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Supporting Information

Synthesis of Dinitrogen-Fused Spirocyclic Heterocycles via Organocatalytic 1,3-dipolar Cycloaddition of 2-Arylidene-1,3-indandiones and an Azomethine Imine

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Contents

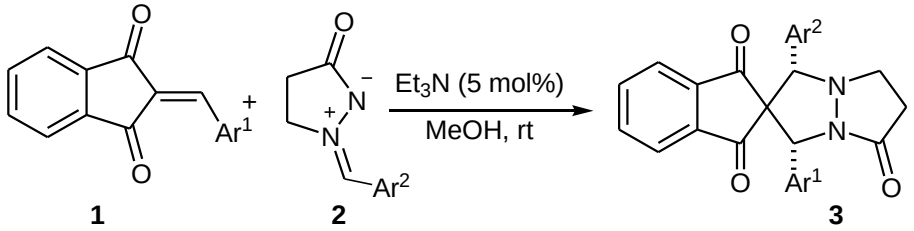
Experimental section

General

All reactions were carried out with dry, freshly distilled solvents in anhydrous conditions. All chemicals were used without further purification as commercially available unless otherwise noted. Thin-layer chromatography (TLC) was performed on silica gel plates (60F-254) using UV-light (254 and 365 nm). Flash chromatography was conducted on silica gel (300-400 mesh). NMR (400 MHz for ^{1}H NMR, 100 MHz for ^{13}C NMR) spectra were recorded in $CDCl_3$ with TMS as the internal standard. High resolution mass spectral (HRMS) analyses were measured using ESI techniques. UV detection was monitored at 254 nm. IR spectra were measured using IRPrestige-21.

A variety of 2-arylidene-1,3-indandiones **1** were synthesized via Knoevenagel reactions as reported in the literature,[1] and azomethine imine **2** was prepared using general procedures reported in the literature.[2]

General procedure for the synthesis of spiro indane-1,3-dione-pyrazolidinones

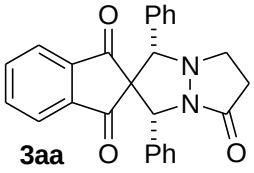


1 **2** **3**

To a stirred mixture of 2-arylidene-1,3-indandiones **1** (0.3 mmol) and azomethine imine **2** (0.36 mmol) in MeOH (2 mL) was added Et_3N (5 mol %) and then kept at room temperature for the time given, which was monitored by TLC. After removal of the solvent, the crude residue was purified by column chromatography (petroleum ether / ethyl acetate 3/1 v/v) on silica gel to give the corresponding products **3**.

Compounds characterization

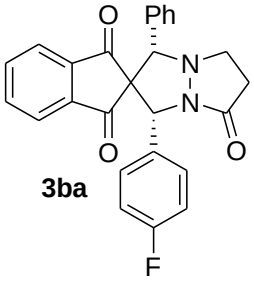
1',3'-Diphenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (**3aa**)



3aa

Prepared according to general procedure to afford **3aa** (120 mg, 98% yield) as a white solid; m.p. 164-165 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.97 (d, *J* = 7.6 Hz, 1H), 7.72–7.68 (m, 1H), 7.58–7.55 (m, 1H), 7.38 (d, *J* = 7.6 Hz, 1H), 7.19–7.18 (m, 2H), 7.16–7.06 (m, 8H), 5.81 (s, 1H), 4.42 (s, 1H), 3.85–3.79 (m, 1H), 3.10–3.02 (m, 2H), 2.94–2.87 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 194.6, 172.5, 143.1, 141.3, 136.4, 135.6, 135.2, 131.6, 128.8, 128.5, 128.4, 127.8, 127.7, 125.7, 123.3, 123.2, 77.4, 72.1, 63.3, 48.2, 32.5; HRMS (ESI): m/z calcd for $C_{26}H_{20}N_2NaO_3$ $[M+Na]^+$ 431.1372, Found 431.1366. IR υ max: 3431, 2943, 1746, 1711, 1587, 1260, 1233, 764, 700 cm^{-1}.

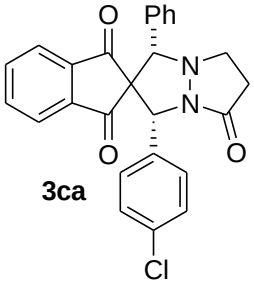
3'-(4-Fluorophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ba)



3ba

Prepared according to general procedure to afford **3ba** (96 mg, 75% yield) as a white solid; m.p. 155-157 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.97 (d, *J* = 7.6 Hz, 1H), 7.74–7.70 (m, 1H), 7.62–7.58 (m, 1H), 7.42 (d, *J* = 7.6 Hz, 1H), 7.19–7.16 (m, 2H), 7.12–7.06 (m, 5H), 6.87–6.82 (m, 2H), 5.76 (s, 1H), 4.40 (s, 1H), 3.85–3.78 (m, 1H), 3.11–3.01 (m, 2H), 2.94–2.85 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.1, 194.6, 172.6, 163.4 ($J_{C\text{-}F}$ = 245.2 Hz), 143.0, 141.2, 136.4, 135.7, 131.5, 130.9 ($J_{C\text{-}F}$ = 3.3 Hz), 128.9, 128.5, 127.8, 127.7 ($J_{C\text{-}F}$ = 8.3 Hz), 123.3, 123.2, 115.6 ($J_{C\text{-}F}$ = 22.2 Hz), 72.0, 62.7, 48.2, 32.5; HRMS (ESI): m/z calcd for $C_{26}H_{19}FN_2NaO_3$ $[M+Na]^+$ 449.1277, Found 449.1272. IR υ max: 3210, 3059, 2926, 1657, 1603, 1508, 1233, 758, 694 cm^{-1}.

3'-(4-Chlorophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ca)

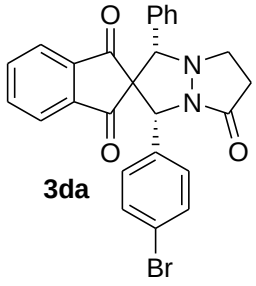


3ca

Prepared according to general procedure to afford **3ca** (112 mg, 85% yield) as a white solid; m.p. 157-158 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.97 (d, *J* = 7.6 Hz, 1H), 7.74–7.70 (m, 1H), 7.62–7.58 (m, 1H), 7.42 (d, *J* = 7.6 Hz, 1H), 7.18–7.09 (m, 7H), 7.05–7.03 (m, 2H), 5.75 (s, 1H), 4.39 (s, 1H), 3.85–3.79 (m, 1H), 3.11–3.01 (m, 2H), 2.93–2.85 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.9, 194.5, 172.7, 143.0, 141.2, 136.5, 135.7, 133.8, 133.7, 131.4, 128.9, 128.7, 128.6, 127.8, 127.3, 123.3, 77.5, 71.9, 62.6, 48.1, 32.4; HRMS (ESI): m/z calcd for $C_{26}H_{19}ClN_2NaO_3$ $[M+Na]^+$ 465.0982, Found

465.0976. IR υ max: 3064, 2918, 1699, 1657, 1593, 1256, 763, 700 cm^{-1}.

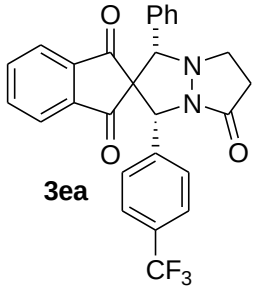
3'-(4-Bromophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3da)



3da

Prepared according to general procedure to afford **3da** (122 mg, 84% yield) as a white solid; m.p. 150-151 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.97 (d, *J* = 7.6 Hz, 1H), 7.74–7.70 (m, 1H), 7.62–7.59 (m, 1H), 7.43 (d, *J* = 7.6 Hz, 1H), 7.29–7.26 (m, 2H), 7.18–7.14 (m, 2H), 7.11–7.09 (m, 3H), 6.99–6.97 (m, 2H), 5.73 (s, 1H), 4.39 (s, 1H), 3.85–3.80 (m, 1H), 3.08–3.03 (m, 2H), 2.93–2.87 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.9, 194.5, 172.7, 142.9, 141.2, 136.5, 135.8, 134.4, 131.6, 131.4, 128.9, 128.6, 127.7, 127.6, 123.3, 121.9, 77.5, 71.9, 62.6, 48.1, 32.4; HRMS (ESI): m/z calcd for $C_{26}H_{19}BrN_2NaO_3$ $[M+Na]^+$ 509.0477, Found 509.0471. IR υ max: 3210, 2931, 1667, 1589, 1485, 1396, 1273, 1069, 1011, 756, 694 cm^{-1}.

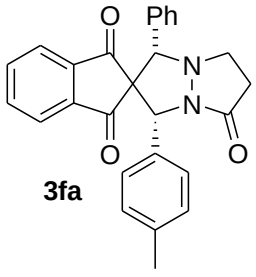
1'-Phenyl-3'-(4-(trifluoromethyl)phenyl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ea)



3ea

Prepared according to general procedure to afford **3ea** (131 mg, 92% yield) as a white solid; m.p. 130-131 °C; For major diastereomer (*dr* = 4:1): ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.01-7.96 (m, 1H), 7.80–7.71 (m, 1H), 7.68–7.59 (m, 1H), 7.44–7.33 (m, 4H), 7.25–7.08 (m, 6H), 5.83 (s, 1H), 4.41 (s, 1H), 3.87–3.80(m, 1H), 3.13–3.03 (m, 2H), 2.95–2.87 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.8, 194.4, 173.0, 142.9, 141.2, 139.5, 136.5, 135.8, 131.2, 129.0, 128.6, 128.3, 127.8, 127.8, 126.5, 126.3, 125.6(q, *J* = 3.7 Hz), 123.4, 123.3, 77.6, 72.0, 62.6, 47.9, 32.2; HRMS (ESI): m/z calcd for $C_{27}H_{20}F_3N_2O_3$ $[M+H]^+$ 477.1426, Found 477.1421. IR υ max: 3063, 2930, 1746, 1711, 1593, 1325, 1125, 768, 735, 700 cm^{-1}.

1'-Phenyl-3'-(p-tolyl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3fa)

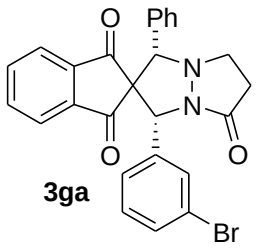


3fa

Prepared according to general procedure to afford **3fa** (105 mg, 83% yield) as a white solid; m.p. 153-154 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.96 (d, *J* = 7.6 Hz, 1H), 7.71–7.67 (m, 1H), 7.57–7.54 (m, 1H), 7.39 (d, *J* = 7.6 Hz, 1H), 7.21–7.18 (m, 2H), 7.11–7.08 (m, 3H), 6.97–6.92 (m, 4H), 5.78 (s, 1H), 4.41 (s, 1H), 3.83–3.78 (m, 1H), 3.09–3.01 (m, 2H), 2.90–2.85 (m, 1H), 2.17 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 194.8, 172.0, 143.1, 141.3, 137.5, 136.3, 135.6, 132.0, 131.6, 129.1, 128.8, 128.5, 127.8, 125.6, 123.2, 123.1, 77.4, 72.1, 63.1, 48.5, 32.8, 21.1; HRMS (ESI): m/z calcd for $C_{27}H_{22}N_2NaO_3$ $[M+Na]^+$ 445.1528, Found 445.1523. IR υ max: 2922, 2853, 1715,

1701, 1653, 1258, 765 cm^{-1}.

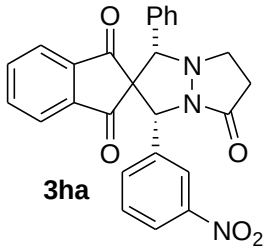
3'-(3-Bromophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ga)



3ga

Prepared according to general procedure to afford **3ga** (95 mg, 65% yield) as a white solid; m.p. 171-172 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.98 (d, *J* = 7.6 Hz, 1H), 7.75–7.71 (m, 1H), 7.63–7.59 (m, 1H), 7.42 (d, *J* = 7.6 Hz, 1H), 7.31–7.25 (m, 2H), 7.18–7.16 (m, 2H), 7.10–7.09 (m, 3H), 7.02–6.95 (m, 2H), 5.74 (s, 1H), 4.39 (s, 1H), 3.86–3.79 (m, 1H), 3.11–2.99 (m, 2H), 2.93–2.85 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.9, 194.4, 173.3, 143.0, 141.2, 137.8, 136.5, 135.8, 131.4, 131.1, 129.9, 129.1, 128.9, 128.5, 127.8, 124.5, 123.4, 123.3, 122.8, 77.5, 71.9, 62.5, 47.7, 32.1; HRMS (ESI): m/z calcd for $C_{26}H_{19}BrN_2NaO_3$ $[M+Na]^+$ 509.0477, Found 509.0472. IR υ max: 3061, 2926, 1744, 1709, 1593, 1260, 1236, 767, 733 cm^{-1}.

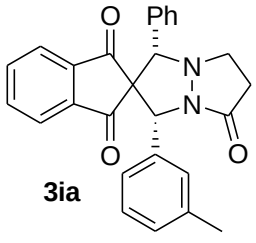
3'-(3-Nitrophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ha)



3ha

Prepared according to general procedure to afford **3ha** (96 mg, 71% yield) as a white solid; m.p. 166-168 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 8.04–7.98 (m, 3H), 7.77–7.73 (m, 1H), 7.63–7.59 (m, 1H), 7.47–7.45 (m, 1H), 7.39–7.35 (m, 2H), 7.17–7.09 (m, 5H), 5.85 (s, 1H), 4.40 (s, 1H), 3.89–3.83 (m, 1H), 3.16–3.00 (m, 2H), 2.96–2.87 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 197.6, 194.5, 173.9, 148.2, 142.9, 141.1, 138.1, 136.7, 136.0, 132.2, 131.2, 129.5, 129.1, 128.6, 127.8, 123.6, 123.3, 123.1, 121.3, 77.7, 71.9, 62.2, 47.3, 31.7; HRMS (ESI): m/z calcd for $C_{26}H_{19}N_3NaO_5$ $[M+Na]^+$ 476.1222, Found 476.1217. IR υ max: 2920, 2849, 1744, 1709, 1530, 1350, 1261, 1236, 766, 723, 700 cm^{-1}.

1'-Phenyl-3'-(m-tolyl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ia)

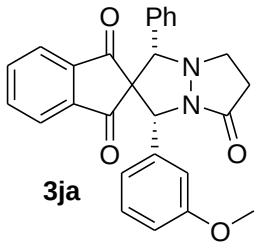


3ia

Prepared according to general procedure to afford **3ia** (117 mg, 93% yield) as a white solid; m.p. 142-143 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.96 (d, *J* = 8.0 Hz, 1H), 7.72–7.68 (m, 1H), 7.59–7.55 (m, 1H), 7.41 (d, *J* = 8.0 Hz, 1H), 7.20–7.18 (m, 2H), 7.09–7.08 (m, 3H), 6.97–6.92 (m, 4H), 5.77 (s, 1H), 4.41 (s, 1H), 3.83–3.78 (m, 1H), 3.10–3.00 (m, 2H), 2.91–2.85 (m, 1H), 2.19 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 194.8, 171.9, 143.1, 141.3, 137.5, 136.3, 135.5, 132.0, 131.7, 129.2, 128.8, 128.5, 127.8, 125.6, 123.2, 123.2, 77.4, 72.1, 63.2, 48.5, 32.8, 21.1; HRMS (ESI): m/z calcd for $C_{27}H_{22}N_2NaO_3$ $[M+Na]^+$ 445.1528, Found 445.1523. IR υ max: 3059, 2922, 1744, 1709, 1591, 1260,

1182, 766, 733, 700 cm^{-1}.

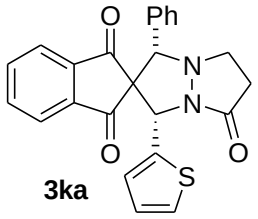
3'-(3-Methoxyphenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ja)



3ja

Prepared according to general procedure to afford **3ja** (108 mg, 82% yield) as a white solid; m.p. 148-150 ºC; For major diastereomer (*dr* = 7:1): ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.97-7.95 (m, 1H), 7.73–7.69 (m, 1H), 7.61–7.57 (m, 1H), 7.43 (d, *J* = 7.6 Hz, 1H), 7.20–7.04 (m, 6H), 6.67–6.59 (m, 3H), 5.77 (s, 1H), 4.39 (s, 1H), 3.85–3.79 (m, 1H), 3.61 (s, 3H), 3.09–3.02 (m, 2H), 2.92–2.87 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 194.5, 172.6, 159.6, 143.2, 141.2, 136.7, 136.3, 135.5, 131.6, 129.6, 128.9, 128.5, 127.8, 125.7, 123.3, 118.1, 113.7, 111.3, 77.4, 71.9, 63.3, 55.1, 48.2, 32.5; HRMS (ESI): m/z calcd for $C_{27}H_{22}N_2NaO_4$ $[M+Na]^+$ 461.1477, Found 461.1472. IR υ max: 3059, 2932, 1744, 1709, 1589, 1260, 1042, 768, 731, 698 cm^{-1}.

1'-Phenyl-3'-(thiophen-2-yl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3ka)



3ka

Prepared according to general procedure to afford **3ka** (87 mg, 70 % yield) as a white solid; m.p. 160-161 ºC; ^{1}H NMR (400 MHz, $CDCl_3$) δ (ppm) 7.97 (d, *J* = 8.0 Hz, 1H), 7.73–7.69 (m, 1H), 7.59–7.55 (m, 1H), 7.39 (d, *J* = 7.6 Hz, 1H), 7.20–7.06 (m, 8H), 5.81 (s, 1H), 4.42 (s, 1H), 3.85–3.79 (m, 1H), 3.10–3.03 (m, 2H), 2.94–2.84 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ (ppm) 198.3, 194.7, 172.4, 143.1, 141.3, 136.3, 135.6, 135.1, 131.6, 128.9, 128.5, 128.4, 127.9, 127.8, 125.7, 123.3, 123.2, 72.1, 63.3, 48.2, 32.6; HRMS (ESI): m/z calcd for $C_{24}H_{19}N_2O_3S$ $[M+H]^+$ 415.1116, Found 415.1111. IR υ max: 2922, 2851, 1701, 1657, 1593, 1256, 764 cm^{-1}.

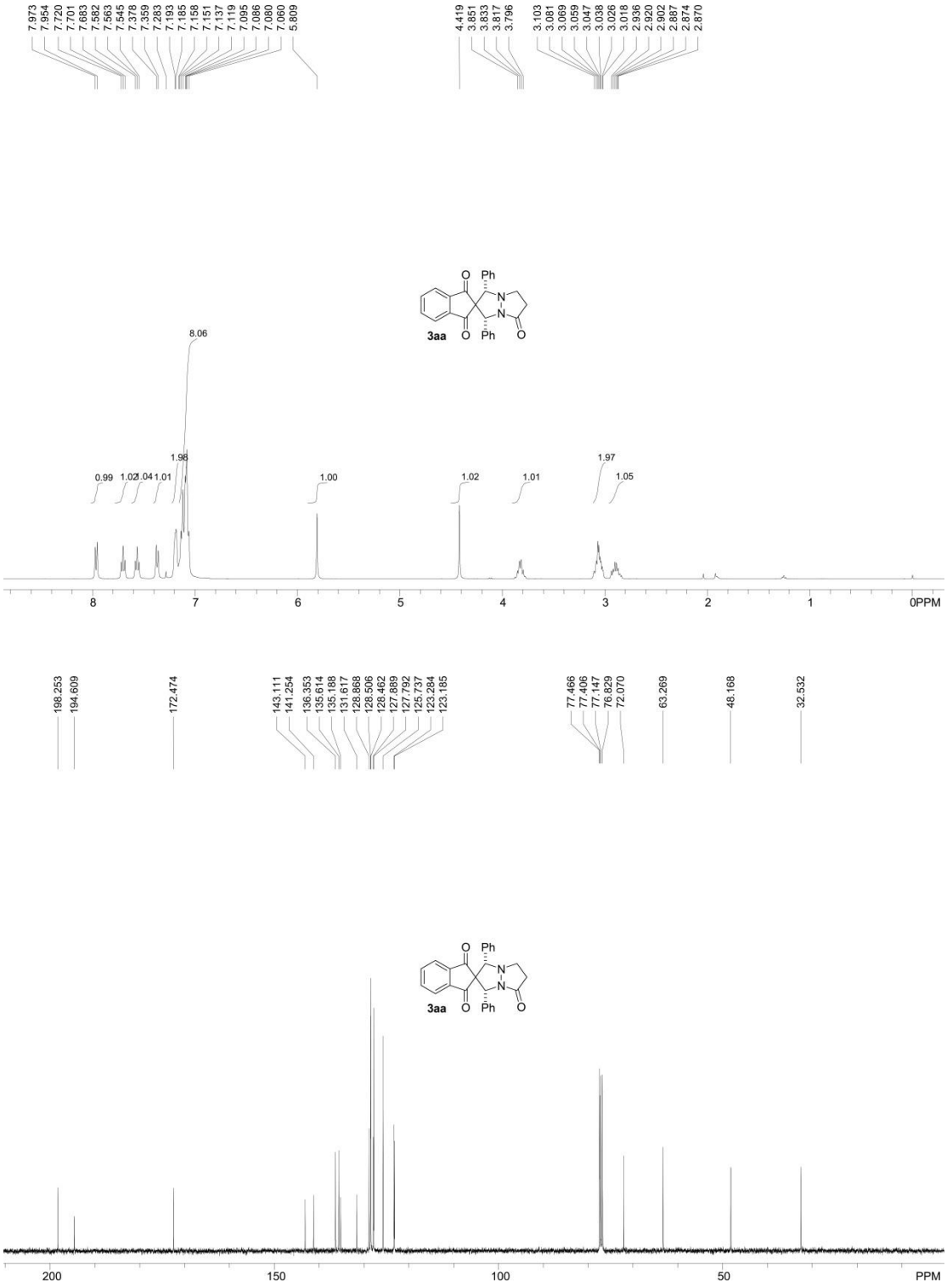
References

[1] Li, E.; Huang, Y.; Liang, L.; Xie, P. *Org. Lett*. **2013**, *15*, 3138.

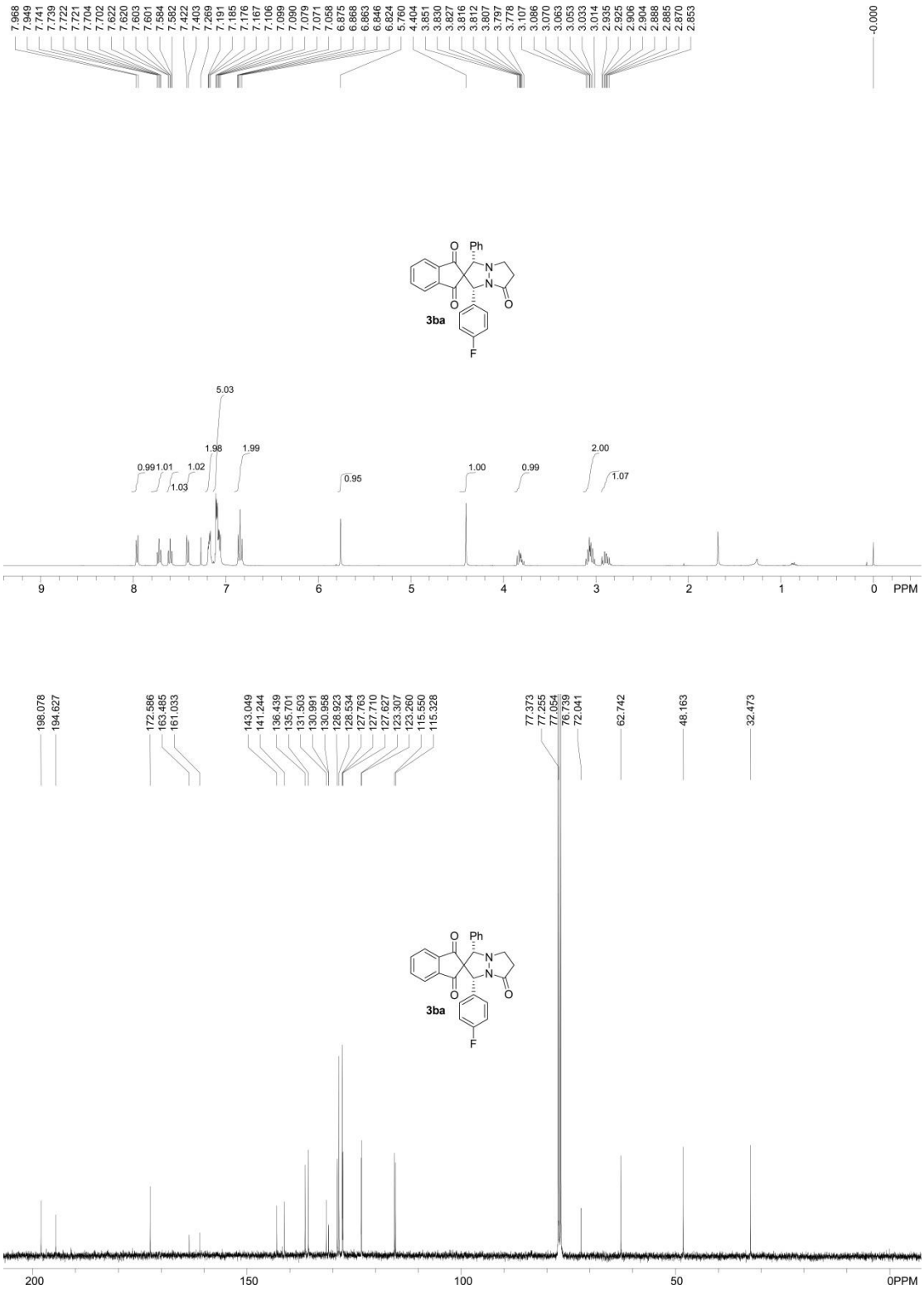
[2] Li, J.-T.; Lian, X.-J.; Liu, X.-H.; Lin, L.-L.; Feng, X.-M. *Chem. Eur. J*. **2013**, *19*, 5134.

Copies of ^{1}H and ^{13}C NMR spectra of 3aa-ka

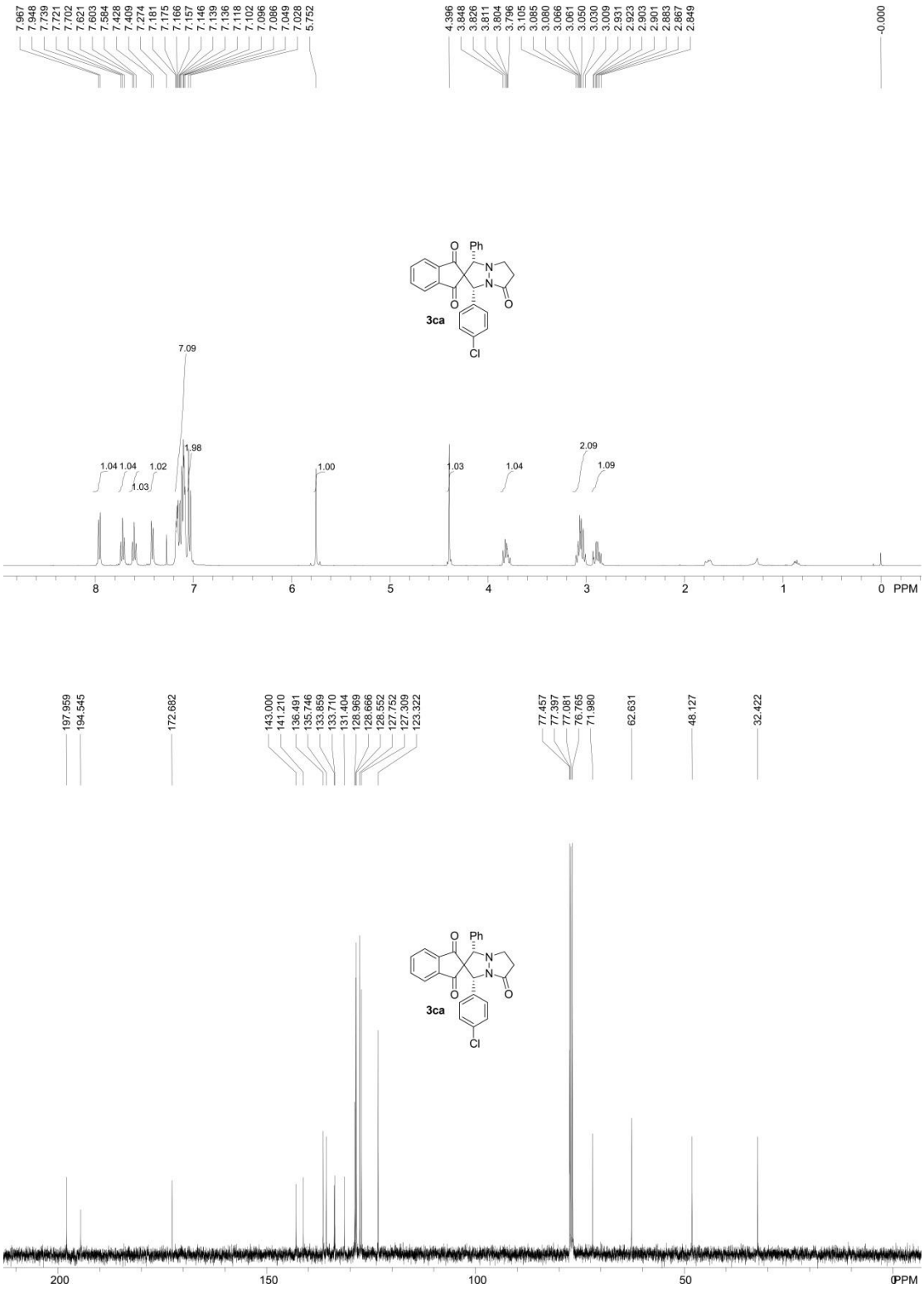
1',3'-Diphenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-a]pyrazole]-1,3,5'(3'H)-trione (3aa)



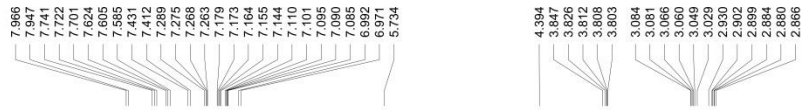
3'-(4-Fluorophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3ba)

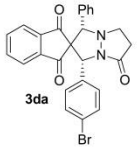


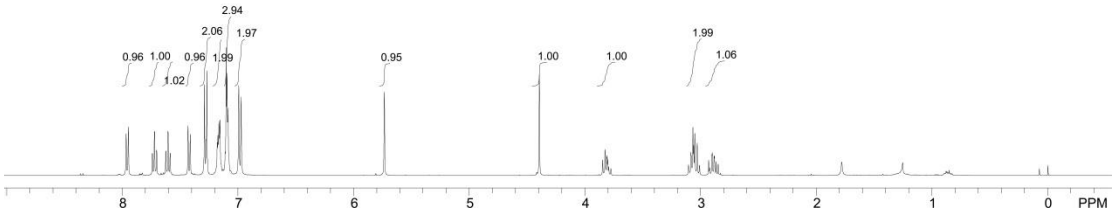
3'-(4-Chlorophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3ca)

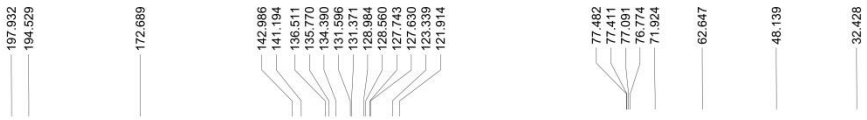


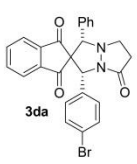
3'-(4-Bromophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3da)



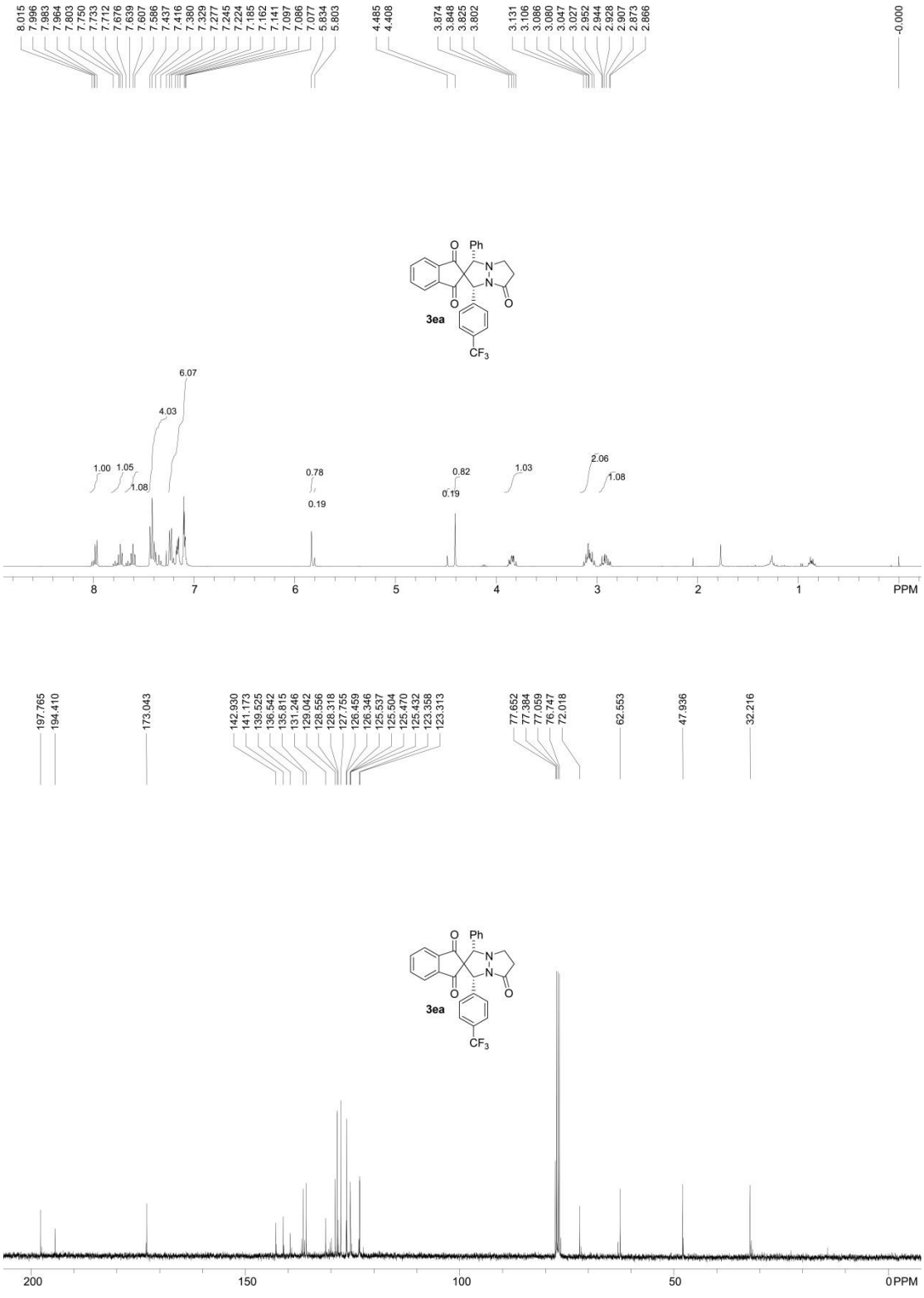




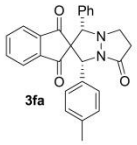


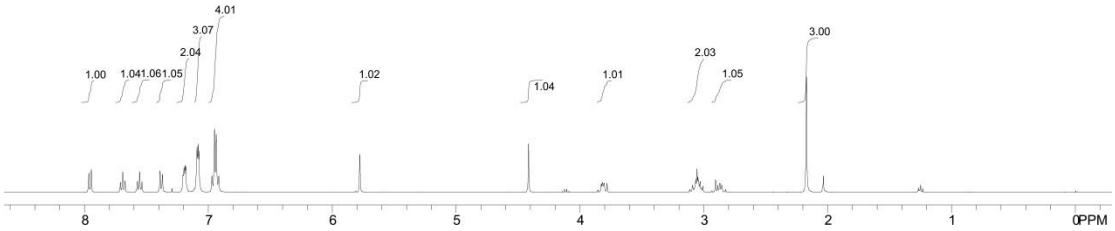


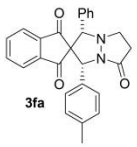
1'-Phenyl-3'-(4-(trifluoromethyl)phenyl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3ea)

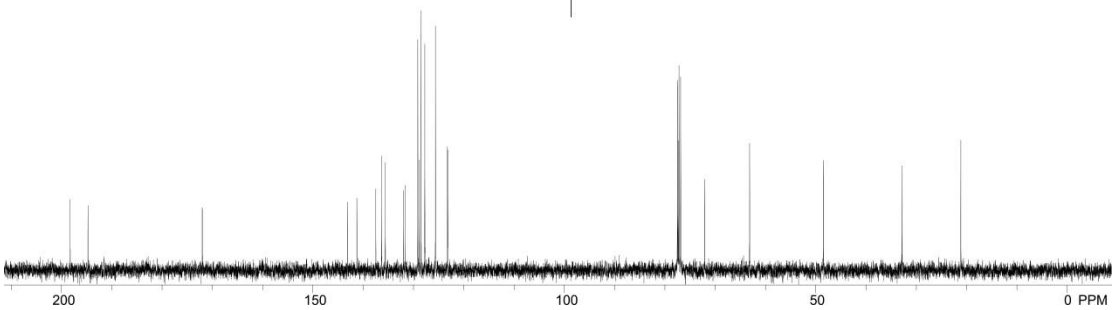


1'-Phenyl-3'-(p-tolyl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3fa)

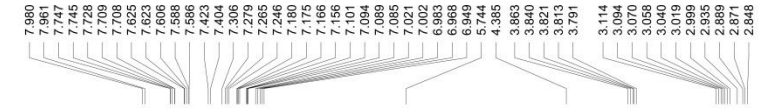


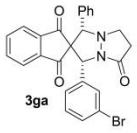


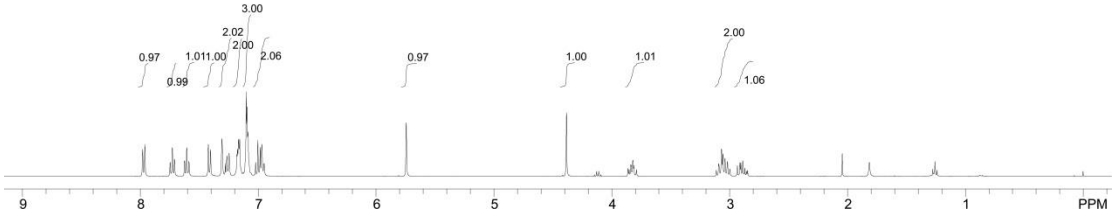


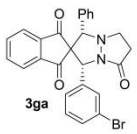


3'-(3-Bromophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3ga)

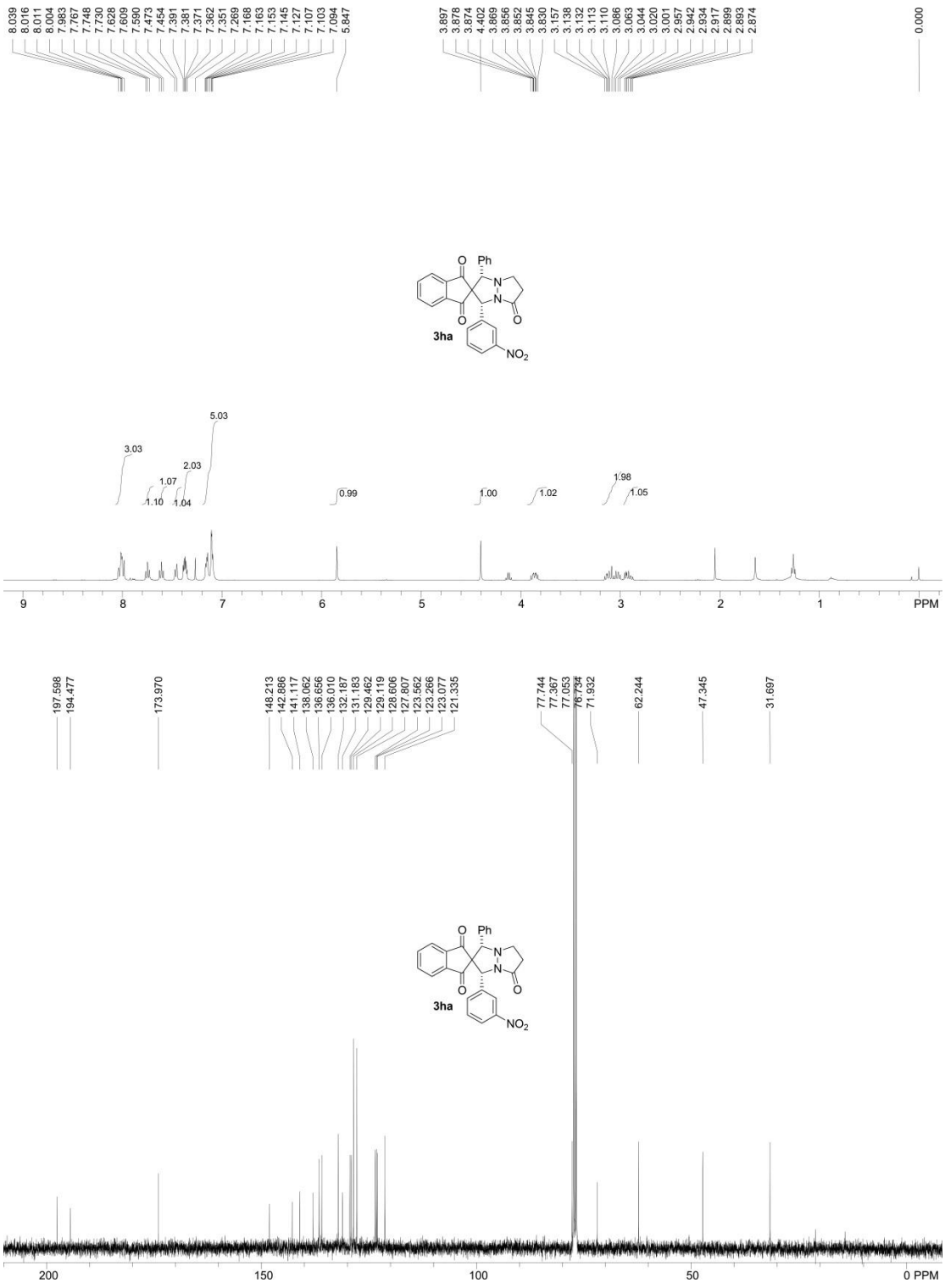




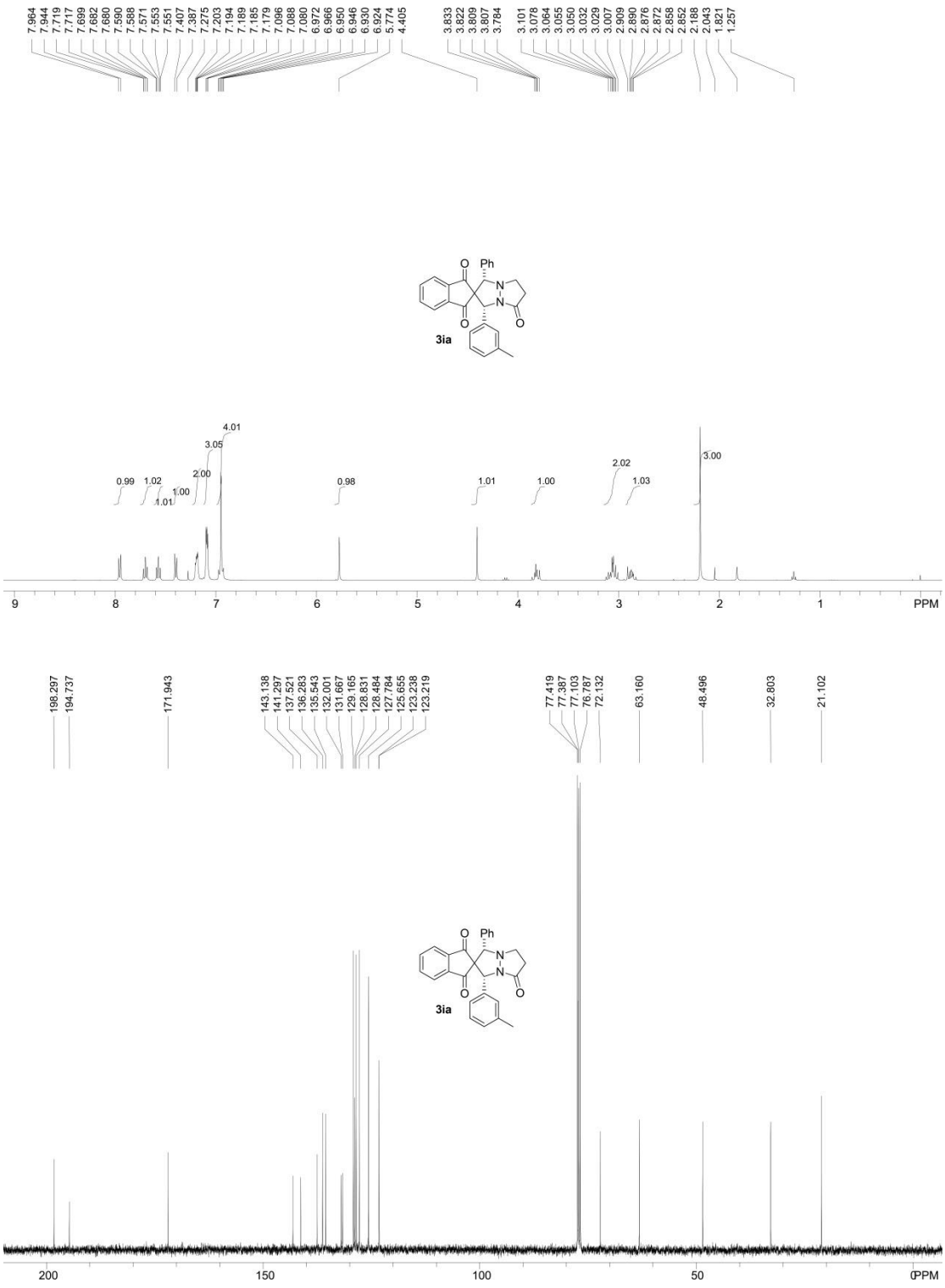




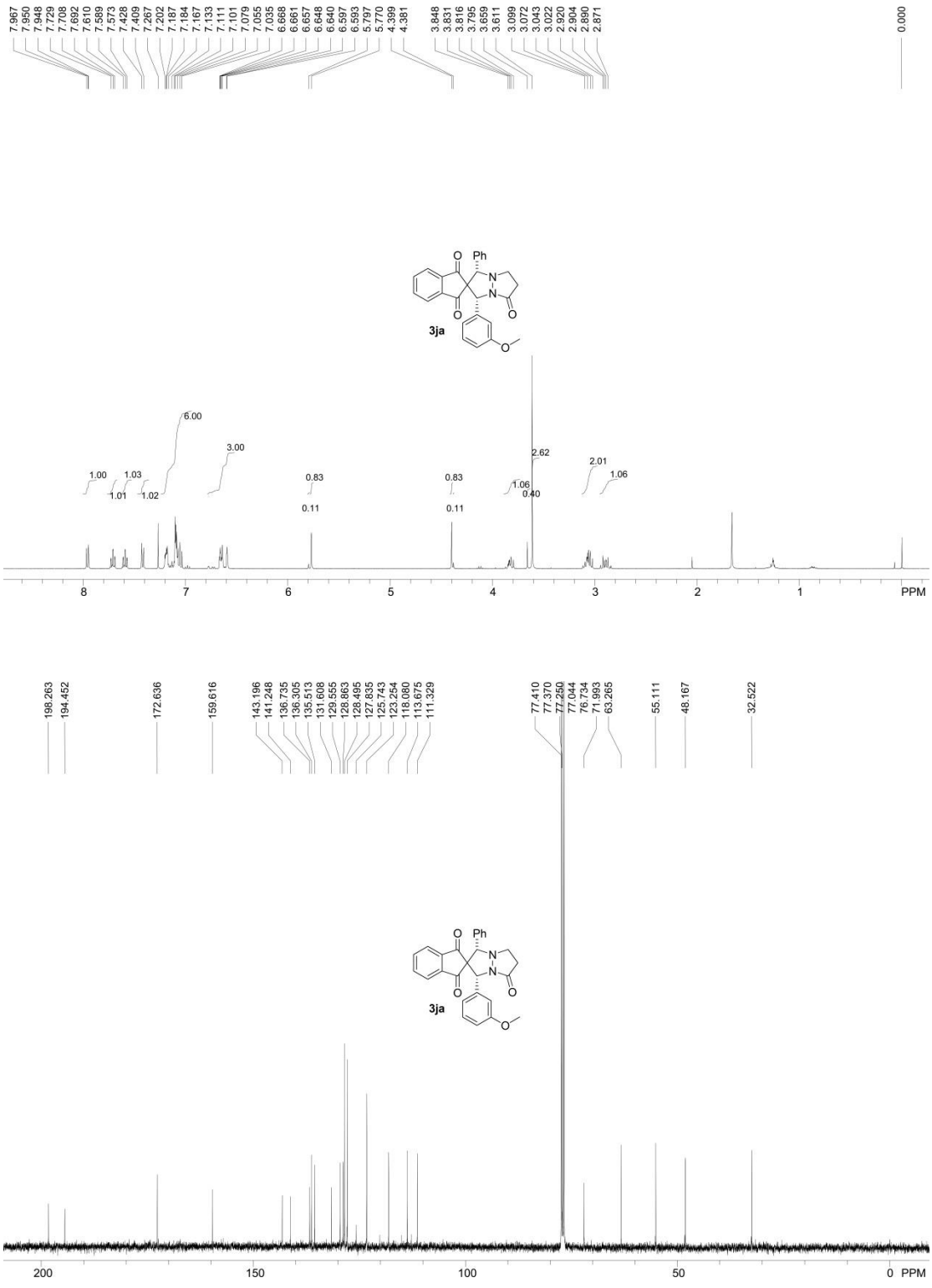
3'-(3-Nitrophenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*] pyrazole]-1,3,5'(3'H)-trione (3ha)



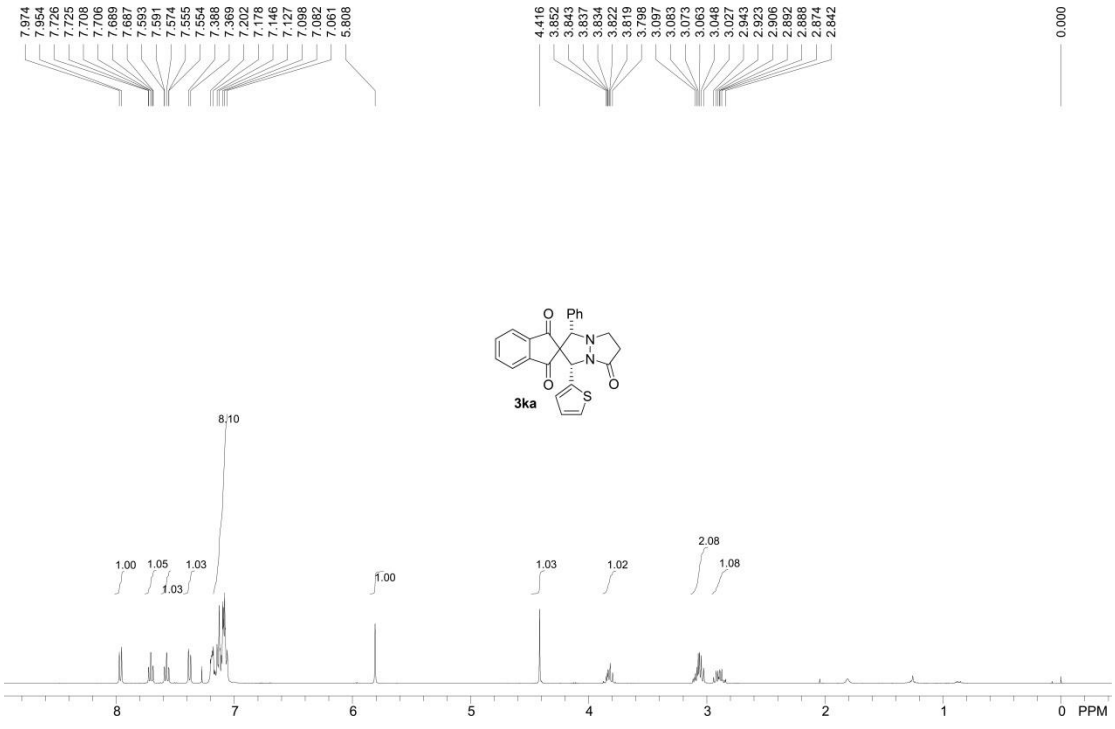
1'-Phenyl-3'-(m-tolyl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3ia)

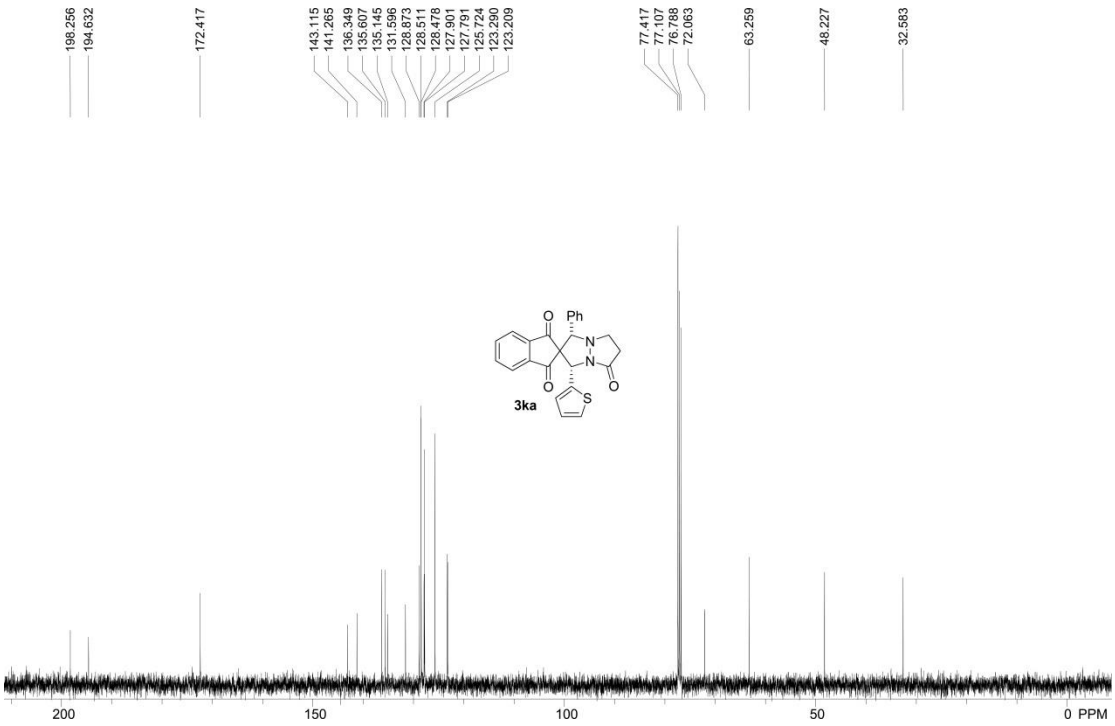


3'-(3-Methoxyphenyl)-1'-phenyl-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione (3ja)

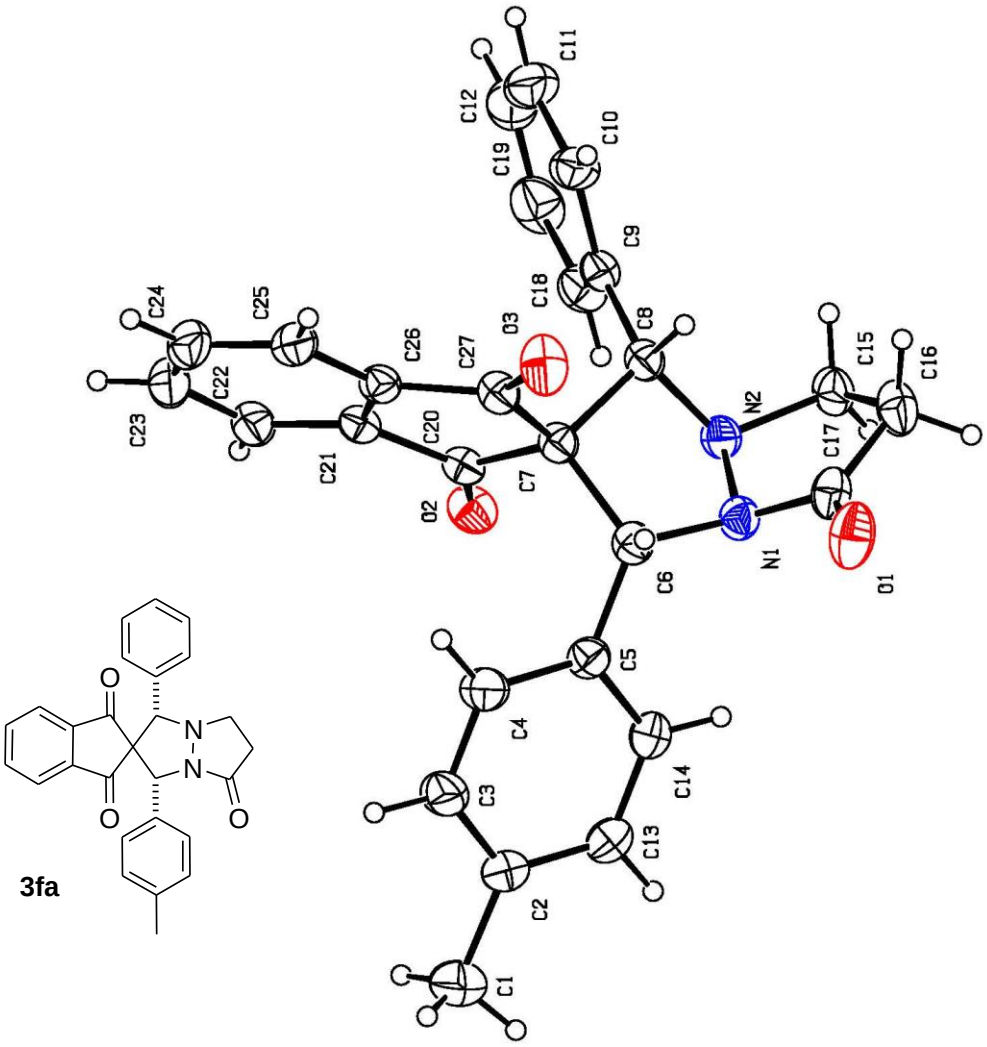


1'-Phenyl-3'-(thiophen-2-yl)-6',7'-dihydro-1'H-spiro[indene-2,2'-pyrazolo[1,2-*a*]pyrazole]-1,3,5'(3'H)-trione(3ka)





Crystal structure and data for compound 3fa



3fa

Crystal data and structure refinement for **3fa**

Identification code	shelx	
Empirical formula	$C_{27}H_{22}N_2O_3$	
Formula weight	422.46	
Temperature	293(2) K	
Wavelength	1.54187 Å	
Crystal system	Triclinic	
Space group	P -1	
Unit cell dimensions	a = 9.34320(10) Å	a= 113.841(8)°.
	b = 11.3125(2) Å	b= 108.881(8)°.
	c = 12.1914(8) Å	g = 96.208(7)°.
Volume	1071.85(11) $Å^3$	
Z	2	
Density (calculated)	1.309 Mg/m^3	
Absorption coefficient	0.690 mm^{-1}	
F(000)	444	
Crystal size	0.20 x 0.20 x 0.20 mm^3	
Theta range for data collection	7.267 to 89.479°.	
Index ranges	-11<=h<=11, -13<=k<=13, -14<=l<=14	
Reflections collected	12669	
Independent reflections	3796 [R(int) = 0.0440]	
Completeness to theta = 67.687°	96.6 %	
Absorption correction	Semi-empirical from equivalents	
Max. and min. transmission	0.871 and 0.637	
Refinement method	Full-matrix least-squares on F^2	
Data / restraints / parameters	3796 / 0 / 290	
Goodness-of-fit on F^2	1.141	
Final R indices [I>2sigma(I)]	R1 = 0.0506, wR2 = 0.1244	
R indices (all data)	R1 = 0.0558, wR2 = 0.1300	
Extinction coefficient	n/a	
Largest diff. peak and hole	0.238 and -0.297 $e.Å^{-3}$	