(*S*)-3-Allyl-9-methyl-3-(prop-2-yn-1-yl)-1,2,3,9-tetrahydro-4*H*-carbazol-4-one (1b)

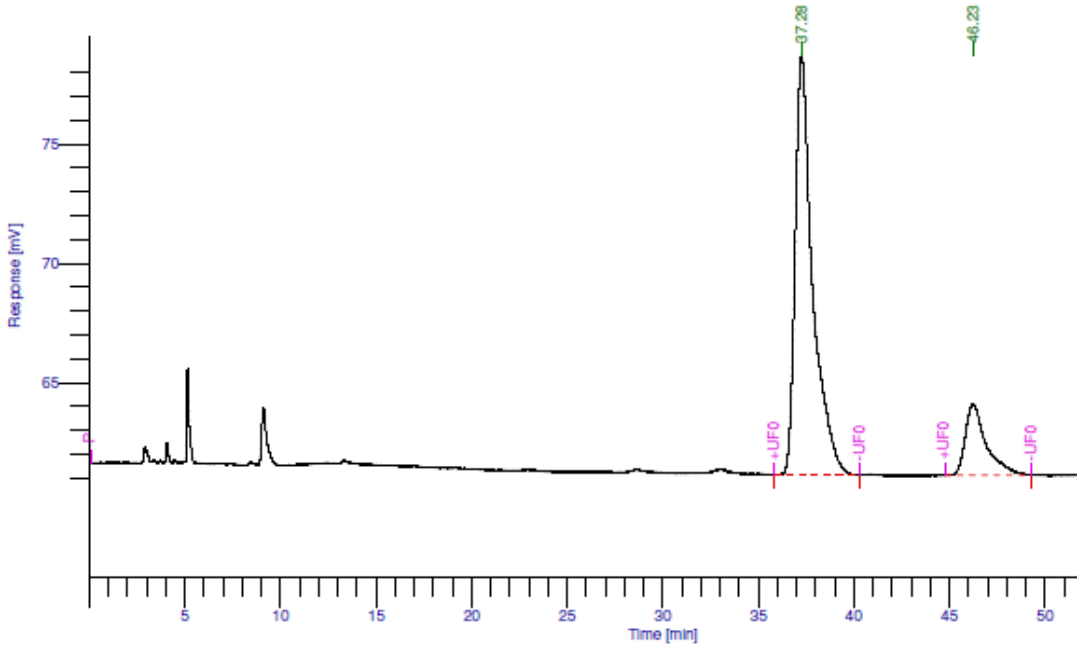




9-Methyl-5'-methylene-1,4',5',9-tetrahydro-2'*H*-spiro[carbazole-3,3'-furan]-2',4(2*H*)-dione (9)







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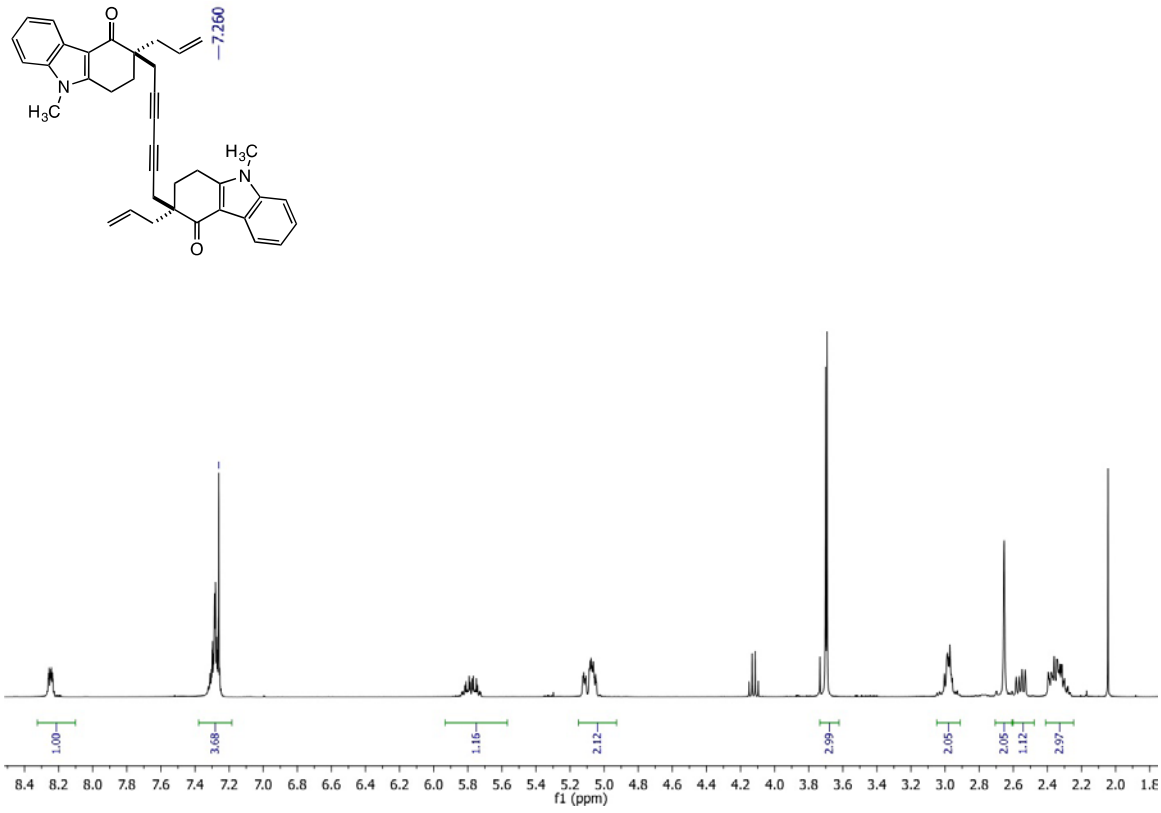
			1344263.90	20551.67	100.00	100.00		1.3443	1.3443

3,3'-(hexa-2,4-diyne-1,6-diyl)bis(3-allyl-9-methyl-1,2,3,9-tetrahydro-4*H*-carbazol-4-one) (10)



9-Methyl-5'-(methylene-d_2)-1,4',5',9-tetrahydro-2'*H*-spiro[carbazole-3,3'-furan]-2',4(2*H*)-dione (D_2-9) and (*E*)-9-methyl-5'-(methylene-*d*)-1,4',5',9-tetrahydro-2'*H*-spiro[carbazole-3,3'-furan]-2',4(2*H*)-dione (D *–trans*-9)