An Unprecedented Benzannulation of Oxindoles With Enalcarbenoids: A Regioselective Approach to Functionalized Carbazoles

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1. General methods

All the reactions performed in an oven-dried glassware under argon atmosphere. Solvents were dried using standard methods. Tetrahydrofuran and diethyl ether dried over sodium benzophenone ketyl. Acetonitrile, dichloromethane and toluene were distilled over calcium hydride. Unless otherwise stated, all the commercial reagents were used as received. The progress of the reaction was monitored by thin layer chromatography (Merck Silica gel 60 F-254, precoated plates on alumina). Column chromatographic purifications performed on Merck silica gel (100-200 mesh). Melting points recorded on a digital melting point apparatus and are uncorrected.

Spectroscopic characterizations were carried at the Central Instrumentation Facility (CIF), Indian Institute of Science Education and Research (IISER) Bhopal. $^1$H-NMR spectra were recorded on Bruker Avance III FT-NMR spectrometers at 400 MHz, 500 or 700 MHz and $^{13}$C-NMR spectra were recorded at 101 MHz, 126 MHz or 176 MHz. $^1$H-NMR chemical shifts reported in ppm relative to the TMS (δ=0) and are abbreviated as follows: s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), br (broad). $^{13}$C-NMR chemical shifts reported in ppm relative to the residual CDCl$_3$ signal (δ= 77.16). IR spectra recorded on a Perkin-Elmer FT-IR spectrometer. HRMS data obtained on a Bruker micro TOF-QII or Agilent 5975C high-resolution mass spectrometers.

2. Starting materials

Preparation of diazoenals 1a-c and 1e-g was reported in our earlier work.$^1$ Oxindoles 2a-d and 2i were obtained from Sigma-Aldrich. Known oxindoles 2e-h, 2j and new oxindole 2k were prepared according to the known procedures.$^{2-5}$
Preparation of chiral menthyl ester diazoenal 1d

The new chiral menthyl ester diazoenal 1d was prepared from the known keto diazo ester $S_1$ via new vinyldiazo ester $S_2$.

1. NaBH$_4$, MeOH, 0 °C, 93%
2. POCl$_3$/Et$_3$N, 0 °C - rt, 55%

$S_1$ → $S_2$ → 1d
(1R,2S,5R)-2-isopropyl-5-methylcyclohexyl 2-diazobut-3-enoate (S2): The unstable vinyl diazoester S2 was prepared from the known keto diazo ester S1 \(^6\) in two steps by following literature procedure. \(^6\) Obtained as a yellow liquid; yield = 51% (for two steps); \(R_f = 0.53\) (ethyl acetate/hexane : 10:90); \(^1H\) NMR (400 MHz, CDCl\(_3\)) \(\delta 6.10\) (dd, \(J = 17.4, 11.0\) Hz, 1H), 4.77 (d, \(J = 17.4\) Hz, 1H), 4.76 – 4.65 (m, 1H), 2.02 – 1.92 (m, 1H), 1.84 – 1.74 (m, 1H), 1.66 – 1.57 (m, 2H), 1.49 – 1.28 (series of m, 2H), 1.05 – 0.90 (m, 2H), 0.84 (d, \(J = 5.4\) Hz, 3H), 0.82 (d, \(J = 5.4\) Hz, 3H), 0.84 – 0.78 (m, 1H), 0.71 (d, \(J = 7.0\) Hz, 3H); \(^13C\) NMR (101 MHz, CDCl\(_3\)) \(\delta 164.4\), 120.7, 107.1, 75.2, 63.3, 47.1, 41.2, 34.2, 31.4, 26.5, 23.7, 22.0, 20.7, 16.6; IR (neat): 2088, 1703, 1616 cm\(^{-1}\).

(E)-(1R,2S,5R)-2-isopropyl-5-methylcyclohexyl 2-diazo-5-oxopent-3-enoate (1d): Formylation of freshly the prepared vinyldiazo ester S2 by our earlier reported procedure\(^1\) gave chiral menthyl ester diazoenal 1d. Obtained as a yellow liquid; yield = 76%; \(R_f = 0.43\) (Ethyl acetate/Hexane = 30:70); \([\alpha]_D^{23} = -59^\circ\) (c 0.67, CHCl\(_3\)); \(^1H\) NMR (400 MHz, CDCl\(_3\)) \(\delta 9.51\) (d, \(J = 7.6\) Hz, 1H), 7.16 (d, \(J = 15.7\) Hz, 1H), 5.94 (dd, \(J = 15.7, 7.6\) Hz, 1H), 4.85 (td, \(J = 10.9, 4.4\) Hz, 1H), 2.06-1.99 (m, 1H), 1.85-1.76 (m, 1H), 1.72-1.64 (m, 2H), 1.55-1.37 (m, 2H), 1.12-0.96 (m, 2H), 0.90 (d, \(J = 6.0\) Hz, 3H), 0.88 (d, \(J = 6.5\) Hz, 3H), 0.88-0.81 (m, 1H), 0.76 (d, \(J = 6.9\) Hz, 3H); \(^13C\) NMR (101 MHz, CDCl\(_3\)) \(\delta 190.7, 161.8, 139.4, 121.9, 47.1, 41.1, 34.0, 31.4, 26.6, 23.6, 21.9, 20.6, 16.5; IR (neat): 2102, 1713, 1679, 1609, 1320 cm\(^{-1}\); HRMS (ESI) \(m/z\) calc. for C\(_{15}\)H\(_{23}\)N\(_2\)O\(_3\) (M+H\(^+\)) 279.1703, found 279.1687.

5-((tert-butyldimethylsilyl)oxy)indolin-2-one (2i): Prepared from 2k by TBS-protection of hydroxyl group. \(^1H\) NMR (400 MHz, CDCl\(_3\)) \(\delta 8.23\) (s, 1H), 6.69 (m, 4H),
3.48 (s, 2H), 0.96 (s, 9H), 0.16 (s, 6H). $^{13}$C NMR (101 MHz, CDCl$_3$) δ 177.3, 151.3, 136.2, 126.4, 118.9, 117.3, 109.9, 36.6, 25.7, 18.2, -4.5; HRMS (ESI) m/z Calc. for C$_{14}$H$_{22}$NO$_2$Si [M+H]$^+$ 264.1414, Found: 264.1442.

3. Optimization of the tandem benzannulation reaction

![Chemical reaction diagram]

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<th>entry</th>
<th>Rh$_2$L$_n$</th>
<th>solvent</th>
<th>t (°C)</th>
<th>yield (%)$^b$</th>
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<td>Rh$_2$(OAc)$_4$</td>
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<tr>
<td>2</td>
<td>Rh$_2$(TFA)$_4$</td>
<td>CH$_2$Cl$_2$</td>
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<td>CH$_2$Cl$_2$</td>
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<tr>
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<td>CH$_2$Cl$_2$</td>
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<td>17</td>
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<tr>
<td>5</td>
<td>Rh$_2$(oct)$_4$</td>
<td>CH$_2$Cl$_2$</td>
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<td>CHCl$_3$</td>
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<td>PhCH$_3$</td>
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<tr>
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<td>Rh$_2$(oct)$_4$</td>
<td>CH$_2$Cl$_2$</td>
<td>25</td>
<td>0</td>
</tr>
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</table>

$^a$ Reaction conditions: 1a/2a = 0.56/0.225 mmol. $^b$ Yield of isolated product. $^c$ Diazo compound was decomposed.

Optimization procedure:

A 0.28M solution of 1a was added with a flow rate of 1 ml/h using a syringe pump to a 0.23 M solution of 2-oxindole 2a (30 mg, 0.225 mmol) in a 10 ml round bottom flask containing Rh$_2$L$_n$, 5 mol% BINOL phosphoric acid (±)-BPA (4 mg, 0.011 mmol) and 4 Å MS (80 mg), at the respective temperature under argon atmosphere. After addition of 1a, the reaction was continued at the same temperature for an additional 3 h (or as judged by TLC). Solvent was evaporated under reduced pressure and the carbazole product 3a was purified by a silica gel flash column chromatography using Ethyl acetate/Hexanes (2:98) as the eluent.
4. Substrate scope of the benzannulation

General procedure: A solution of 1 (0.56 mmol) in 2 ml DCM was added slowly with a flow rate of 1 ml/h using a syringe pump to a DCM solution (1 ml) of 2-oxindole 2 (0.225 mmol), Rh$_2$(Oct)$_4$ (3.5 mg, 0.0045 mmol) and (±)-BINOL phosphoric acid BPA (4 mg, 0.011 mmol) in a 10 ml round bottom flask in the presence of 4 Å MS (80 mg), maintained at 84 °C under argon atmosphere. After addition of 1 (2 h), reaction was continued at the same temperature for an additional 3 h. Solvent was evaporated under reduced pressure and the residue was purified by a silica gel flash column chromatography using Ethyl acetate/Hexanes as the eluent (2:98) to furnish carbazole 3 ($R_f = 0.2–0.3$; Ethyl acetate/Hexanes = 2:98).

**Ethyl 1-hydroxy-9H-carbazole-2-carboxylate (3a):** White solid; 35 mg, yield = 62%; m.p.=176-178 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 11.38 (s, 1H), 8.52 (s, 1H), 8.06 (d, $J = 7.9$ Hz, 1H), 7.67 (d, $J = 8.4$ Hz, 1H), 7.55 (d, $J = 8.4$ Hz, 1H), 7.51 – 7.44 (m, 2H), 7.22-7.27 (m, 1H), 4.45 (q, $J = 7.1$ Hz, 2H), 1.45 (t, $J = 7.1$ Hz, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 171.4, 149.2, 140.4, 128.7, 128.5, 127.3, 123.2, 121.3, 120.1, 120.0, 111.6, 111.2, 108.1, 61.4, 14.4; IR (neat): 3425, 3311, 3001, 2921, 1715 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{15}$H$_{13}$NO$_3$ [M+H] 256.0968, Found: 256.0974.

**Methyl 1-hydroxy-9H-carbazole-2-carboxylate (3b):** White solid; 26 mg, yield = 48%; m.p.= 207-208 °C; $^1$H NMR (500 MHz, CDCl$_3$)
\[ \delta 11.32 \text{ (s, 1H)}, 8.54 \text{ (s, 1H)}, 8.10 \text{ (d, } J = 7.8 \text{ Hz, 1H)}, 7.69 \text{ (d, } J = 8.4 \text{ Hz, 1H)}, 7.60 \text{ (d, } J = 8.4 \text{ Hz, 1H)}, 7.55 - 7.49 \text{ (m, 2H)}, 7.31 - 7.27 \text{ (m, 1H)}, 4.03 \text{ (s, 3H); }^{13}\text{C NMR (126 MHz, CDCl}_3) \delta 171.7, 149.1, 140.4, 128.7, 128.4, 127.3, 123.2, 121.3, 120.1, 120.07, 111.6, 111.4, 107.9, 52.4; \text{IR (neat): 3545, 3371, 3006, 2918, 1620 cm}^{-1}; \text{HRMS (ESI) m/z Calc. for C}_{14}\text{H}_{10}\text{NO}_3 [M-H] 240.0655, \text{Found: 240.0658.}

Methyl 8-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3d): White solid; 32 mg, yield = 51%; m.p. = 182-184 °C; \textsuperscript{1}H NMR (400 MHz, CDCl\textsubscript{3}) \delta 11.32 \text{ (s, 1H)}, 8.67 \text{ (s, 1H)}, 7.93 \text{ (d, } J = 7.9 \text{ Hz, 1H)}, 7.67 \text{ (d, } J = 8.4 \text{ Hz, 1H)}, 7.52 \text{ (d, } J = 8.4 \text{ Hz, 1H)}, 7.46 \text{ (dd, } J = 7.7, 0.6 \text{ Hz, 1H)}, 7.18 \text{ (t, } J = 7.8 \text{ Hz, 1H)}, 3.99 \text{ (s, 3H); }^{13}\text{C NMR (101 MHz, CDCl}_3) \delta 171.41, 149.15, 137.51, 128.72, 128.22, 126.31, 124.47, 120.63, 120.61, 119.64, 116.84, 111.49, 108.35, 52.31; \text{IR (neat): 3410, 3058, 2850, 1635 cm}^{-1}; \text{HRMS (ESI) m/z Calc. for C}_{14}\text{H}_{11}\text{ClNO}_3 [M+H] 276.0422, \text{Found: 276.0383.}
Benzyl 8-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3e): White solid; 56 mg, yield = 71%; m.p. = 146-148 °C; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.36 (s, 1H), 8.73 (s, 1H), 7.97 (dd, \(J = 7.6, 2.2\) Hz, 1H), 7.75 (dd, \(J = 8.4, 1.8\) Hz, 1H), 7.56 - 7.51 (m, 3H), 7.49 (d, \(J = 7.7\) Hz, 1H), 7.46 (t, \(J = 7.5\) Hz, 2H), 7.41 (t, \(J = 7.2\) Hz, 1H), 7.22 (td, \(J = 7.8, 1.7\) Hz, 1H), 5.48 (s, 2H); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)) \(\delta\) 170.8, 149.3, 140.9, 137.5, 135.5, 128.8, 127.5, 128.3, 128.2, 126.3, 124.5, 120.7, 120.6, 119.7, 116.8, 111.5, 108.4, 67.0; HRMS (ESI) m/z Calc. for C\(_{20}\)H\(_{15}\)ClNO\(_3\) [M+H] 352.0735, Found: 352.0760.

Methyl 7-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3f): White solid; 35 mg, yield = 56%; m.p. = 206-208°C; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.31 (s, 1H), 8.51 (s, 1H), 7.98 (d, \(J = 8.4\) Hz, 1H), 7.70 (d, \(J = 8.4\) Hz, 1H), 7.54 (d, \(J = 8.4\) Hz, 1H), 7.51 (d, \(J = 1.7\) Hz, 1H), 7.25 (dd, \(J = 8.4, 1.8\) Hz, 1H), 4.03 (s, 3H); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \(\delta\) 171.6, 149.1, 140.7, 133.1, 128.7, 128.2, 122.2, 121.8, 120.9, 120.7, 111.6, 111.2, 108.2, 52.4. IR(neat): 3390, 3060, 2940, 2840, 1630 cm\(^{-1}\); LRMS (ESI): 274.2 (M-H).

Benzyl 7-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3g): White solid; 58 mg, yield = 73%; m.p. = 169-170 °C; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.27 (s, 1H), 8.48 (s, 1H), 7.93 (d, \(J = 8.4\) Hz, 1H), 7.70 (d, \(J = 8.4\) Hz, 1H), 7.50 - 7.45 (m, 4H), 7.44 - 7.39 (m, 2H), 7.39 - 7.35 (m, 1H), 7.20 (dd, \(J = 8.4, 1.8\) Hz, 1H), 5.43 (s, 2H); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \(\delta\) 170.8, 149.0, 140.6, 135.5, 133.0, 128.7, 128.5, 128.2, 128.1, 128.1, 122.1, 121.6, 120.7, 120.6, 111.4, 111.1, 108.0, 66.9; IR (neat): 3379, 3151, 3046, 2920, 2848, 1666 cm\(^{-1}\); HRMS (ESI) m/z Calc. for C\(_{20}\)H\(_{15}\)ClNO\(_3\) [M-

**Benzyl 6-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3h):**
White solid; 52 mg, yield = 66%; m.p. = 157-160 °C; $^1$H NMR (500 MHz, CDCl$_3$) δ 11.27 (s, 1H), 8.51 (s, 1H), 8.00 (s, 1H), 7.70 (d, $J = 8.5$ Hz, 1H), 7.51 – 7.45 (m, 3H), 7.44 – 7.32 (m, 5H), 5.43 (s, 2H); $^{13}$C NMR (101 MHz, CDCl$_3$) δ 171.0, 149.3, 138.6, 135.6, 129.1, 128.9, 128.7, 128.5, 128.4, 127.8, 127.5, 125.6, 124.3, 121.0, 120.5, 112.6, 111.4, 108.4, 67.1; IR (neat): 3395, 3309, 3060, 2912, 1642 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{20}$H$_{13}$ClNO$_3$ [M-H] 350.0578, Found: 350.0567.

**Ethyl 6-bromo-1-hydroxy-9H-carbazole-2-carboxylate (3i):** White solid; 38 mg, yield = 52%; m.p. = 187-189 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 11.33 (d, $J = 6.5$ Hz, 1H), 8.51 (s, 1H), 8.16 (d, $J = 1.7$ Hz, 1H), 7.67 (d, $J = 8.5$ Hz, 1H), 7.54 (dd, $J = 7.1$, 5.2 Hz, 1H), 7.48 (d, $J = 8.4$ Hz, 1H), 7.36 (d, $J = 8.7$ Hz, 1H), 4.45 (q, $J = 7.1$ Hz, 2H), 1.45 (t, $J = 7.1$ Hz, 3H); $^{13}$C NMR (101 MHz, CDCl$_3$) δ 171.1, 149.1, 138.7, 129.9, 128.8, 127.4, 124.8, 123.9, 120.4, 112.9, 112.7, 111.1, 108.5, 61.4, 14.3; IR (neat) 3400, 3298, 2921, 2832, 1690 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{15}$H$_{12}$BrNO$_3$ [M$^+$] 332.9995, Found: 333.0013.

**Methyl 1-hydroxy-9-methyl-9H-carbazole-2-carboxylate (3j):** White solid; 3 mg, yield = 6%; m.p. = 112-113 °C; $^1$H NMR (400 MHz, CDCl$_3$) δ 11.62 (s, 1H), 7.99 (d, $J = 7.9$ Hz, 1H), 7.57 (d, $J = 8.4$ Hz, 1H), 7.50 (d, $J = 8.5$ Hz, 1H), 7.48 – 7.43 (m, 1H), 7.36 (d, $J = 8.3$ Hz, 1H), 7.18 – 7.15 (m, 1H), 4.19 (s, 3H), 3.93 (s, 3H); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 172.1, 150.9, 142.4, 128.7, 128.7, 127.0, 122.2, 121.0, 119.6, 119.3, 111.1, 109.2, 107.8, 52.2, 32.1; IR(neat): 3470, 3284, 3118, 2910, 1677, 1460 cm$^{-1}$
**Methyl 1-hydroxy-8-methyl-9H-carbazole-2-carboxylate (3k):**

White solid; 30 mg, yield = 52%; m.p.= 104-106 °C; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.38 (s, 1H), 8.45 (s, 1H), 7.94 (d, \(J = 7.9\) Hz, 1H), 7.69 (d, \(J = 8.4\) Hz, 1H), 7.59 (d, \(J = 8.2\) Hz, 1H), 7.33 – 7.30 (m, 1H), 7.21 (t, \(J = 7.5\) Hz, 1H), 4.03 (s, 3H), 2.62 (s, 3H). \(^{13}\)C NMR (176 MHz, CDCl\(_3\)) \(\delta\) 171.7, 149.0, 139.8, 129.2, 128.1, 127.6, 122.6, 120.7, 120.1, 120.0, 118.8, 111.4, 107.6, 52.2, 16.9; IR(neat): 3450, 3320, 3095, 2970, 1675 cm\(^{-1}\). HRMS (ESI) m/z Calc. for C\(_{15}\)H\(_{14}\)NO\(_3\) [M+H] 256.0968, Found: 256.0990.

**Ethyl 1-hydroxy-8-methyl-9H-carbazole-2-carboxylate (3l):**

White solid; 33 mg, yield = 55%; m.p.= 132-134 °C; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.47 (s, 1H), 8.43 (s, 1H), 7.94 (d, \(J = 7.9\) Hz, 1H), 7.71 (d, \(J = 8.4\) Hz, 1H), 7.58 (d, \(J = 8.4\) Hz, 1H), 7.32 (d, \(J = 7.2\) Hz, 1H), 7.21 (t, \(J = 7.5\) Hz, 1H), 4.49 (q, \(J = 7.1\) Hz, 2H), 2.62 (s, 3H), 1.50 (t, \(J = 7.1\) Hz, 4H); \(^{13}\)C NMR (176 MHz, CDCl\(_3\)) \(\delta\) 171.3, 149.1, 139.8, 129.1, 128.1, 127.6, 122.6, 120.7, 120.1, 120.0, 118.8, 111.3, 107.8, 61.3, 16.9, 14.3; IR(neat): 3465, 3350, 3095, 2970, 1660 cm\(^{-1}\); HRMS (ESI) m/z Calc. for C\(_{16}\)H\(_{16}\)NO\(_3\) [M+H] 270.1125, Found: 270.1111.

**Benzyl 1-hydroxy-8-methyl-9H-carbazole-2-carboxylate (3m):**

White solid; 46 mg, yield = 62%; m.p.= 116-118 °C; \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.36 (s, 1H), 8.44 (s, 1H), 7.94 (d, \(J = 7.9\) Hz, 1H), 7.74 (d, \(J = 8.4\) Hz, 1H), 7.57 (d, \(J = 8.4\) Hz, 1H), 7.54 – 7.50 (m, 2H), 7.48 – 7.43 (m, 2H), 7.41 (dd, \(J = 5.0\) Hz, 3.6 Hz, 1H), 7.32 (d, \(J = 7.1\) Hz, 1H), 7.21 (t, \(J = 7.5\) Hz, 1H), 5.47 (s, 2H), 2.62 (s, 3H). \(^{13}\)C NMR (176 MHz, CDCl\(_3\)) \(\delta\) 171.1, 149.2, 139.8, 135.6, 129.2, 128.7, 128.5, 128.3, 128.1, 127.7, 122.5, 120.7, 120.1, 120.1, 118.8, 111.4, 107.6, 66.9, 16.9; IR(neat): 3490, 3352, 2920, 1647 cm\(^{-1}\); HRMS (ESI) m/z Calc. for C\(_{21}\)H\(_{18}\)NO\(_3\) [M+H] 332.1281, Found: 332.1292.
Methyl 1-hydroxy-6-methyl-9H-carbazole-2-carboxylate (3n): White solid; 32 mg, yield = 55%; m.p. = 185-187 °C; $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 11.29 (s, 1H), 8.42 (s, 1H), 7.88 (s, 1H), 7.67 (d, $J$ = 8.4 Hz, 1H), 7.56 (d, $J$ = 8.4 Hz, 1H), 7.42 (d, $J$ = 8.3 Hz, 1H), 7.33 (dd, $J$ = 8.3, 1.2 Hz, 1H), 4.02 (s, 3H), 2.55 (s, 3H). $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 171.8, 149.1, 138.7, 129.5, 128.9, 128.7, 128.6, 123.4, 121.0, 119.9, 111.3, 111.2, 107.7, 52.3, 21.6; IR(neat): 3400, 3308, 2921, 2802, 1670 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{15}$H$_{14}$NO$_3$ [M+H] 256.0968, Found: 256.0950.

Benzyl 1-hydroxy-6-methyl-9H-carbazole-2-carboxylate (3o): White solid; 49 mg, yield = 66%; m.p. = 133-134 °C; $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 11.29 (s, 1H), 8.43 (s, 1H), 7.88 (s, 1H), 7.72 (d, $J$ = 8.4 Hz, 1H), 7.55 (d, $J$ = 8.4 Hz, 1H), 7.52 (d, $J$ = 7.1 Hz, 2H), 7.45 (t, $J$ = 7.3 Hz, 2H), 7.42 – 7.38 (m, 2H), 7.33 (dd, $J$ = 8.3, 1.1 Hz, 1H), 5.47 (s, 2H), 2.55 (s, 3H). $^{13}$C NMR (176 MHz, CDCl$_3$) $\delta$ 171.1, 149.3, 138.7, 135.8, 129.5, 128.9, 128.8, 128.7, 128.6, 128.4, 123.4, 121.1, 120.0, 111.3, 111.2, 107.7, 67.0, 21.6; IR(neat): 3450, 3309, 3085, 2980, 1670 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{21}$H$_{18}$NO$_3$ [M+H] 332.1281, Found: 332.1282.

Benzyl 6-((tert-butyldimethylsilyl)oxy)-1-hydroxy-9H-carbazole-2-carboxylate (3p): White solid; 54 mg, yield = 54%; m.p. = 134-136 °C; $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 11.26 (s, 1H), 8.34 (s, 1H), 7.66 (d, $J$ = 8.4 Hz, 1H), 7.53 – 7.30 (m, 8H), 7.02 (dd, $J$ = 8.7, 2.3 Hz, 1H), 5.43 (s, 2H), 1.03 (s, 9H), 0.23 (s, 6H). $^{13}$C NMR (101 MHz, CDCl$_3$) $\delta$ 171.01, 149.44, 149.22, 135.71, 135.65, 129.08, 128.71, 128.49, 128.45, 128.22, 123.74, 121.22, 119.55, 111.81, 111.26, 110.84, 107.55, 66.81, 25.80, -4.37. IR(neat): 3520,
3395, 3061, 2921, 1665 cm\(^{-1}\); HRMS (ESI) m/z Calc. for C\(_{26}\)H\(_{28}\)N\(_4\)Si [M+Na] 470.1777, Found: 470.1758.

(1S,3S,4R)-4-isopropyl-3-methylcyclohexyl 1-hydroxy-9H-carbazole-2-carboxylate (3q): White solid; 43 mg, yield = 53%; m.p. = 56-58 °C; [\(\alpha\)\(_D\)]\(^{23}\) = 69° (c 0.36, CHCl\(_3\)); \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.58 (s, 1H), 8.61 (s, 1H), 8.11 (dd, \(J = 7.8, 0.6\) Hz, 1H), 7.71 (d, \(J = 8.4\) Hz, 1H), 7.60 (d, \(J = 8.4\) Hz, 1H), 7.54 - 7.49 (m, 2H), 7.31 - 7.27 (m, 1H), 5.07 (td, \(J = 10.9, 4.4\) Hz, 1H), 2.25 - 2.19 (m, 1H), 2.09 - 2.02 (m, 1H), 1.83 - 1.76 (m, 2H), 1.70 - 1.59 (m, 2H), 1.26 - 1.15 (m, 2H), 1.00 (d, \(J = 3.8\) Hz, 3H), 0.98 (d, \(J = 4.2\) Hz, 3H), 0.97 - 0.92 (m, 1H), 0.87 (d, \(J = 6.9\) Hz, 3H); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \(\delta\) 170.9, 149.1, 140.3, 128.5, 128.4, 127.1, 123.1, 121.2, 120.0, 119.8, 111.4, 111.1, 108.3, 75.4, 47.2, 41.0, 34.3, 31.5, 26.6, 23.7, 22.1, 20.8, 16.6; IR (neat): 3391, 3020, 2987, 1667, 1313 cm\(^{-1}\); HRMS (ESI) m/z Calc. for C\(_{23}\)H\(_{27}\)NaNO\(_3\) [M+Na] 388.1883, Found: 388.1909.

(1S,3S,4R)-4-isopropyl-3-methylcyclohexyl 8-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3r): White solid; 60 mg, yield = 67%; m.p. = 114-116 °C; [\(\alpha\)\(_D\)]\(^{23}\) = 74° (c 0.34, CHCl\(_3\)); \(^1\)H NMR (500 MHz, CDCl\(_3\)) \(\delta\) 11.61 (s, 1H), 8.76 (s, 1H), 7.98 (d, \(J = 7.9\) Hz, 1H), 7.72 (d, \(J = 8.4\) Hz, 1H), 7.56 (d, \(J = 8.4\) Hz, 1H), 7.50 (dd, \(J = 7.7, 0.6\) Hz, 1H), 7.21 (t, \(J = 7.8\) Hz, 1H), 5.06 (td, \(J = 10.9, 4.4\) Hz, 1H), 2.25 - 2.19 (m, 1H), 2.09 - 2.02 (m, 1H), 1.83 - 1.76 (m, 2H), 1.70 - 1.59 (m, 2H), 1.26 - 1.15 (m, 2H), 0.99 (d, \(J = 5.2\) Hz, 3H), 0.98 (d, \(J = 5.6\) Hz, 3H), 0.97 - 0.92 (m, 1H), 0.87 (d, \(J = 6.9\) Hz, 3H); \(^{13}\)C NMR (126 MHz, CDCl\(_3\)) \(\delta\) 170.7, 149.3, 137.5, 128.6, 128.3, 126.2, 124.5, 120.63, 120.56, 119.6, 116.8, 111.3, 108.9, 75.6, 47.2, 41.0, 34.3, 31.5, 26.6, 23.7, 22.0, 20.7, 16.6; IR (neat): 3334, 3014, 2989, 1656, 1310 cm\(^{-1}\); HRMS (ESI) m/z Calc. for C\(_{23}\)H\(_{26}\)ClNaNO\(_3\) [M+Na] 422.1493, Found: 422.1525.
(1S,3S,4R)-4-isopropyl-3-methylcyclohexyl 7-chloro-1-hydroxy-9H-carbazole-2-carboxylate (3s): White solid; 68 mg, yield = 76%; m.p.= 158-160 °C; [α]d$^23$ = 66° (c 0.35, CHCl$_3$); $^1$H NMR (500 MHz, CDCl$_3$) δ 11.58 (s, 1H), 8.60 (s, 1H), 7.97 (d, $J$ = 8.4 Hz, 1H), 7.71 (d, $J$ = 8.4 Hz, 1H), 7.53 (d, $J$ = 8.4 Hz, 1H), 7.49 (d, $J$ = 1.2 Hz, 1H), 7.24 (dd, $J$ = 8.4, 1.8 Hz, 1H), 5.06 (td, $J$ = 10.9, 4.4 Hz, 1H), 2.25 - 2.19 (m, 1H), 2.09 – 2.00 (m, 1H), 1.83 - 1.76 (m, 2H), 1.70 – 1.58 (m, 2H), 1.26 – 1.15 (m, 2H), 0.99 (d, $J$ = 5.1 Hz, 1H), 0.98 (d, $J$ = 5.5 Hz, 1H), 0.97 – 0.92 (m, 1H), 0.86 (d, $J$ = 7.0 Hz, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$) δ 170.7, 149.0, 140.6, 132.9, 128.7, 127.9, 122.0, 121.7, 120.6, 120.5, 111.4, 110.9, 108.6, 75.6, 47.2, 40.9, 34.3, 31.5, 26.6, 23.7, 22.0, 20.7, 16.6; IR (neat): 3419, 3022, 2989, 1660, 1314 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{23}$H$_{26}$ClNaNO$_3$ [M+Na] 422.1493, Found: 422.1533.

(4-Chlorophenyl)(1-hydroxy-9H-carbazol-2-yl)methanone (3t): Yellow solid; 25 mg, yield = 35% (reaction without (±)-BPA was clean and gave similar yield); m.p.= 130-132 °C; $^1$H NMR (500 MHz, CDCl$_3$) δ 12.84 (s, 1H), 8.69 (s, 1H), 8.11 (dd, $J$ = 7.9, 0.7 Hz, 1H), 7.75 – 7.72 (m, 2H), 7.59 – 7.53 (m, 5H), 7.39 (d, $J$ = 8.5 Hz, 1H), 7.33 – 7.29 (m, 1H); $^{13}$C NMR (176 MHz, CDCl$_3$) δ 200.7, 151.2, 140.8, 138.1, 137.0, 130.8, 129.4, 128.8, 128.7, 128.0, 123.7, 123.0, 121.6, 120.3, 114.9, 111.7, 111.0; IR (neat): 3372, 3010, 2918, 1629, 1590 cm$^{-1}$; HRMS (ESI) m/z Calc. For C$_{19}$H$_{13}$ClNO$_2$ [M+H] 322.0629, Found: 322.0601. CCDC 1033506 contains crystallographic data of this compound.
(4-bromophenyl)(1-hydroxy-9H-carbazol-2-yl)methanone (3u):
Yellow solid; 23 mg, yield = 29% (reaction without (±)-BPA was clean and gave similar yield); m.p. = 153-155 °C; $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 12.83 (s, 1H), 8.68 (s, 1H), 8.11 (d, $J = 7.5$ Hz, 1H), 7.72 – 7.65 (m, 4H), 7.59 – 7.53 (m, 3H), 7.39 (d, $J = 8.5$ Hz, 1H), 7.32 – 7.29 (m, 1H); $^{13}$C NMR (126 MHz, CDCl$_3$) $\delta$ 200.8, 151.2, 140.9, 137.5, 131.7, 131.0, 129.4, 128.7, 128.0, 126.6, 123.7, 123.0, 121.6, 120.3, 114.9, 111.7, 111.0; IR (neat): 3369, 2956, 3011, 2917, 1670, 1261 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{19}$H$_{12}$BrNO$_2$ [M$^+$] 365.9948, Found: 365.9965.

(1-hydroxy-9H-carbazol-2-yl)(4-methoxyphenyl)methanone (3v):
Yellow solid; 22 mg, yield = 31% (reaction without (±)-BPA was clean and gave similar yield); m.p.= 137-139 °C; $^1$H NMR (500 MHz, CDCl$_3$) $\delta$ 12.97 (s, 1H), 8.68 (s, 1H), 8.11 (d, $J = 7.9$ Hz, 1H), 7.82 (d, $J = 8.8$ Hz, 2H), 7.57 (t, $J = 8.2$ Hz, 2H), 7.55 – 7.51 (m, 1H), 7.50 (d, $J = 8.4$ Hz, 1H), 7.31 – 7.29 (m, 1H), 7.05 (d, $J = 8.8$ Hz, 2H), 3.94 (s, 3H); $^{13}$C NMR (176 MHz, CDCl$_3$) $\delta$ 200.7, 162.8, 150.9, 140.8, 132.0, 131.2, 128.95, 128.8, 127.7, 124.0, 123.1, 121.5, 120.2, 115.4, 113.7, 111.7, 110.7, 55.7; IR (neat): 3369, 3002, 2956, 2851, 1697, 1454 cm$^{-1}$; HRMS (ESI) m/z Calc. for C$_{20}$H$_{16}$NO$_3$ [M+H] 318.1125, Found: 318.1140.
5. Mechanistic Studies:

Characterization of 5b

(E)-methyl 2,5-dihydroxy-2-(1H-indol-2-yl)pent-3-enoate (5b): A solution of the methyl ester diazenal 1b (290 mg, 1.87 mmol) in 2 ml CH₂Cl₂ was added over 2 h using a syringe pump to a solution of oxindole 2a (100 mg, 0.75 mmol) and Rh₂(OAc)₄ (0.015 mmol, 2 mol%) in 2 ml CH₂Cl₂ maintained at 40 °C. The reaction was continued until all the diazenal 1b was consumed (additional 3 h). Thin layer chromatography (TLC) of the reaction mixture indicated the presence of an unstable intermediate. Attempts to isolate the intermediate by flash column chromatography (using silica gel or aluminium oxide) were unsuccessful due to decomposition in the column.

About half of the volume of the reaction mixture was evaporated at room temperature under reduced pressure and dried. To a solution of the residue (100 mg) in 2 ml methanol at 0 °C was added excess NaBH₄ and stirred for 20 min. TLC showed formation of one major product. The reaction was quenched with ice-cold water (2 ml) and extracted with 10 ml ethyl acetate. The organic phase was washed with water, brine and dried over anhydrous sodium sulphate. Solvent was evaporated at room temperature and the crude material was dried under vacuum. Purification of the residue by silica gel flash column chromatography (Ethyl acetate/Hexanes = 3:2) afforded partially purified alcohol 5b as a white foam (28 mg). Rf = 0.12 (Ethyl Acetate/Hexane = 60:40); ¹H NMR (500 MHz, CDCl₃) δ 8.58 (s, 1H), 7.60 (d, J = 7.9 Hz, 1H), 7.37 (dd, J = 8.1, 0.8 Hz, 1H), 7.22 - 7.18 (m, 1H), 7.15 - 7.09 (m, 1H), 6.56 (dd, J = 2.1, 0.8 Hz, 1H), 6.27 (dt, J = 15.4, 1.3 Hz, 1H), 6.21 (dt, J = 15.4, 4.5 Hz, 1H), 4.26 (dd, J = 4.4, 0.9 Hz, 2H), 3.89 (s, 3H); ¹³C NMR (126 MHz, CDCl₃) δ 173.5, 137.1, 135.7, 131.0, 129.4, 128.4, 122.5, 120.8, 120.2, 111.2,
100.7, 75.2, 62.6, 54.1; IR (neat): 3361, 3021, 1731 cm⁻¹; HRMS (ESI) m/z Calc. for C_{14}H_{14}NO_{4} [M-H] 260.0917, Found: 260.0895.

Remaining half of the volume of the reaction mixture was allowed to continue stirring at 40 °C in the presence of (±)-BINOL phosphoric acid. After 12 h the intermediate was completely consumed leading to carbazole 3b as the only detectable product.

**Formation of Deuterium Labeled Carbazole 3b**

![Chemical structure of carbazole 3b](image)

A solution of 1b (87 mg, 0.58 mmol) in 2 ml DCM was added slowly with a flow rate of 1 ml/h using a syringe pump to a DCM solution (1 ml) of 2-oxindole 2a (30 mg, 0.225 mmol), Rh₂(OOct)₄ (3.5 mg, 0.0045 mmol), (±)-BINOL phosphoric acid BPA (4 mg, 0.011 mmol) and D₂O (12 mg, 0.67 mmol) in a 10 ml round bottom flask, maintained at 84 °C under argon atmosphere. After addition of 1b (2 h), the reaction was continued at the same temperature for an additional 3 h. Solvent was evaporated under the reduced pressure and the residue was purified by a silica gel flash column chromatography using Ethyl acetate/Hexanes as the eluent (2:98) which furnished carbazole 3b as a white solid (12 mg, 26%). Based on the comparison of integration values of C-4 and C-3 attached protons in the ¹H-NMR spectra, 20% deuterium incorporation was observed at the C-3 position of the carbazole 3b. A plausible mechanism for the formation of deuterium labeled carbazole 3b (H/D= 80:20) is proposed below.
\textsuperscript{1}H NMR spectra of 3b and deuterium labeled 3b (H/D = 80:20)
Plausible mechanism for the formation of deuterium labeled carbazole 3b

\[
\begin{align*}
\text{N}_2\text{CHCO}_2\text{Me} + \text{1b} & \xrightarrow{2 \text{ mol}\% \text{Rh}_2(\text{Oct})_4} \xrightarrow{5 \text{ mol}\% \text{(±)-BPA}} \xrightarrow{3 \text{ eq. D}_2\text{O}} \text{MeO}_2\text{C} \xrightarrow{\text{DCE, 80 °C, 5 h}} \text{H/D} \rightarrow \text{CO}_2\text{Me} \\
\end{align*}
\]

Plausible alternate mechanism of benzannulation via intermolecular oxa-Michael addition

\[
\begin{align*}
\text{(±)-BPA (H\textsuperscript{+})} & \leftrightarrow \text{D}_2\text{O} \leftrightarrow \text{H}_2\text{O} \\
\end{align*}
\]
6. References


7. NMR spectra
(dt, $J = 15.4$, 4.5 Hz)

6.21 (dt)

6.56 H

4.26 (dd)

H

6.27 (dt, $J = 15.5$, 1.3 Hz)

OMe 3.89

8.58

Partially purified 5b
SK-KSR-OX-INT

Partially purified 5b

SK-KSR-OX-INT DEPT-135