

Supplementary Information

Coupling of carboxylic acids with internal alkynes by supported ruthenium catalysts: Direct and selective syntheses of multi-substituted phthalide derivatives

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Experimental procedures and analytical data

Contents:

1. General considerations
2. Experimental procedures
3. Effect of bases on the coupling of benzoic acid **1a** with internal alkynes **2a**
4. Analytical data
5. Copies of NMR spectra for the products

1. General considerations

Materials and methods.

All manipulations were performed under an argon atmosphere using standard Schlenk techniques. $[\text{RuCl}_2(p\text{-cymene})]_2$ (Aldrich), all of the carboxylic acids (TCI), alkynes, sodium formate, mesitylene (Wako), cerium(III) nitrate hexahydrate, potassium acetate, and methanol (THF; Wako) were obtained commercially and used without further purification. Ceria was prepared by treating a solution of cerium(III) nitrate hexahydrate (12.6 g, 29 mmol) in 400 mL of deionized water with 40 mL of 3M KOH aqueous solution with stirring for 1 h at room temperature. The resulting precipitates were collected by centrifugation, washed thoroughly with deionized water and then air-dried overnight at 80 °C. The product was heated in a box furnace at a rate of 10 °C min⁻¹ and maintained at 400 °C for 30 min to afford ceria in an excellent ceramic yield. Ytria was prepared from yttrium(III) nitrates by a method similar to that used to obtain ceria. Zirconia (JRC-ZRO-3), titania (JRC-TIO-4), γ -alumina (JRC-ALO-8) and silica (JRC-SIO-9(2)) were used as received from Catalysis Society of Japan.

Physical and analytical measurements.

The products of the catalytic runs were analyzed by GC-MS (Shimadzu GCMS-QP5050, CBP-10 capillary column, i.d. 0.25 mm, length 30 m, at 50–250 °C) and gas chromatography (Shimadzu GC-2014, CBP-10 capillary column, i.d. 0.25 mm, length 30 m at 50–250 °C). NMR spectra were recorded on a Bruker Avance 500 (FT, 500 MHz (¹H), 125 MHz (¹³C)), instrument. Chemical shifts (δ) of ¹H and ¹³C{¹H} NMR spectra are referenced to SiMe₄. Elemental analyses were performed by using EAI CE-440 CHN/O/S Elemental Analyzer (Exeter Analytical, Inc.).

The solid catalysts were analyzed by XRD, nitrogen gas adsorption and XAFS. X-ray powder diffraction analyses were performed using Cu $K\alpha$ radiation and a one-dimensional X-ray detector (XRD: MiniFlex600, RIGAKU). The Brunauer—Emmett—Teller (BET) specific

surface area was estimated from N₂ isotherm obtained using a BELSORP-miniIII (BEL Japan, Osaka, Japan) at 77 K. The analyzed samples were evacuated at 573 K for 2 h prior to the measurement. Ru K-edge XAFS measurements were performed at the BL01B1 beam line at SPring-8 operated at 8 GeV using a Si(311) two-crystal monochromator. XAFS spectra were taken at room temperature. XANES were analyzed using the REX2000 version 2.5 program (Rigaku). Leaching of ruthenium species from the catalysts during the reaction was investigated by ICP atomic emission spectroscopic analysis with a Thermo Scientific iCAP 6300 Duo.

2. Experimental procedure

Typical preparation of a Ru/Support catalyst

Supported catalysts were prepared by the impregnation method. 1.0 g of a support was added to a solution of [RuCl₂(*p*-cymene)]₂ (79.5 mg, 0.20 mmol) in 10 mL of methanol in air at 323 K. After impregnation, the resulting powder was calcined in air for 30 min to afford the Ru(2.0 wt%)/Support catalyst.

Representative procedure for catalytic reaction

A 20 mL Schlenk tube was charged with 2,4-dimethylbenzoic acid **1b** (1.0 mmol), 1-phenyl-1-propyne **2a** (1.3 mmol), Ru/ZrO₂ (150 mg, 0.030 mmol as Ru), potassium acetate (0.15 mmol) and mesitylene (1.0 mL) under an argon atmosphere. The reaction mixture was stirred at 170 °C for 24 h on a hot stirrer with a cooling block. After the reaction, the reaction solution was separated from the reaction mixture by centrifugation and concentrated under reduced pressure. The products were isolated by a column chromatography (hexane : EtOAc = 20 : 1, v/v) to give the product **3b** as a white solid (206 mg, 77%).

Recycling of the Ru/ZrO₂ catalyst

After the reaction, the solid was separated from the reaction mixture by centrifugation and

washed with 10 mL of diethyl ether, methanol/H₂O (1 : 1), and again by diethyl ether . The resulting solid was dried overnight at 80 °C and calcined in air at 400 °C for 30 min to recover the Ru/ZrO₂ catalyst for reuse.

Hot filtration tests.

A 20 mL Schlenk tube was charged with **1a** (1.0 mmol), **2a** (1.3 mmol), Ru/ZrO₂ (150 mg, 0.030 mmol as Ru), potassium acetate (0.15 mmol) and mesitylene (1.0 mL) together with an internal standard (*o*-terphenyl, ca. 50 mg) under an argon atmosphere. After the reaction was allowed to proceed for 3 h at 170 °C, the mixture was filtered through a 0.45 μm syringe filter (Millipore Millex LH) into another preheated Schlenk tube containing 0.15 mmol of potassium acetate. The filtrate was stirred at 170 °C. The conversion and yields of the product after filtration were followed by GC and GC-MS analyses. The results are shown in Figure S1. The reaction was not completely stopped by the removal of solid Ru/ZrO₂. This result indicates that not only Ru species on the solid surface but also Ru species that have leached into the reaction solution show activity for the reaction.

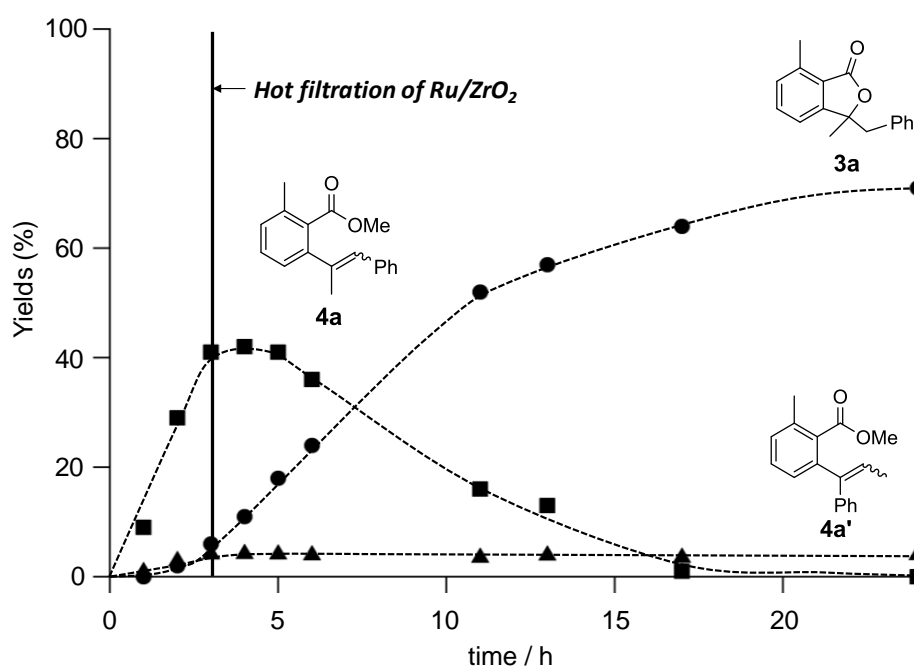
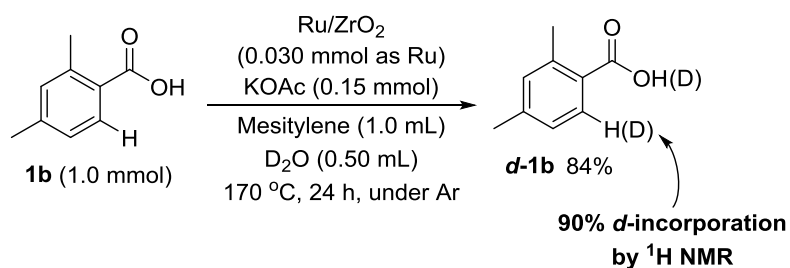
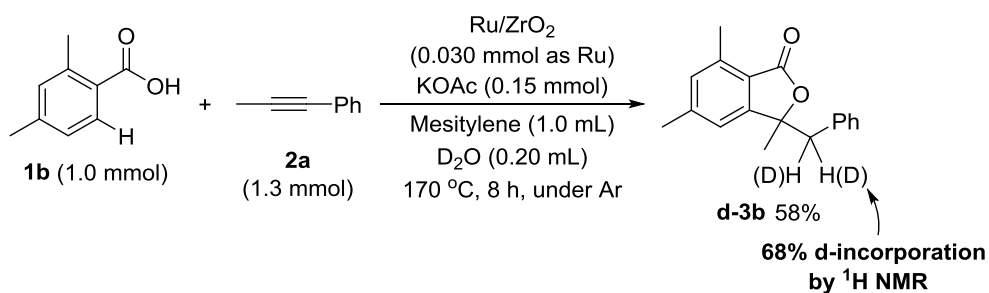


Figure S1. Hot filtration of Ru/ZrO₂; yield of **3a**(●), **4a**(■) and **4a'**(▲)

Deuterium labeling experiments

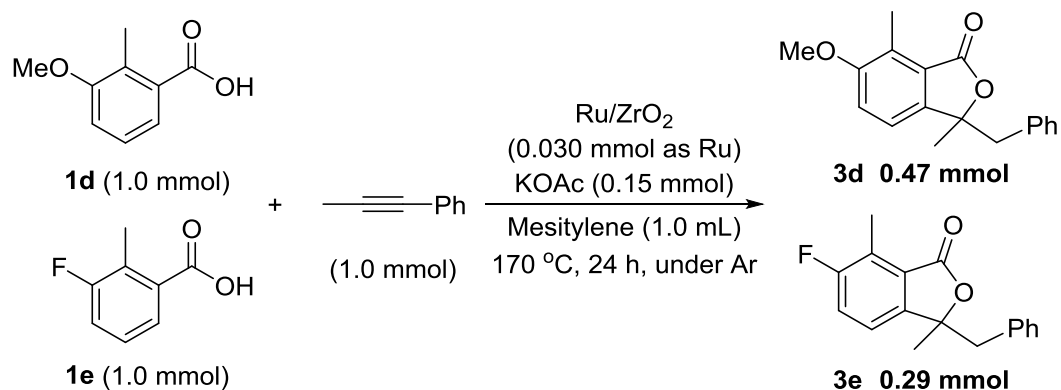


A 20 mL Schlenk tube was charged with 2,4-dimethylbenzoic acid **1b** (1.0 mmol), Ru/ZrO₂ (150 mg, 0.030 mmol as Ru), potassium acetate (0.15 mmol), mesitylene (1.0 mL) and D₂O (0.50 mL) under an argon atmosphere. The reaction mixture was stirred at 170 °C for 24 h on a hot stirrer with a cooling block. After cooling the reaction mixture, Ru catalyst was separated from the reaction mixture by centrifugation and solvent was removed under reduced pressure. The product was isolated in 84% yield and 90% deuterium incorporation at the ortho position was judged by ¹H NMR.



A 20 mL Schlenk tube was charged with 2,4-dimethylbenzoic acid **1b** (1.0 mmol), 1-phenyl-1-propyne **2a** (1.3 mmol), Ru/ZrO₂ (150 mg, 0.030 mmol as Ru), potassium acetate (0.15 mmol), mesitylene (1.0 mL) and D₂O (0.20 mL) under an argon atmosphere. The reaction mixture was stirred at 170 °C for 8 h on a hot stirrer with a cooling block. After cooling the reaction mixture, Ru catalyst was separated from the reaction mixture by centrifugation and solvent was removed under reduced pressure. The product was isolated through column chromatography in 58% yield and 68% deuterium incorporation at the methylene position of **3b** was observed by ¹H NMR.

Intermolecular competition experiment

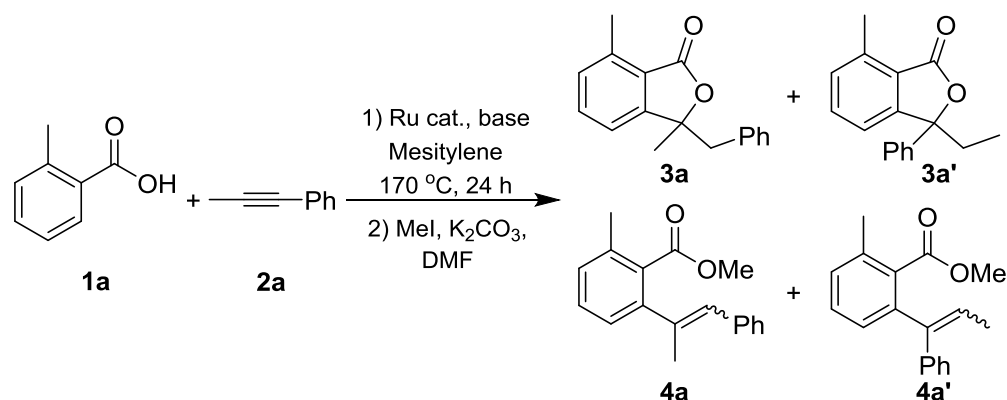


A 20 mL Schlenk tube was charged with 3-methoxy-2-methylbenzoic acid **1d** (1.0 mmol), 3-fluoro-2-methylbenzoic acid **1e** (1.0 mmol), 1-phenyl-1-propyne **2a** (1.0 mmol), Ru/ZrO₂ (150 mg, 0.030 mmol as Ru), potassium acetate (0.15 mmol) and mesitylene (1.0 mL) together with an internal standard (*o*-terphenyl, ca. 50 mg) under an argon atmosphere. The reaction mixture was stirred at 170 °C for 24 h on a hot stirrer with a cooling block. After cooling the reaction mixture, yields of the products **3d** and **3e** were followed by FID-GC analyses. Substrate with electron-donating substituent preferentially converted to corresponding product **3d**, suggesting that the reaction included electrophilic C-H bond metalation.

3. Effect of base on the coupling of benzoic acid **1a** with internal alkynes **2a**

Table S1 shows the effect of bases on the coupling of benzoic acid **1a** with internal alkynes **2a**. Of the bases examined, potassium or sodium salts afforded good yields of the products (entries 1-4). In case of Ru/CeO₂, the combination with sodium formate resulted in superior yield of **3a** to that with potassium acetate (entry 5). The present reaction requires catalytic amount of base and the products were not obtained in the absence of base (entry 6).

Table S1. Effect of bases on coupling of **1a** with **2a**^a



entry	catalyst	additive	yield (%) ^b			
			3a	3a'	4a	4a'
1	Ru/ZrO ₂	KOAc	93	0	0	3
2	Ru/ZrO ₂	KOH	86	0	4	1
3	Ru/ZrO ₂	K ₂ CO ₃	68	0	4	3
4	Ru/ZrO ₂	HCO ₂ Na	74	0	3	7
5	Ru/CeO ₂	HCO ₂ Na	80	0	2	12
6	Ru/ZrO ₂	—	0	0	0	0

^a Reaction conditions: (1) **1a** (1.0 mmol), **2a** (1.3 mmol), Ru catalyst (0.030 mmol as Ru), base (0.15 mmol), mesitylene (1.0 mL), at 170 °C, 24 h, under Ar. (2) MeI, K₂CO₃, DMF at rt.

^b Yields were determined by GLC based on **1a**.

4. Analytical data

Characterization of supported Ru catalysts

i) BET surface area

The BET surface areas of supported Ru catalysts were characterized by nitrogen gas adsorption.

The results are summarized in Table S2. The surface areas of Ru/ZrO₂ and Ru/CeO₂ were 96 and 135 m²g⁻¹, respectively. Although Ru/SiO₂, Ru/Al₂O₃ and Ru/TiO have higher surface areas, they were not effective catalysts for the present reactions.

Table S2. Characterization data by nitrogen gas adsorption of supported Ru catalysts

entry	Ru catalyst	surface area / m ² g ⁻¹
1	Ru/ZrO ₂	96
2	Ru/CeO ₂	135
3	Ru/Y ₂ O ₃	13
4	Ru/SiO ₂	314
5	Ru/Al ₂ O ₃	171
6	Ru/TiO ₂	56

ii) XRD patterns

XRD patterns of supported Ru catalysts are shown in Figure S2. Although the peaks due to crystalline RuO₂ were observed for Ru catalysts supported on SiO₂ and Al₂O₃, they did not appear for Ru/TiO₂, Ru/ZrO₂, Ru/Y₂O₃ and Ru/CeO₂. This indicates that Ru species on TiO₂, ZrO₂, Y₂O₃ and CeO₂ are highly dispersed. Although peaks due to RuO₂ were not observed on TiO₂, these catalysts did not show any catalytic activities. Note that the EXAFS study clearly indicates the formation of RuO₂-like phase on TiO₂ (See Figure S3), suggesting the formation of microcrystals of RuO₂ on TiO₂ which cannot be detected by the XRD.

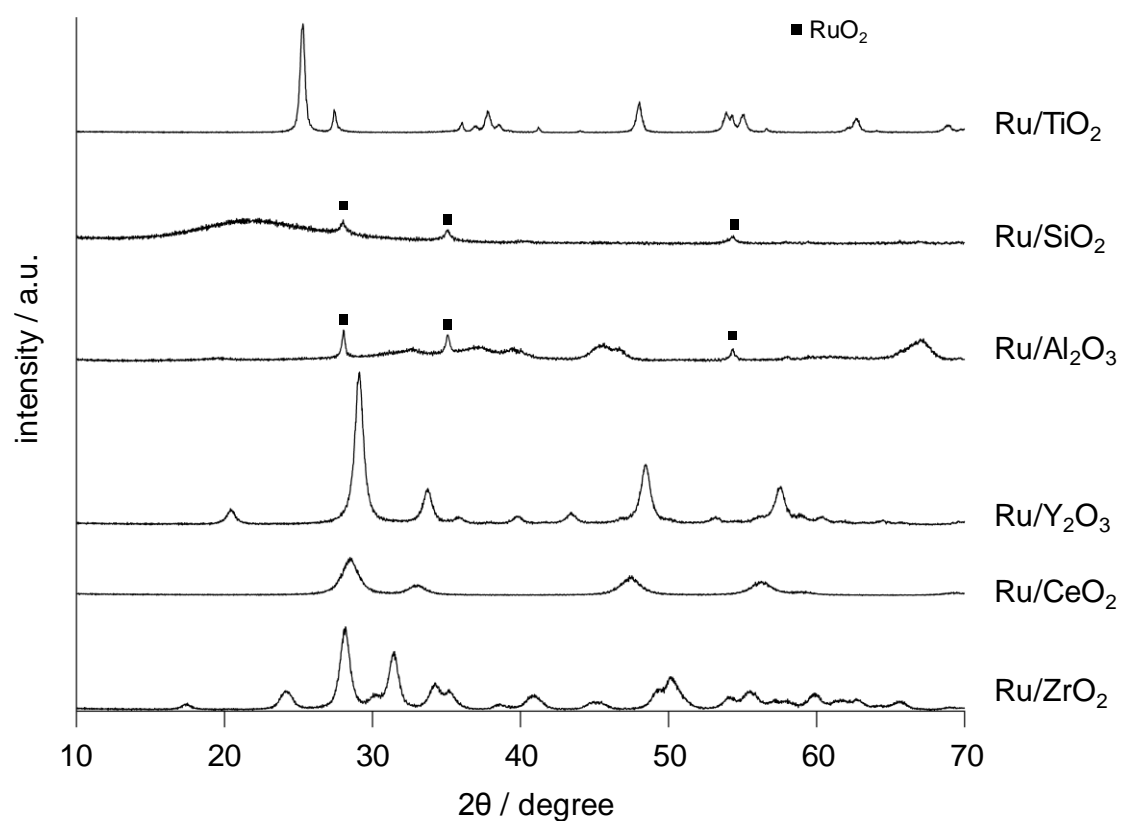


Figure S2. XRD patterns of supported Ru catalysts

iii) Ru K-edge EXAFS spectra

Ru K-edge EXAFS spectra of supported Ru catalysts and RuO₂ are shown in Figure S3. The oscillations of Ru catalysts supported on SiO₂, Al₂O₃ and TiO₂ resembled that of RuO₂. On the other hand, the oscillations of Ru/CeO₂ and Ru/ZrO₂ were very weak and completely different from that of RuO₂. This suggests that Ru species are highly dispersed on CeO₂ and ZrO₂.

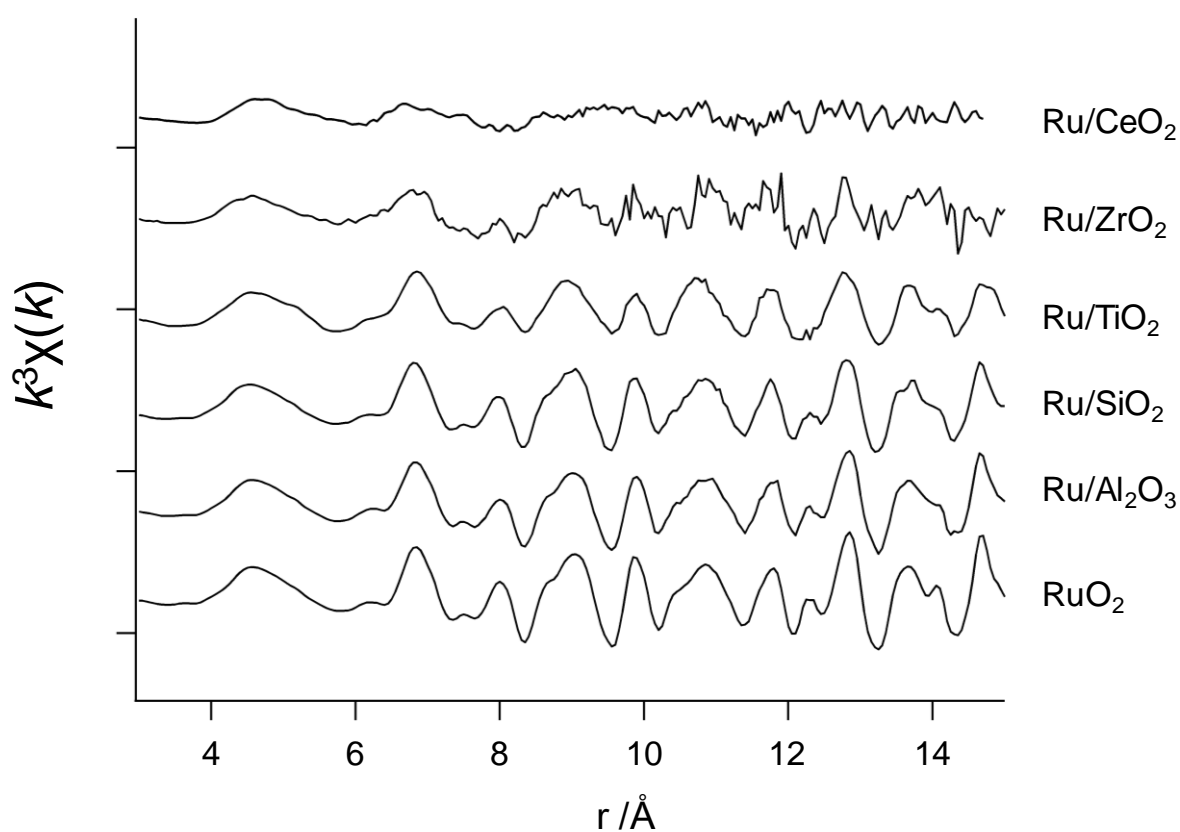


Figure S3. EXAFS spectra of supported Ru catalysts

iv) Fourier-transformed Ru K-edge EXAFS spectra

Fourier-transforms of EXAFS spectra are shown in Figure S4. The peaks at 2.0-4.0 Å due to a second coordination sphere in the spectra of Ru/CeO₂ and Ru/ZrO₂ were very weak, because of the presence of highly dispersed Ru species on CeO₂ or ZrO₂. On the other hand, the spectra of Ru catalysts on SiO₂, Al₂O₃ and TiO₂ closely resembled that of crystalline RuO₂, indicating that Ru species on SiO₂, Al₂O₃ and TiO₂ exist as crystallized rutile-type RuO₂.

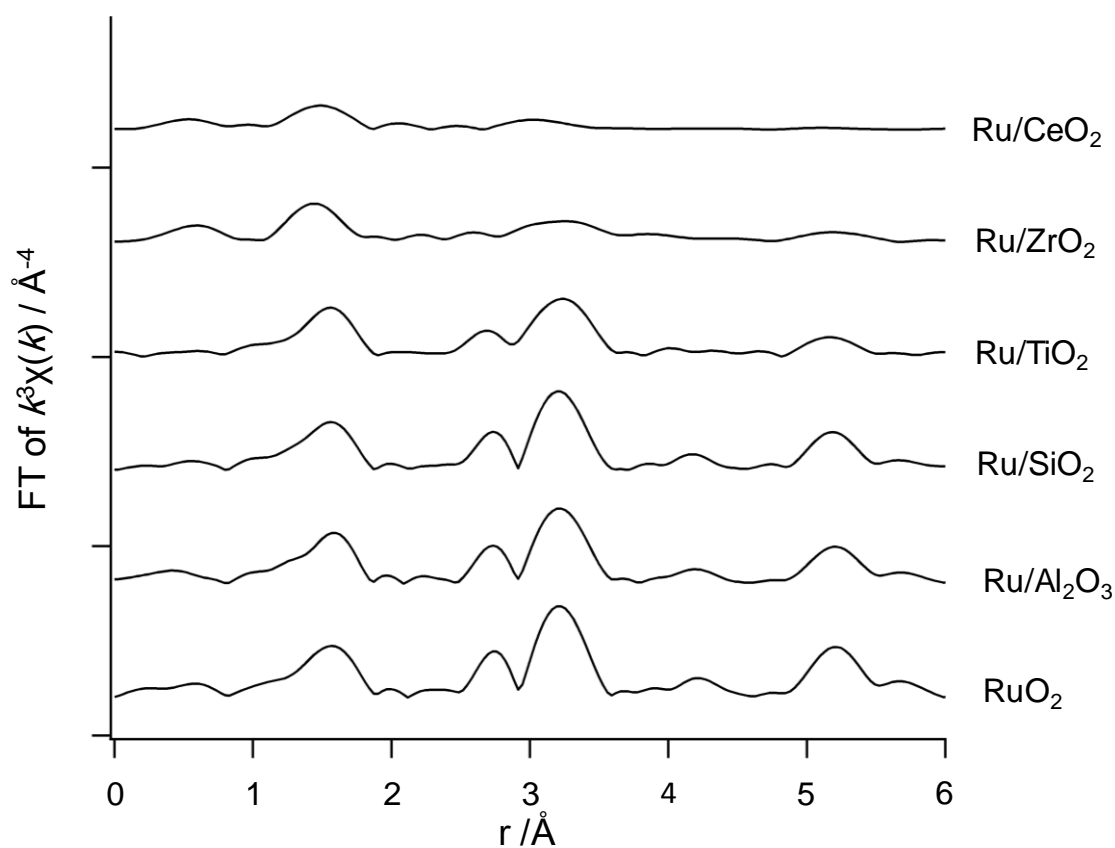


Figure S4. Fourier transformed EXAFS spectra of supported Ru catalysts

v) Ru K-edge XANES spectra

The X-ray absorption near-edge structure (XANES) spectra of Ru catalysts supported on SiO₂, Al₂O₃ and TiO₂ are almost identical to that of rutile-type RuO₂ (Figure S5). In contrast, the coordination environment of Ru species on CeO₂ and ZrO₂ was distinctly different: a pre-edge peak appeared at 22118 eV, indicating the formation of Ru^{IV} species in a distorted coordination environment on CeO₂ and ZrO₂.

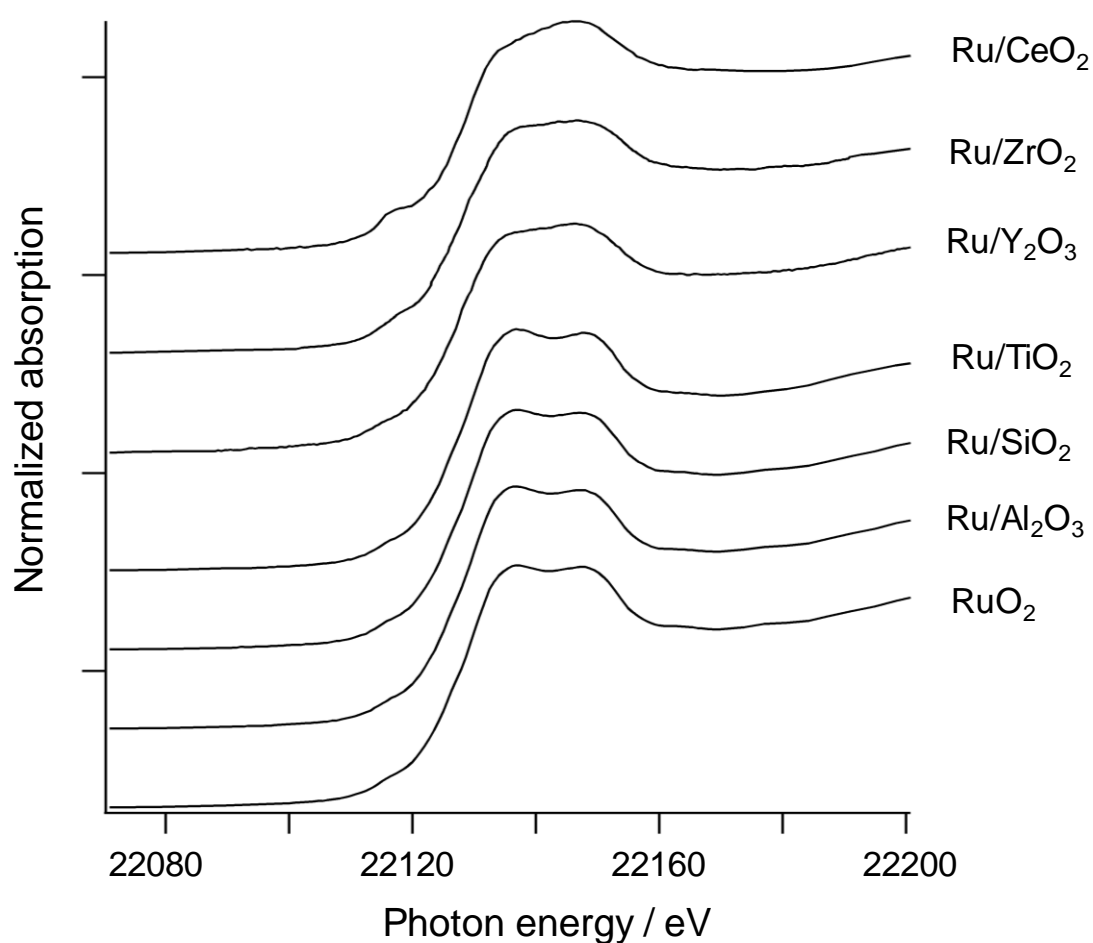
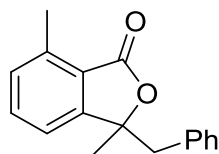
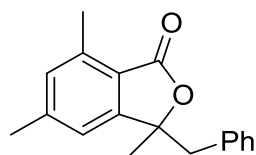


Figure S5. Ru K-edge XANES spectra of supported Ru catalysts

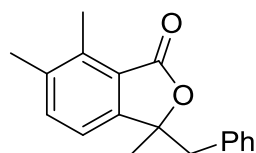
Characterization of the products



3-benzyl-3,7-dimethylisobenzofuran-1(3H)-one (3a): pale yellow solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.47 (t, $J = 8.0$ Hz, 1H), 7.10-7.18 (m, 5H), 7.04-7.06 (m, 2H), 3.21 (d, $J = 14$ Hz, 1H), 3.14 (d, $J = 14$ Hz, 1H), 2.57 (s, 3H), 1.64 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 169.8, 153.7, 139.6, 134.8, 133.4, 130.5, 128.0, 126.9, 123.6, 118.7, 85.9, 46.5, 25.7, 17.3. MS (EI) m/z 252 (M^+). Anal. Calcd for $\text{C}_{17}\text{H}_{16}\text{O}_2$: C, 80.93; H, 6.39. Found: C, 80.84; H, 6.41.

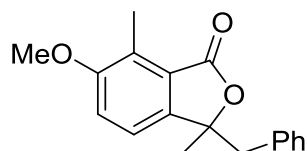


3-benzyl-3,5,7-trimethylisobenzofuran-1(3H)-one (3b): white solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.13-7.21 (m, 3H), 7.05-7.09 (m, 2H), 6.99 (s, 1H), 6.92 (s, 1H), 3.15 (d, $J = 14$ Hz, 1H), 3.12 (d, $J = 14$ Hz, 1H), 2.53 (s, 3H), 2.41 (s, 3H), 1.60 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 169.8, 154.4, 144.4, 139.2, 135.0, 131.6, 130.5, 128.0, 126.9, 121.1, 119.2, 85.6, 46.6, 25.6, 21.9, 17.2. MS (EI) m/z 266 (M^+). Anal. Calcd for $\text{C}_{18}\text{H}_{18}\text{O}_2$: C, 81.17; H, 6.81. Found: C, 81.11; H, 6.81.

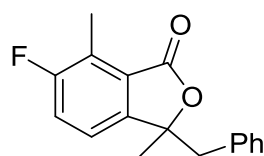


3-benzyl-3,6,7-trimethylisobenzofuran-1(3H)-one (3c): pale yellow solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.36 (d, $J = 7.5$ Hz, 1H), 7.13-7.20 (m, 3H), 7.06 (d, $J = 5.0$ Hz, 2H), 7.01

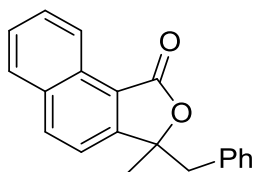
(d, $J = 7.5$ Hz, 1H), 3.17 (d, $J = 14$ Hz, 1H), 3.12 (d, $J = 14$ Hz, 1H), 2.52 (s, 3H), 2.30 (s, 3H), 1.61 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 170.1, 151.6, 138.1, 137.9, 135.0, 130.5, 128.0, 126.8, 123.5, 118.2, 85.6, 46.6, 25.8, 19.1, 13.2. MS (EI) m/z 266 (M^+). Anal. Calcd for $\text{C}_{18}\text{H}_{18}\text{O}_2$: C, 81.17; H, 6.81. Found: C, 81.04; H, 6.85.



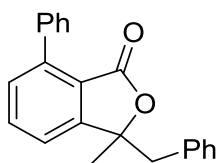
3-benzyl-6-methoxy-3,7-dimethylisobenzofuran-1(3H)-one (3d): white solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.15–7.20 (m, 3H), 7.02–7.08 (m, 4H), 3.86 (s, 3H), 3.17 (d, $J = 14$ Hz, 1H), 3.12 (d, $J = 14$ Hz, 1H), 2.45 (s, 3H), 1.61 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 169.8, 158.0, 145.1, 135.0, 130.5, 128.0, 126.8, 124.7, 118.8, 115.4, 85.3, 56.2, 46.8, 26.0, 9.8. MS (EI) m/z 282 (M^+). Anal. Calcd for $\text{C}_{18}\text{H}_{18}\text{O}_3$: C, 76.57; H, 6.43. Found: C, 76.42; H, 6.40.



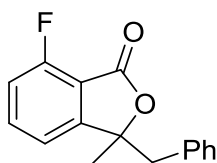
3-benzyl-6-methoxy-3,7-dimethylisobenzofuran-1(3H)-one (3e): pale yellow solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.23–7.27 (m, 1H), 7.15–7.20 (m, 3H), 7.01–7.08 (m, 3H), 3.21 (d, $J = 14$ Hz, 1H), 3.13 (d, $J = 14$ Hz, 1H), 2.48 (s, 3H), 1.65 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 168.7(d, $J_{\text{C-F}} = 3.6$ Hz), 161.1 (d, $J_{\text{C-F}} = 244$ Hz), 148.9 (d, $J_{\text{C-F}} = 2.75$ Hz), 134.5, 130.5, 128.1, 127.0, 126.0 (d, $J_{\text{C-F}} = 19$ Hz), 125.6 (d, $J_{\text{C-F}} = 6.3$ Hz), 120.6 (d, $J_{\text{C-F}} = 25$ Hz), 119.5 (d, $J_{\text{C-F}} = 8.8$ Hz), 85.6, 46.5, 25.8, 8.9 (d, $J_{\text{C-F}} = 3.8$ Hz). MS (EI) m/z 270 (M^+). Anal. Calcd for $\text{C}_{17}\text{H}_{15}\text{FO}_2$: C, 75.54; H, 5.59. Found: C, 75.25; H, 5.59.



3-benzyl-3-methylnaphtho[1,2-*c*]furan-1(3*H*)-one (3f): ocher solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 8.90 (d, $J = 8.5$ Hz, 1H), 8.09 (d, $J = 8.0$ Hz, 1H), 7.91 (d, $J = 8.0$ Hz, 1H), 7.65 (dt, $J = 9.0$ Hz, 1.0 Hz, 1H), 7.57 (dt, $J = 9.0$ Hz, 1.0 Hz, 1H), 7.38 (d, $J = 8.5$ Hz, 1.0 Hz, 1H), 7.07–7.16 (m, 5H), 3.31 (d, $J = 14$ Hz, 1H), 3.24 (d, $J = 14$ Hz, 1H), 1.72 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 169.9, 154.7, 135.2, 134.6, 133.2, 130.4, 129.2, 129.0, 128.4, 127.2, 127.0, 123.6, 120.1, 118.2, 86.1, 46.1, 25.4. MS (EI) m/z 288 (M^+). Anal. Calcd for $\text{C}_{20}\text{H}_{16}\text{O}_2$: C, 83.31; H, 5.59. Found: C, 83.03; H, 5.64.

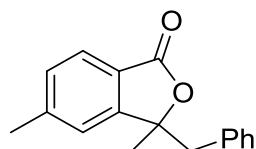


3-benzyl-3-methyl-7-phenylisobenzofuran-1(3*H*)-one (3g): pale yellow solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.63 (t, $J = 7.0$ Hz, 1H), 7.28–7.43 (m, 7H), 7.16 (m, 3H), 7.03 (m, 2H), 3.29 (d, $J = 14$ Hz, 1H), 3.18 (d, $J = 14$ Hz, 1H), 1.73 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 168.3, 154.4, 142.5, 136.5, 134.7, 133.5, 130.6, 130.5, 129.4, 128.3, 128.0, 127.9, 126.9, 122.3, 120.1, 85.3, 46.7, 25.7. MS (EI) m/z 314 (M^+). Anal. Calcd for $\text{C}_{20}\text{H}_{18}\text{O}_2$: C, 84.05; H, 5.77. Found: C, 83.78; H, 5.74.

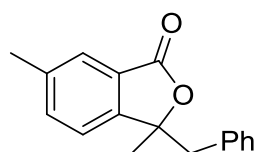


3-benzyl-7-fluoro-3-methylisobenzofuran-1(3*H*)-one (3h): pale brown solid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.54 (m, 1H), 7.05–7.10 (m, 4H), 6.95–6.99 (m, 3H), 3.18 (d, $J = 14$ Hz, 1H), 3.09 (d, $J = 14$ Hz, 1H), 1.62 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 165.6, 159.3

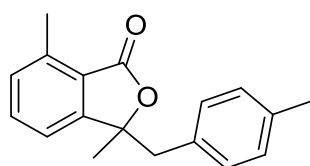
(d, $J_{C-F} = 263$ Hz), 155.8, 136.2 (d, $J_{C-F} = 8.1$ Hz), 134.1, 130.4, 128.1, 127.1, 117.3 (d, $J_{C-F} = 4.3$ Hz), 115.9 (d, $J_{C-F} = 19$ Hz), 114.0 (d, $J_{C-F} = 13.3$ Hz), 86.9, 46.3, 25.7. MS (EI) m/z 256 (M^+). Anal. Calcd for $C_{16}H_{13}FO_2$: C, 74.99.; H, 5.11. Found: C, 74.76; H, 5.18.



3-benzyl-3,5-dimethylisobenzofuran-1(3H)-one (3i): pale yellow liquid; 1H NMR (500 MHz, $CDCl_3$, ppm) δ 7.59 (d, $J = 7.5$ Hz, 1H), 7.23 (d, $J = 7.5$ Hz, 1H), 7.15–7.17 (m, 2H), 7.12 (s, 1H), 7.03–7.06 (m, 2H), 3.22 (d, $J = 14$ Hz, 1H), 3.14 (d, $J = 14$ Hz, 1H), 2.48 (s, 3H), 1.65 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$, ppm) δ 169.7, 153.7, 144.9, 134.7, 130.5, 130.0, 128.0, 126.9, 125.3, 123.6, 86.8, 46.4, 25.5, 22.1. MS (EI) m/z 252 (M^+).

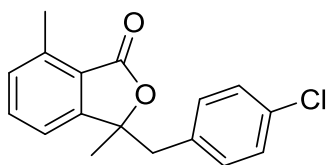


3-benzyl-3,6-dimethylisobenzofuran-1(3H)-one (3j): pale yellow liquid; 1H NMR (500 MHz, $CDCl_3$, ppm) δ 7.50 (s, 1H), 7.42 (d, $J = 7.5$ Hz, 1H), 7.20 (d, $J = 7.5$ Hz, 1H), 7.15–7.16 (m, 3H), 7.03–7.05 (m, 2H), 3.22 (d, $J = 14$ Hz, 1H), 3.15 (d, $J = 14$ Hz, 1H), 2.40 (s, 3H), 1.66 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$, ppm) δ 169.7, 150.5, 139.1, 134.8, 133.2, 130.5, 128.0, 126.9, 126.4, 125.6, 121.1, 87.8, 46.4, 25.8, 21.2. MS (EI) m/z 252 (M^+).

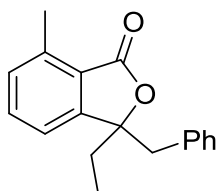


3,7-dimethyl-3-(4-methylbenzyl)isobenzofuran-1(3H)-one (3k): pale yellow liquid; 1H

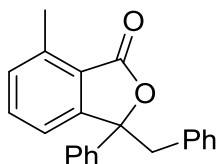
NMR (500 MHz, CDCl₃, ppm) δ 7.47 (t, $J = 7.5$ Hz, 1H), 7.17 (d, $J = 7.5$ Hz, 1H), 7.11 (d, $J = 7.5$ Hz, 1H), 6.93–7.00 (m, 4H), 3.15 (d, $J = 14$ Hz, 1H), 3.10 (d, $J = 14$ Hz, 1H), 2.58 (s, 3H), 2.26 (s, 3H), 1.62 (s, 3H). ¹³C NMR (125 MHz, CDCl₃, ppm) δ 169.9, 153.8, 139.6, 136.4, 133.3, 131.7, 130.5, 130.4, 128.7, 123.6, 118.8, 86.0, 46.1, 25.7, 21.0, 17.3. MS (EI) m/z 266 (M⁺).



3-(4-chlorobenzyl)-3,7-dimethylisobenzofuran-1(3H)-one (3l): pale yellow liquid; ¹H NMR (500 MHz, CDCl₃, ppm) δ 7.49 (t, $J = 7.5$ Hz, 1H), 7.12–7.19 (m, 4H), 6.97–6.98 (d, $J = 7.5$ Hz, 2H), 3.21 (d, $J = 14$ Hz, 1H), 3.10 (d, $J = 14$ Hz, 1H), 2.57 (s, 3H), 1.64 (s, 3H). ¹³C NMR (125 MHz, CDCl₃, ppm) δ 169.6, 153.4, 139.8, 133.5, 133.2, 132.9, 131.7, 127.9, 130.7, 128.2, 123.6, 118.5, 85.6, 45.4, 45.7, 25.8, 17.3. MS (EI) m/z 286 (M⁺).

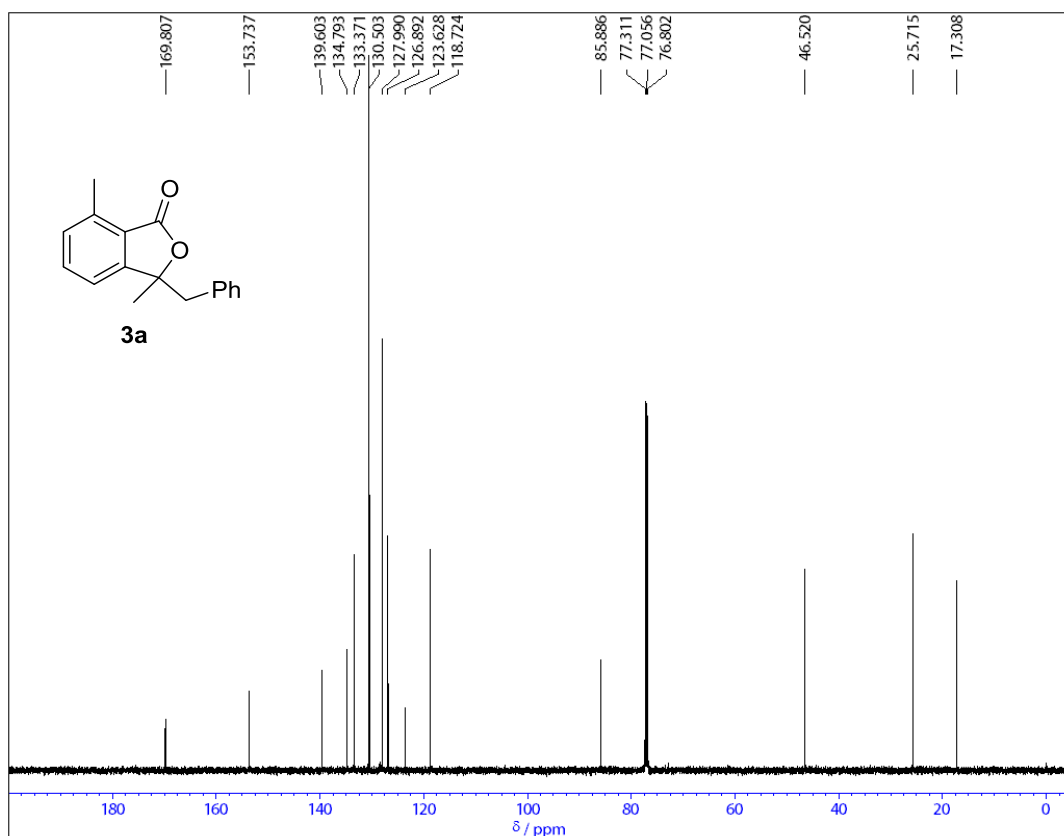
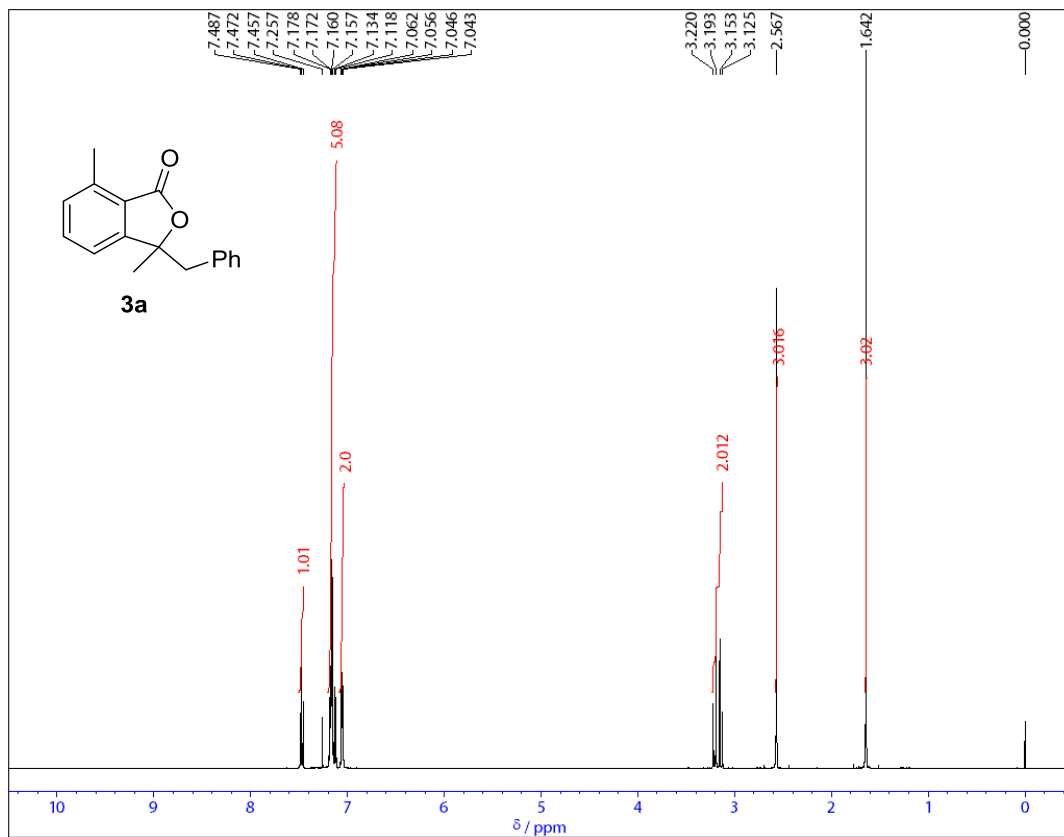


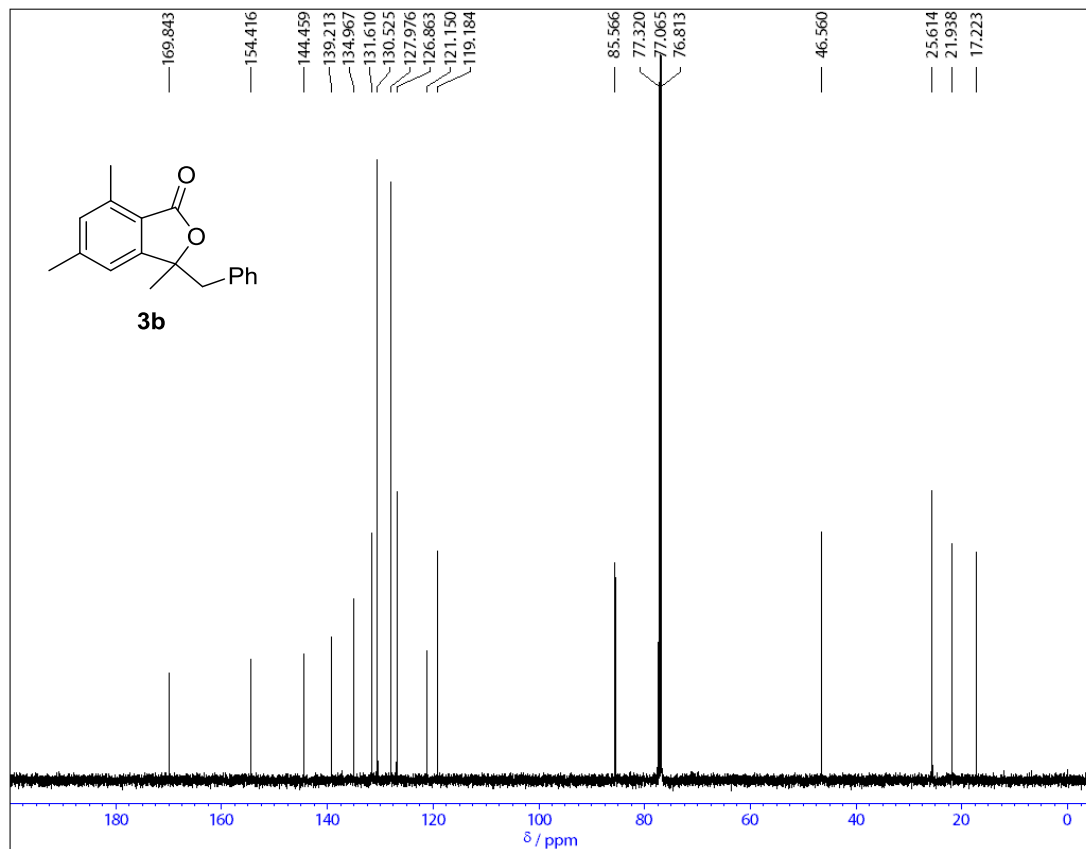
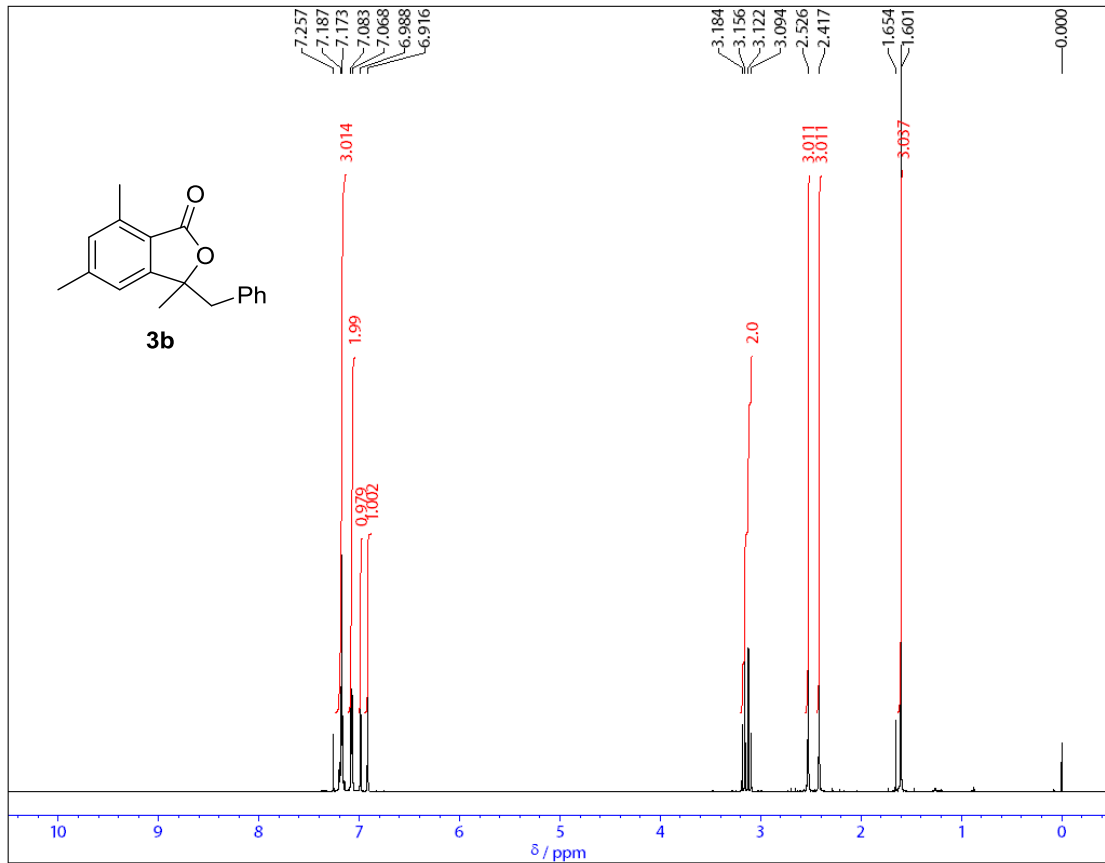
3-benzyl-3-ethyl-7-methylisobenzofuran-1(3H)-one (3m): pale yellow liquid; ¹H NMR (500 MHz, CDCl₃, ppm) δ 7.47 (t, $J = 7.5$ Hz, 1H), 7.08–7.16 (m, 5H), 7.00–7.03 (m, 2H), 3.25 (d, $J = 14$ Hz, 1H), 3.14 (d, $J = 14$ Hz, 1H), 2.55 (s, 3H), 2.12 (dt, $J = 11$ Hz, 7.5 Hz, 1H), 1.97 (dt, $J = 11$ Hz, 7.5 Hz, 1H), 0.71 (t, $J = 7.5$ Hz, 3H). ¹³C NMR (125 MHz, CDCl₃, ppm) δ 170.2, 151.9, 139.4, 134.6, 133.2, 130.5, 130.4, 127.9, 126.8, 124.7, 118.9, 88.7, 45.4, 31.2, 17.3, 7.5. MS (EI) m/z 266 (M⁺). Anal. Calcd for C₁₈H₁₈O₂: C, 81.17; H, 6.81. Found: C, 81.09; H, 6.90.

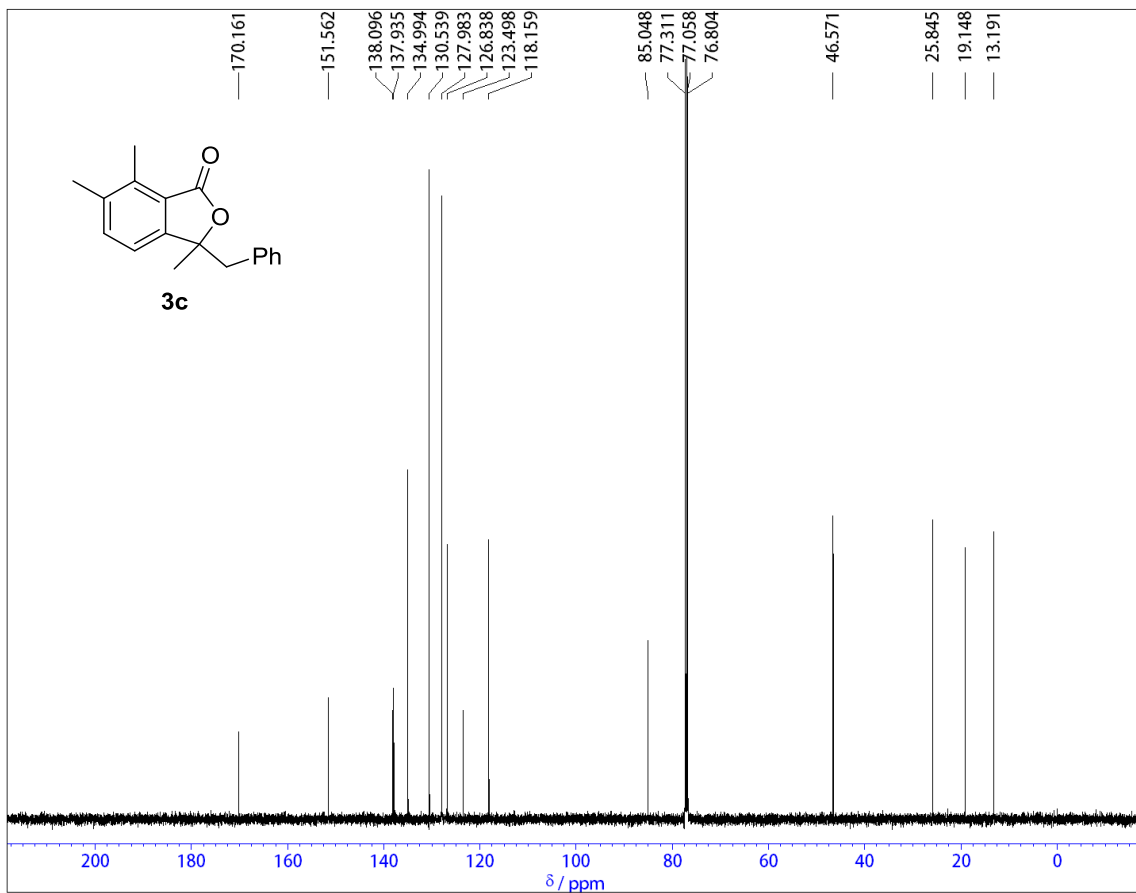
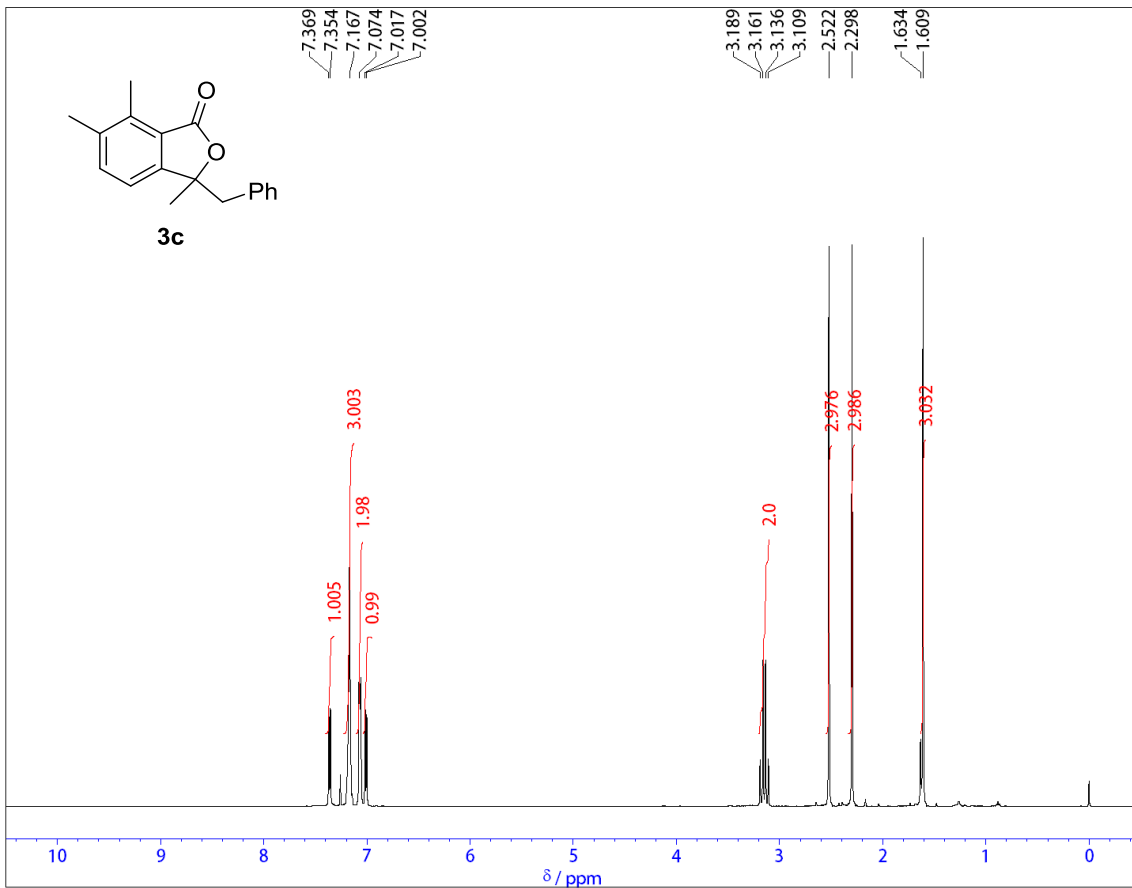


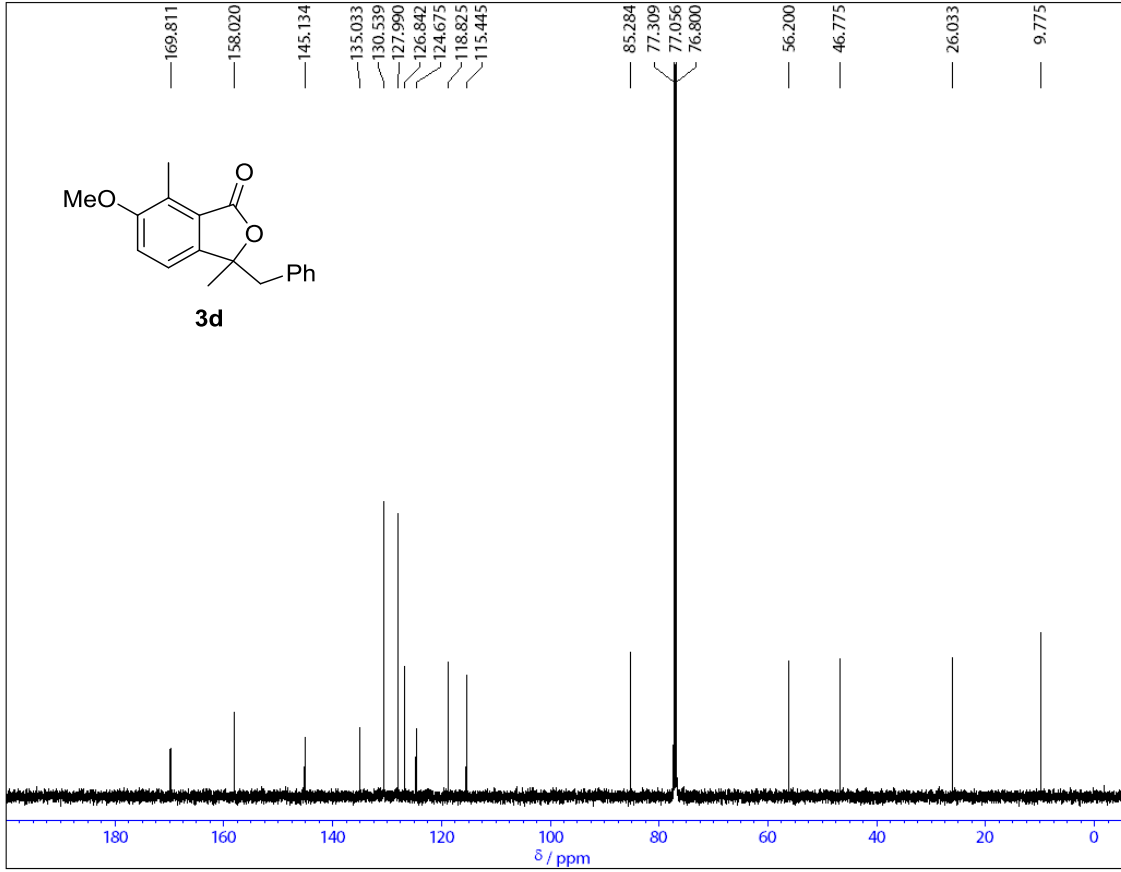
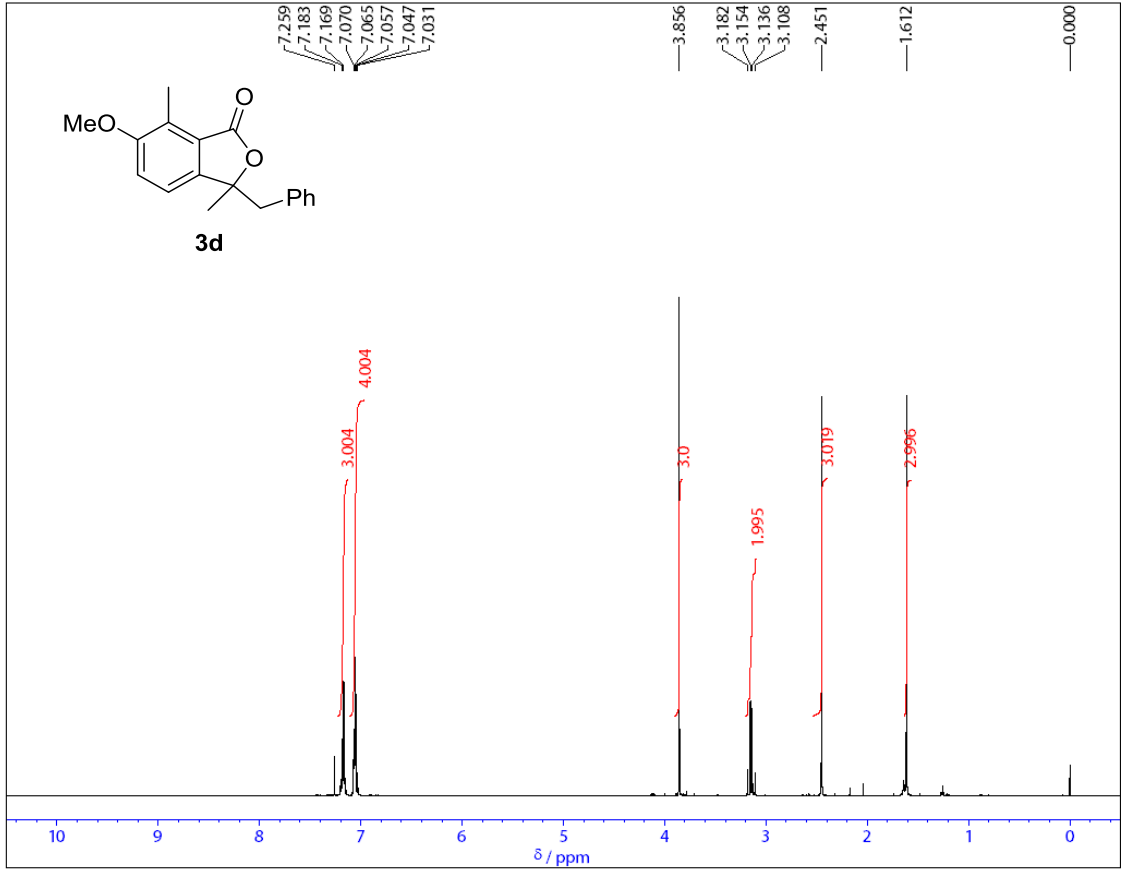
3-benzyl-7-methyl-3-phenylisobenzofuran-1(3H)-one (3n): pale yellow liquid; ^1H NMR (500 MHz, CDCl_3 , ppm) δ 7.57 (d, $J = 7.5$ Hz, 2H), 7.48 (t, $J = 7.5$ Hz, 1H), 7.34–7.39 (m, 3H), 7.28–7.31 (m, 1H), 7.14 (d, $J = 7.5$ Hz, 1H), 7.07–7.09 (m, 3H), 6.94–6.96 (m, 2H), 3.67 (d, $J = 14$ Hz, 1H), 3.56 (d, $J = 14$ Hz, 1H), 2.52 (s, 3H). ^{13}C NMR (125 MHz, CDCl_3 , ppm) δ 169.7, 152.2, 140.6, 139.7, 134.1, 133.4, 130.7, 130.6, 128.7, 128.2, 127.8, 126.9, 125.4, 123.5, 120.2, 88.3, 46.5, 17.3. MS (EI) m/z 314 (M^+). Anal. Calcd for $\text{C}_{22}\text{H}_{18}\text{O}_2$: C, 84.05; H, 5.77. Found: C, 83.97; H, 5.74.

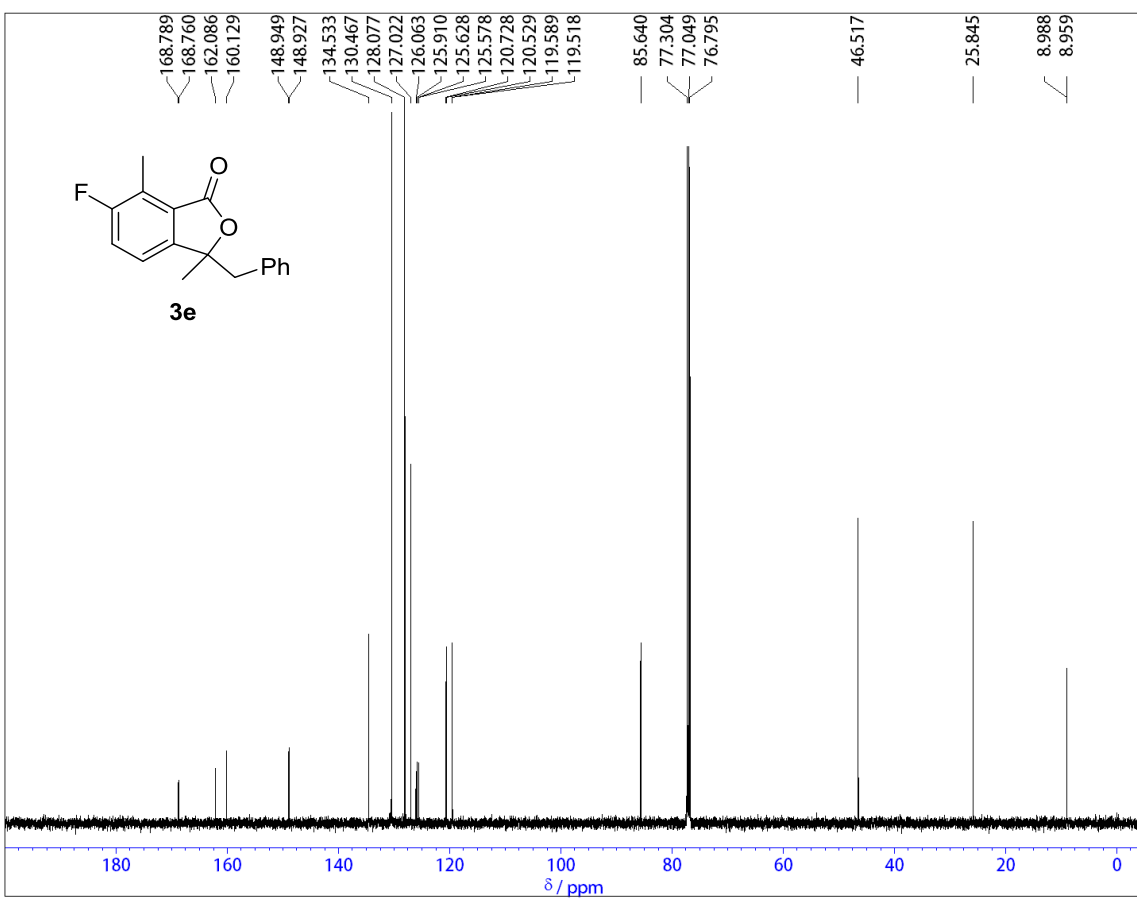
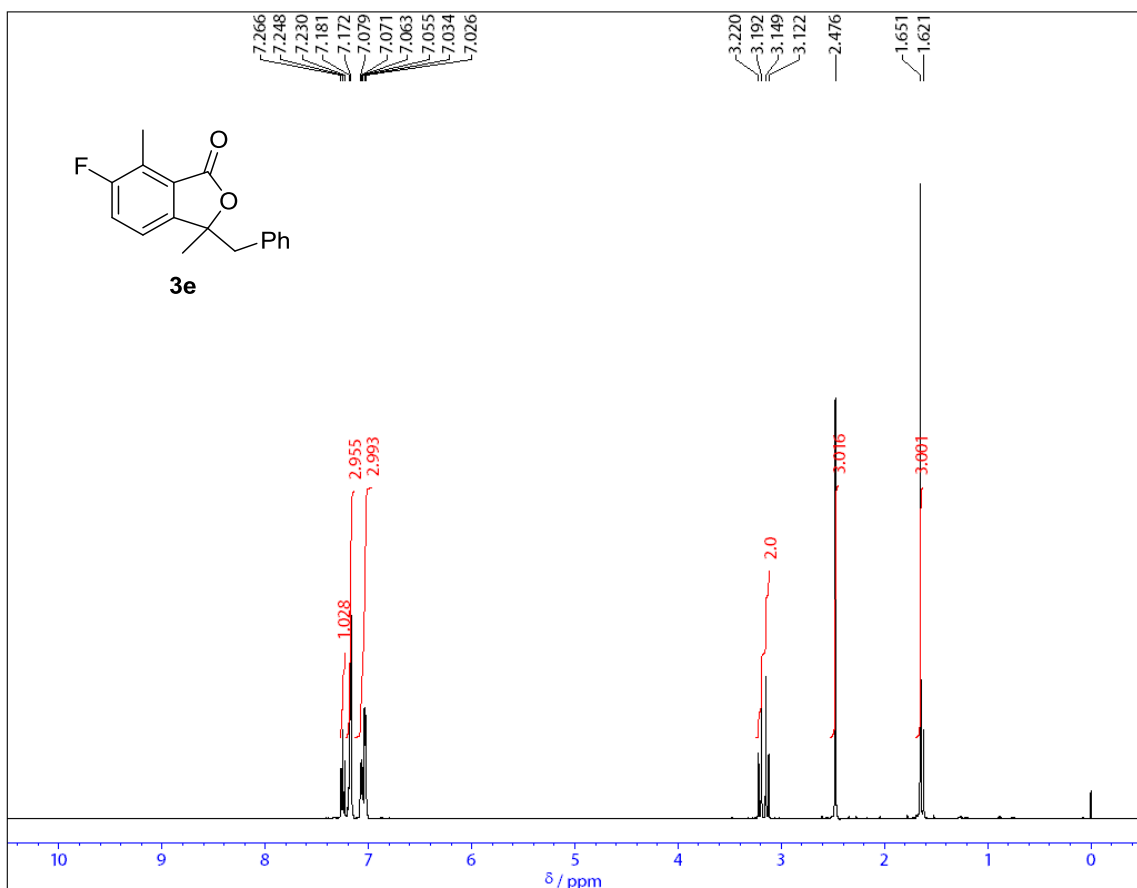
5. Copies of NMR spectra for the products

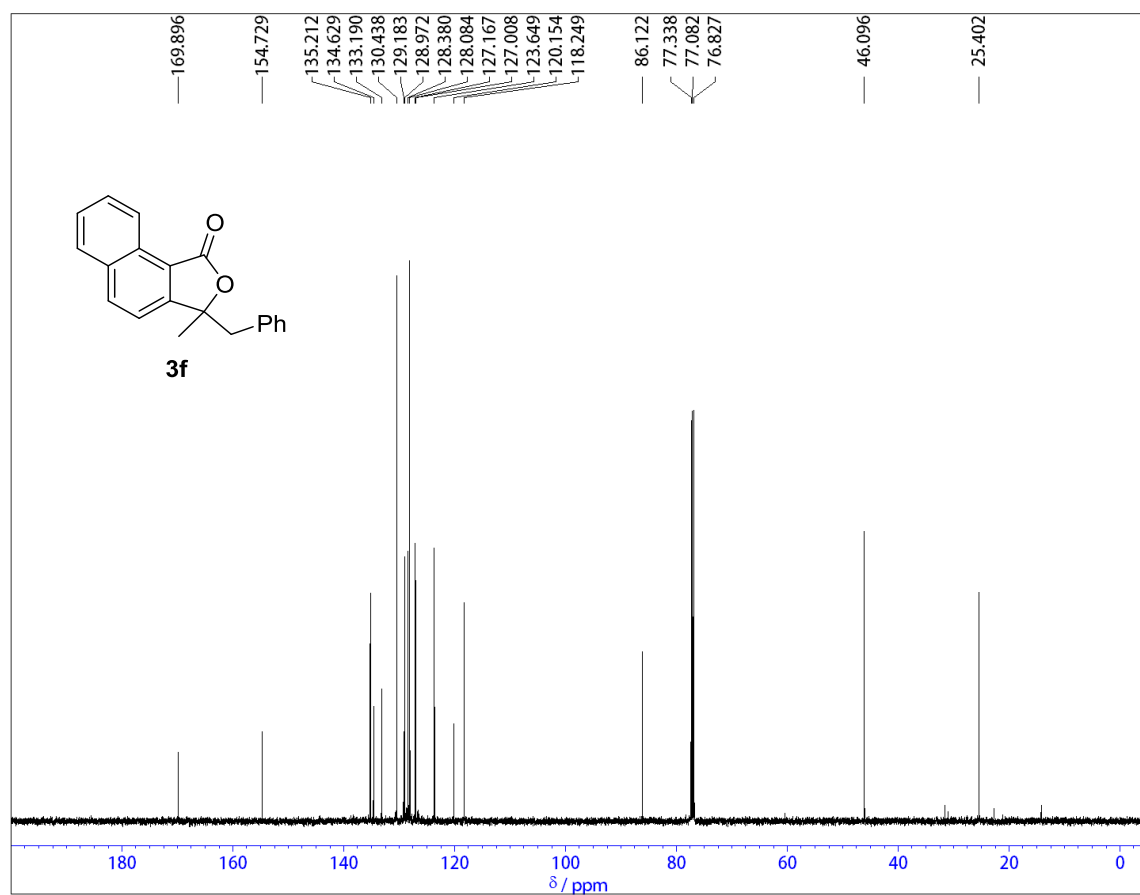
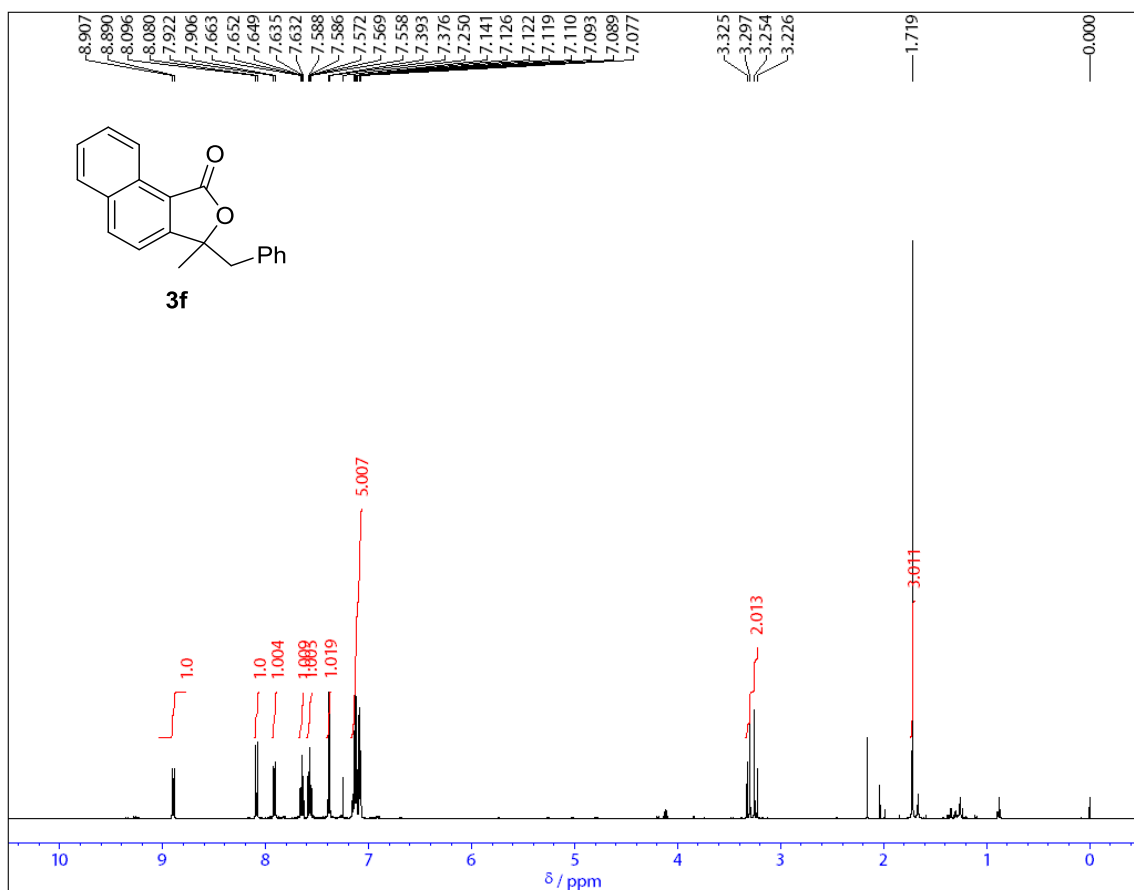


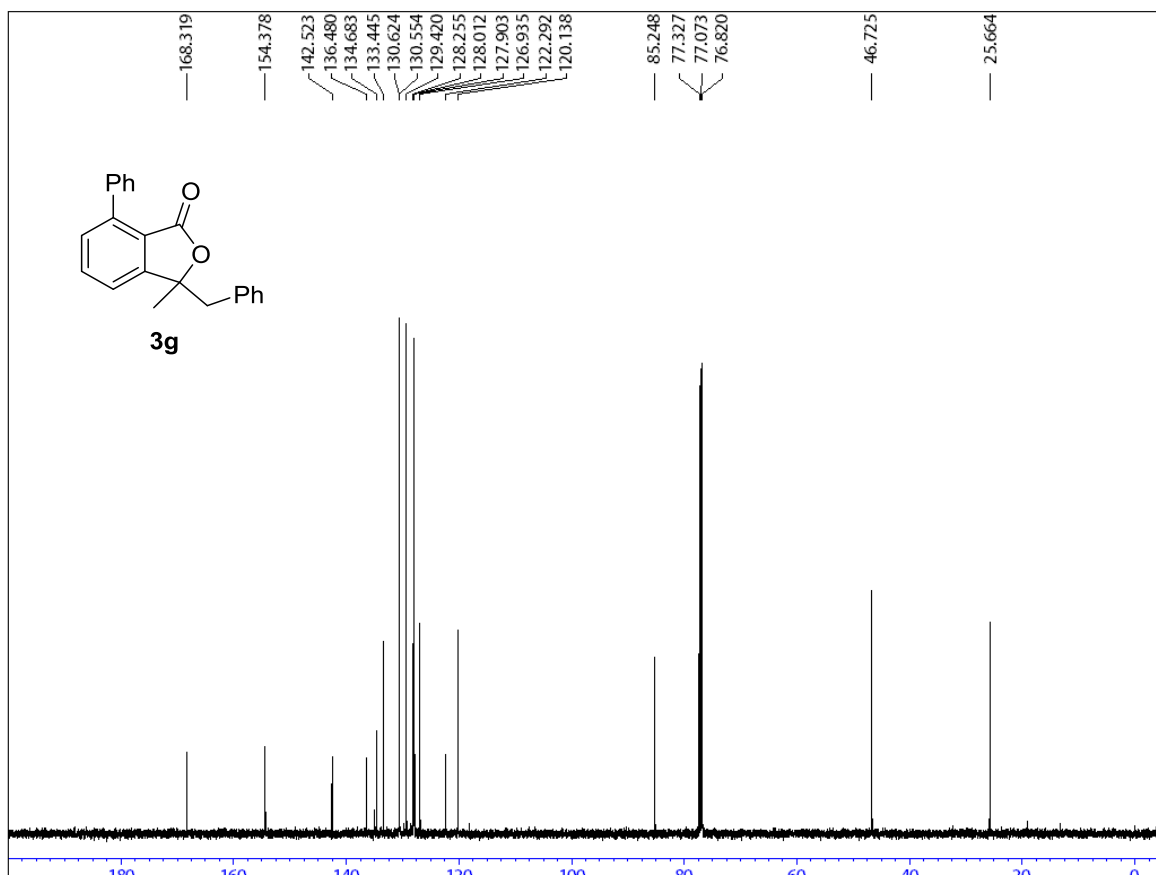
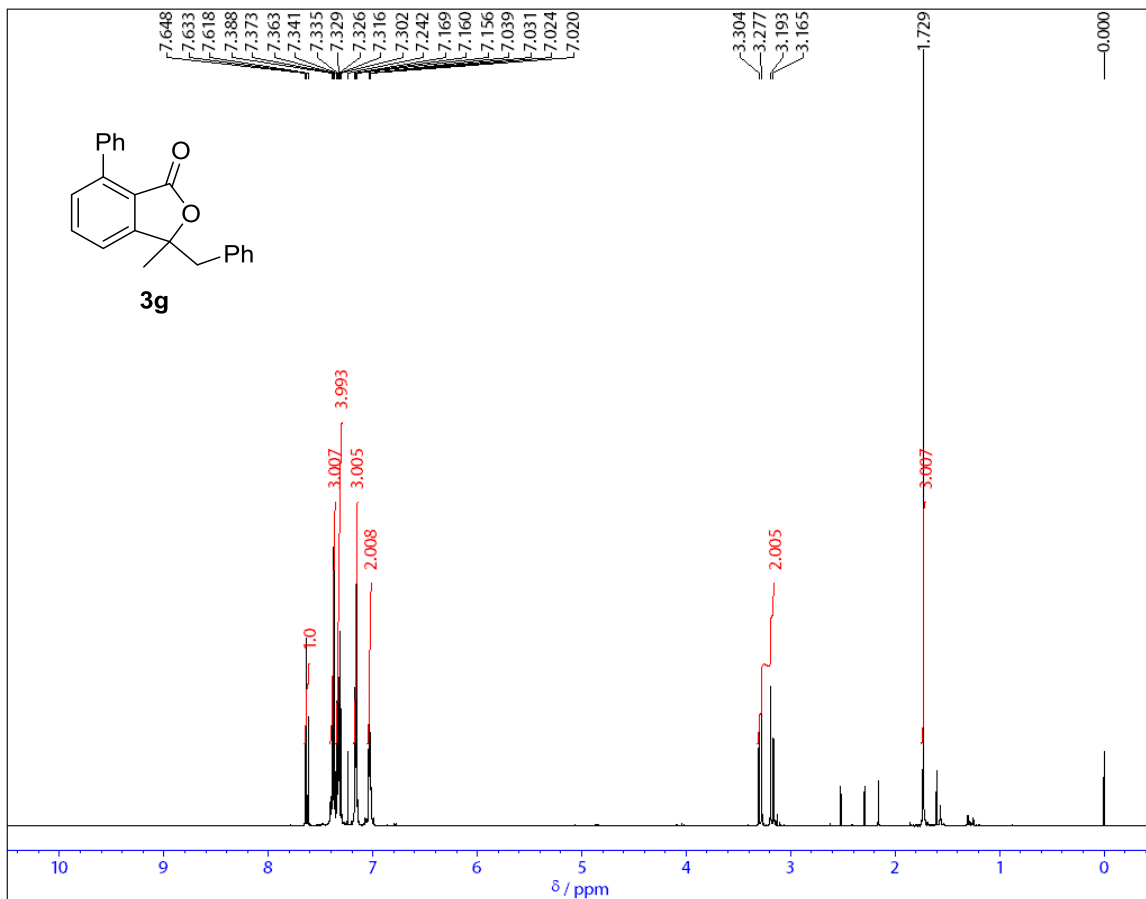


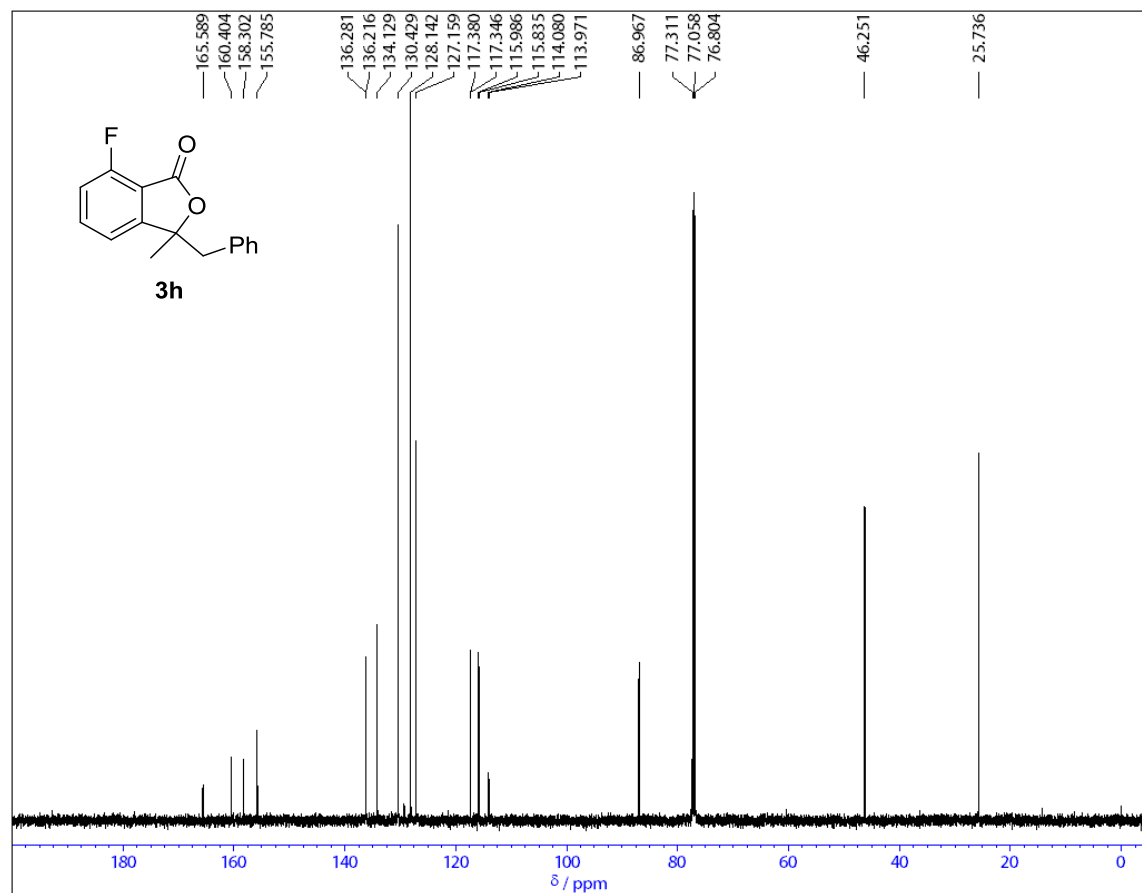
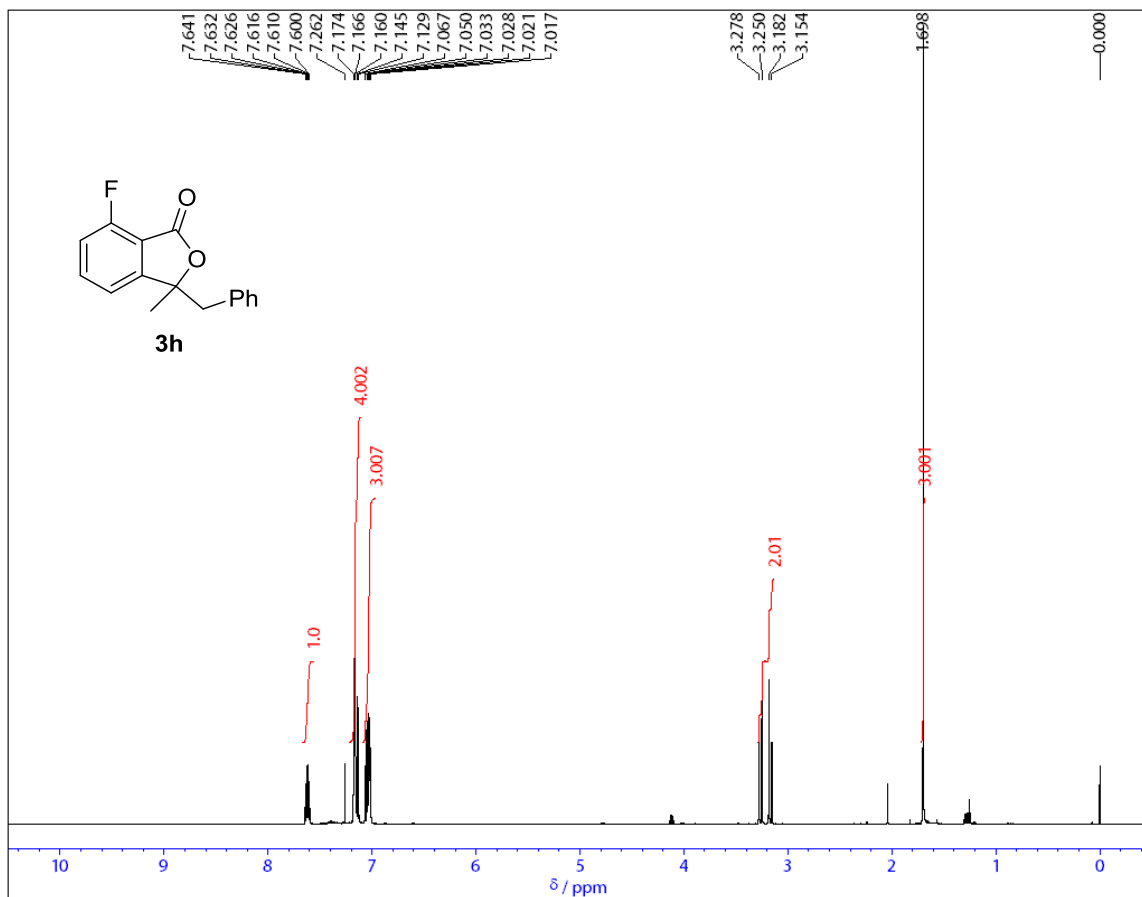


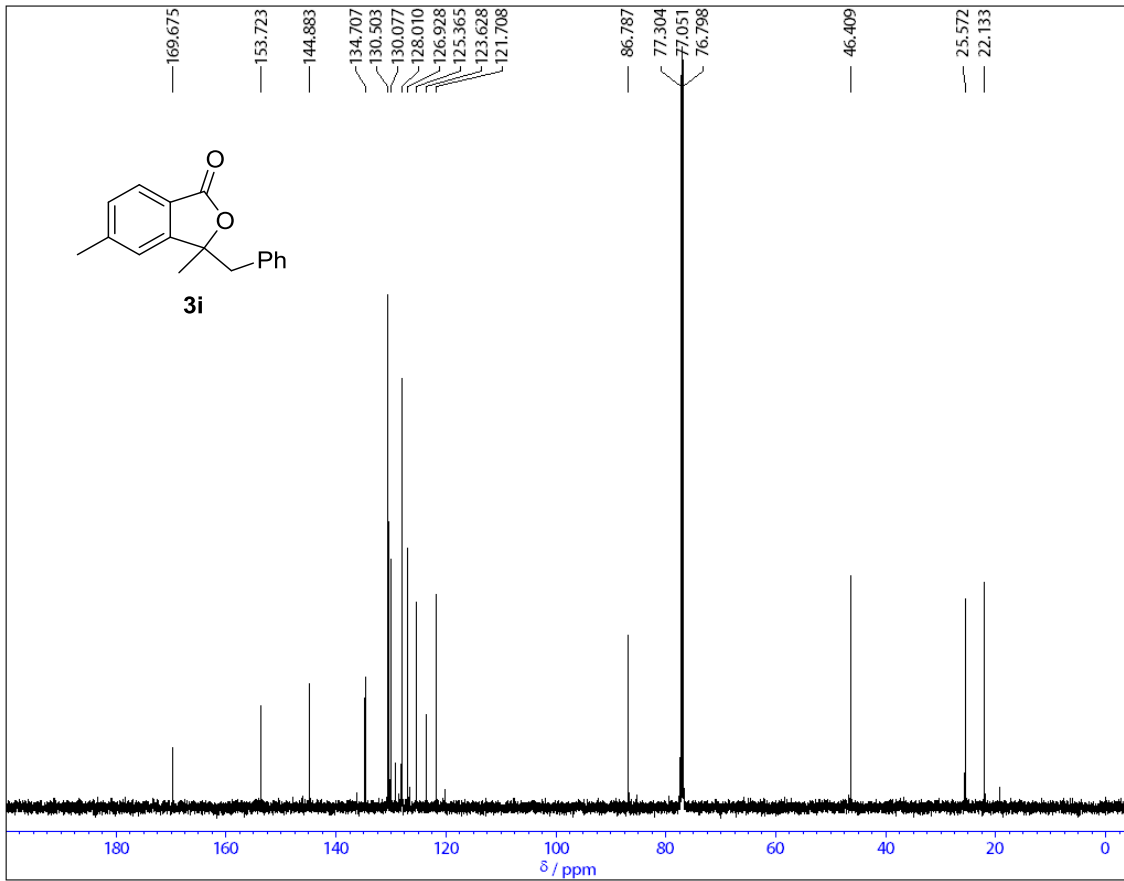
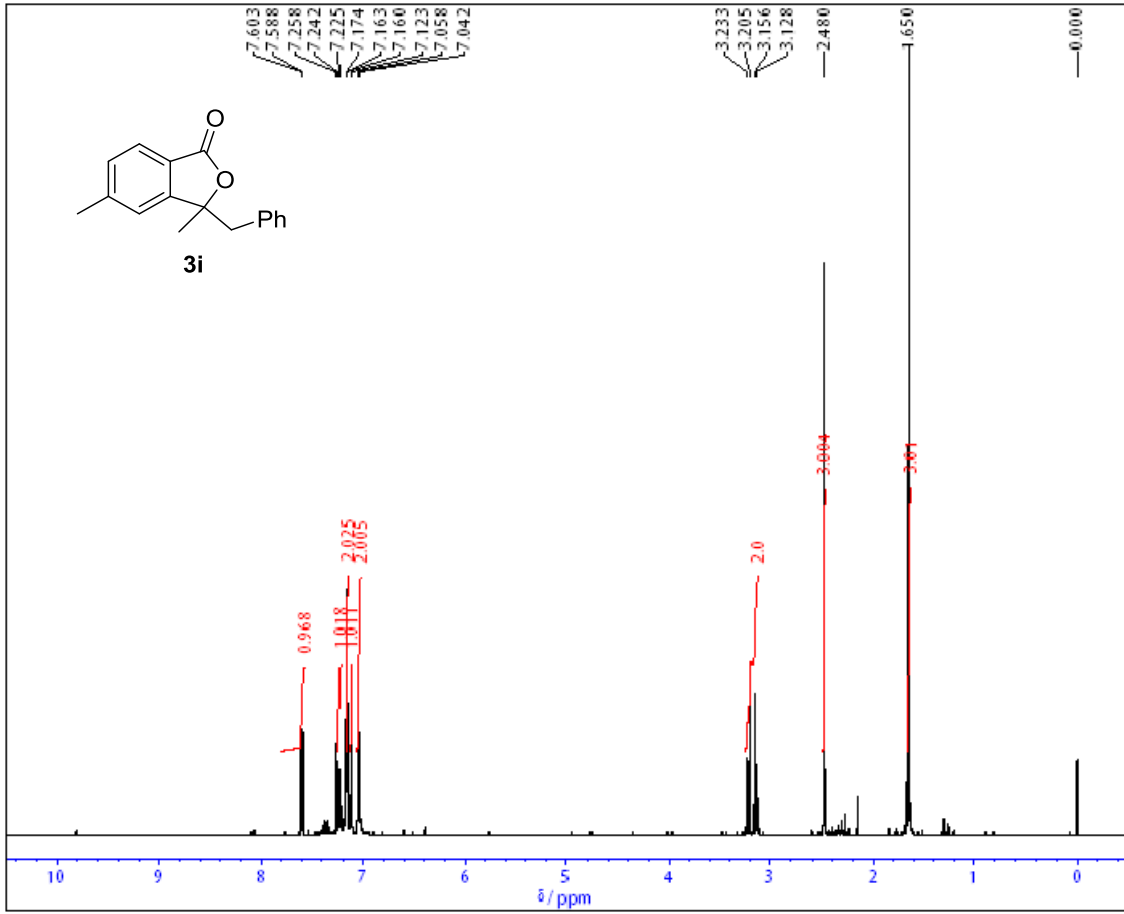


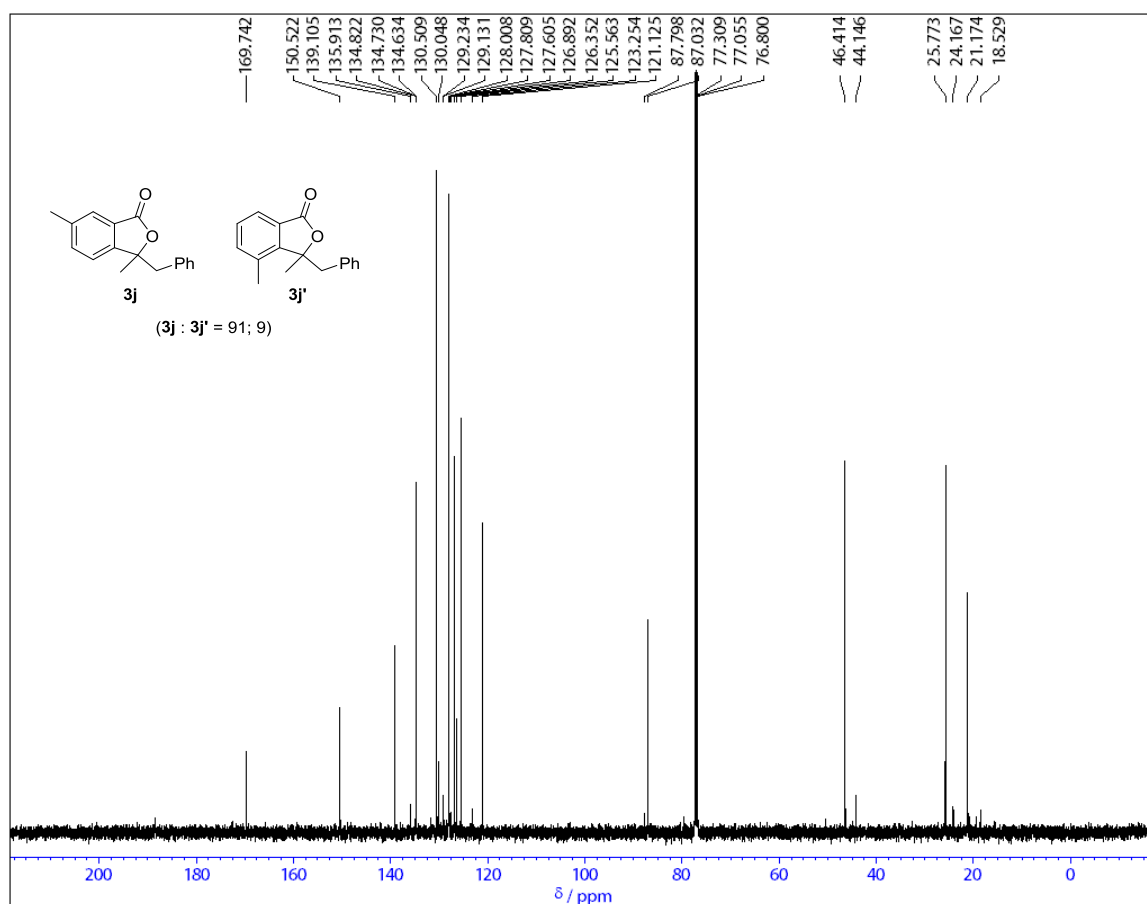
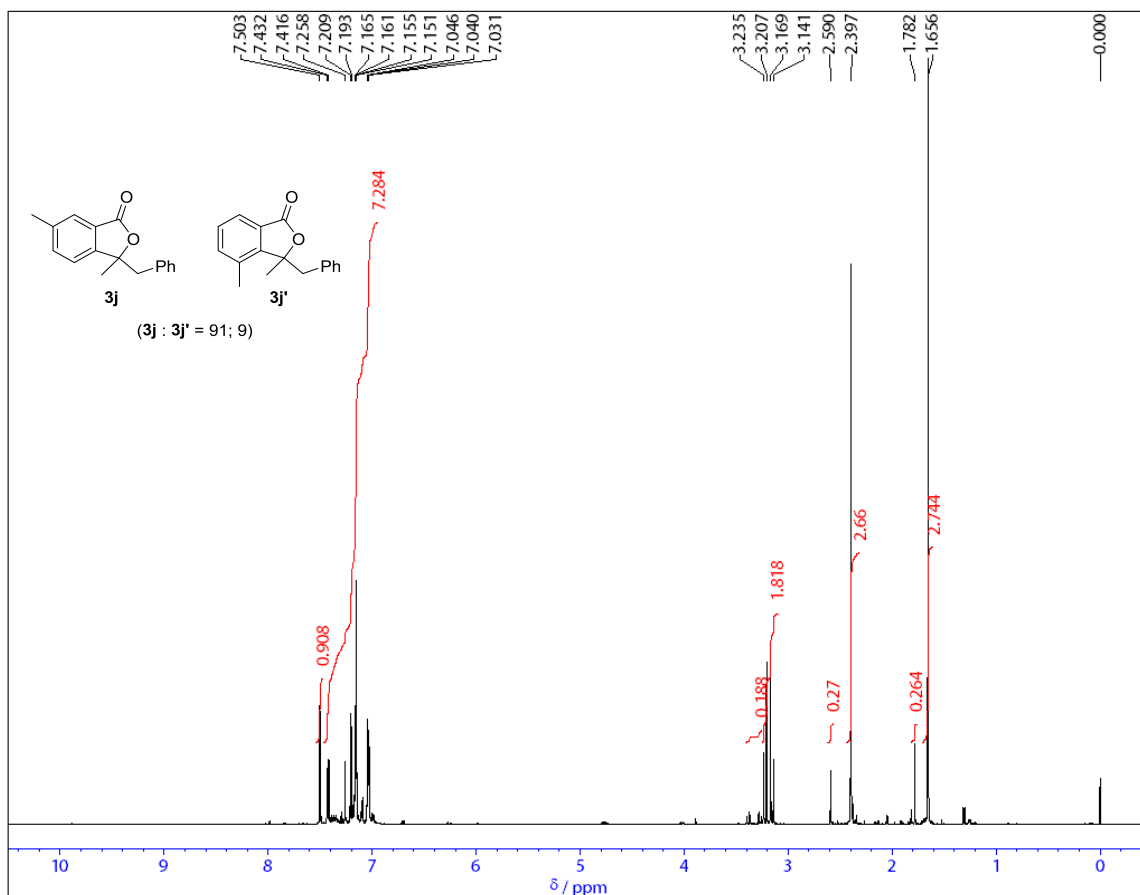


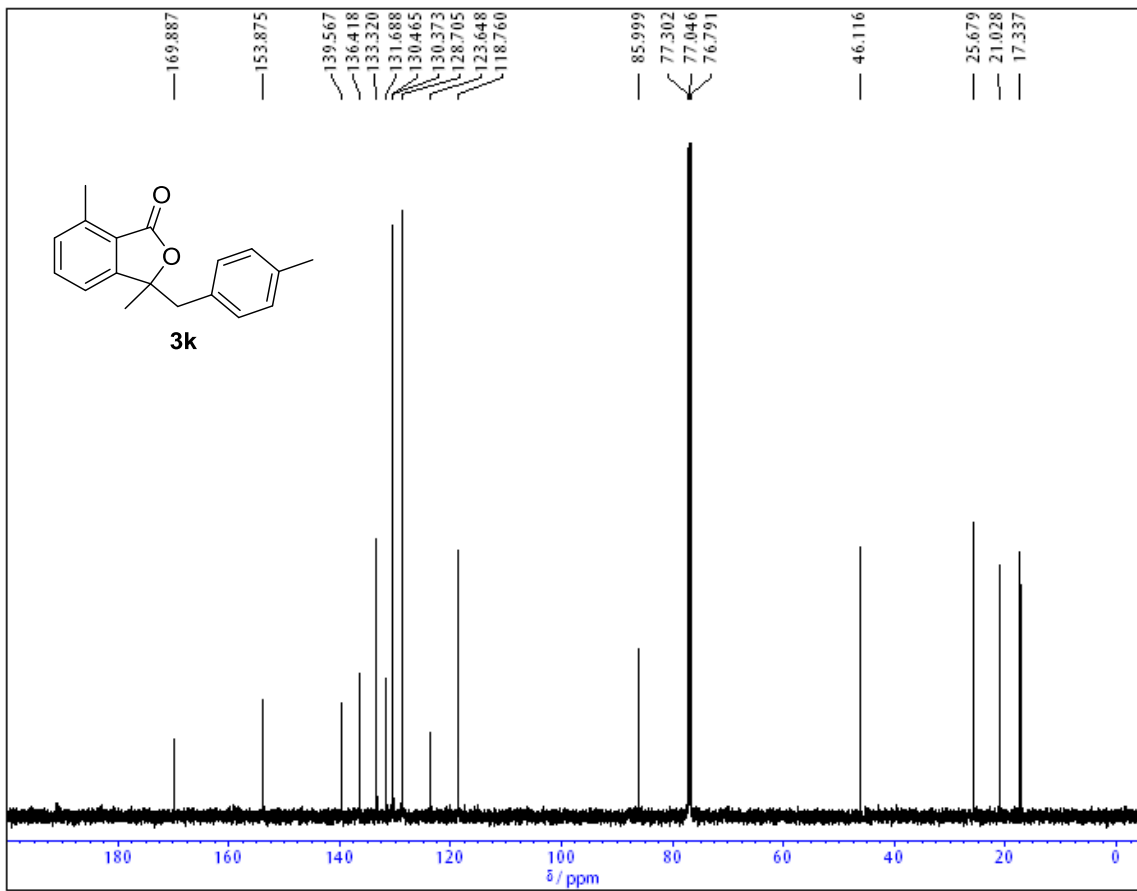
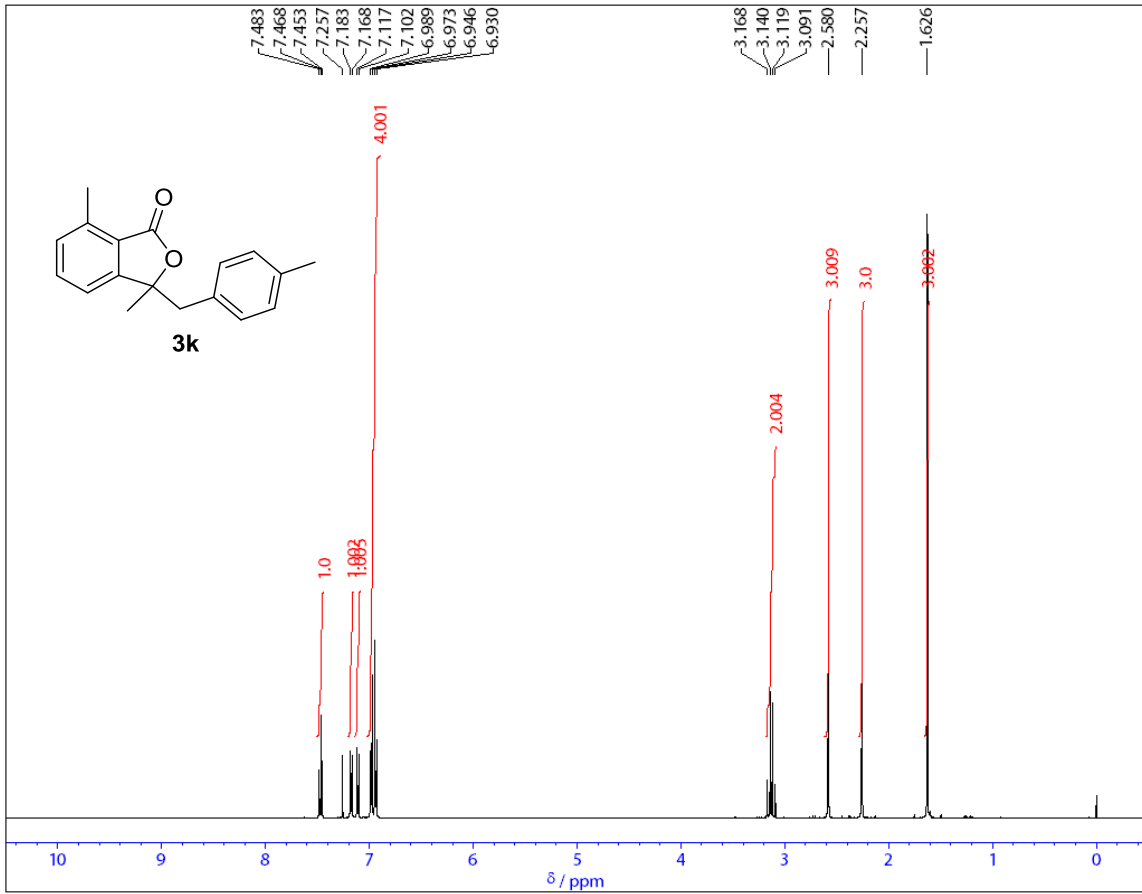


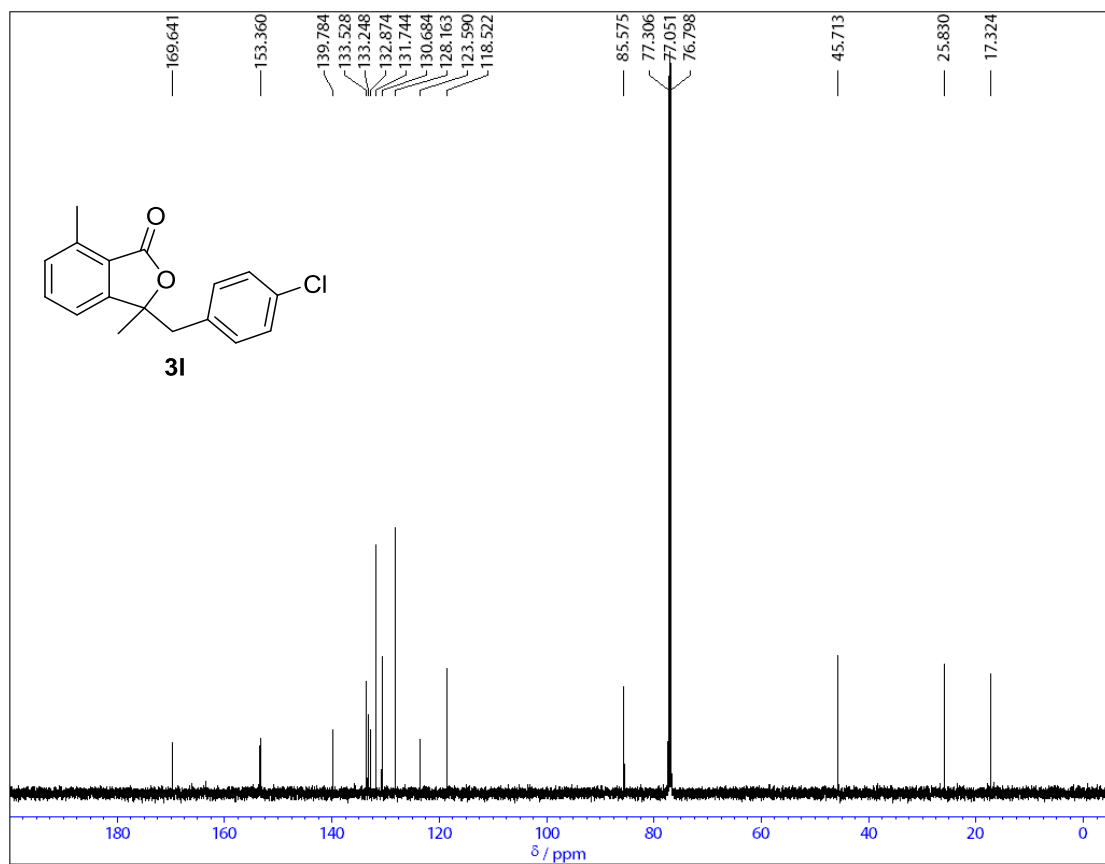
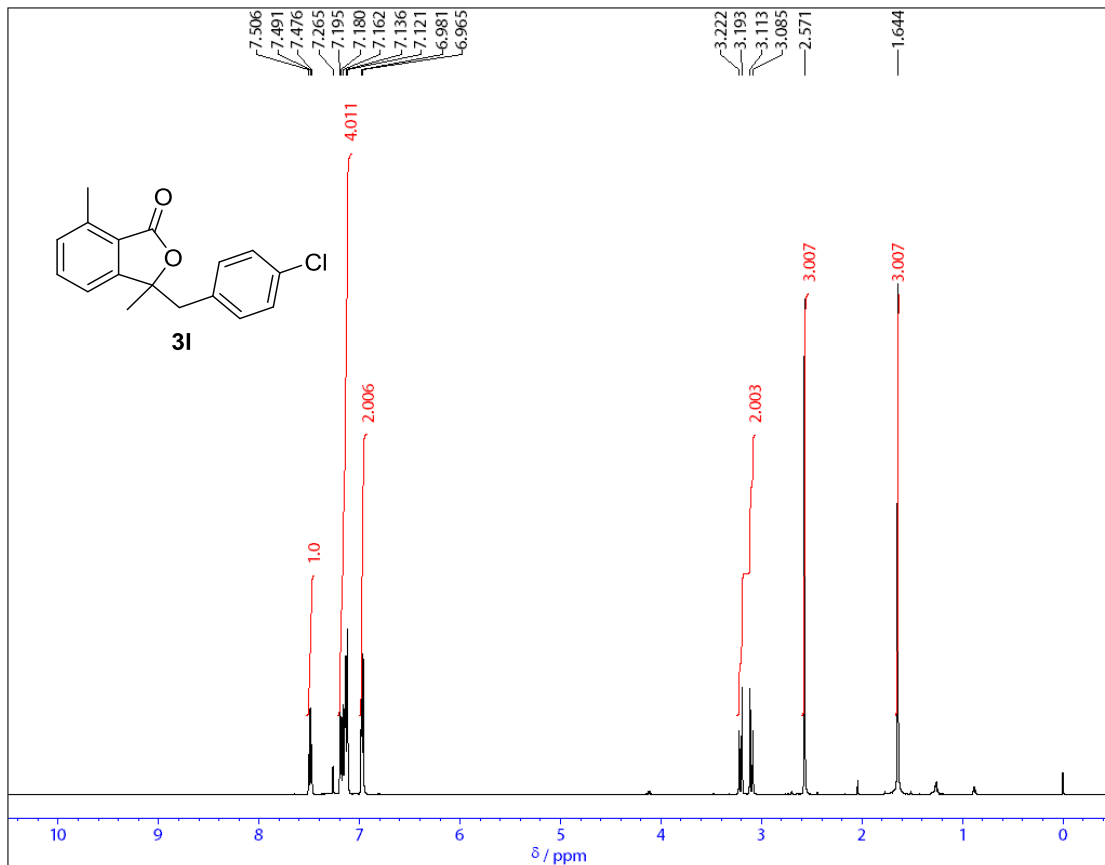


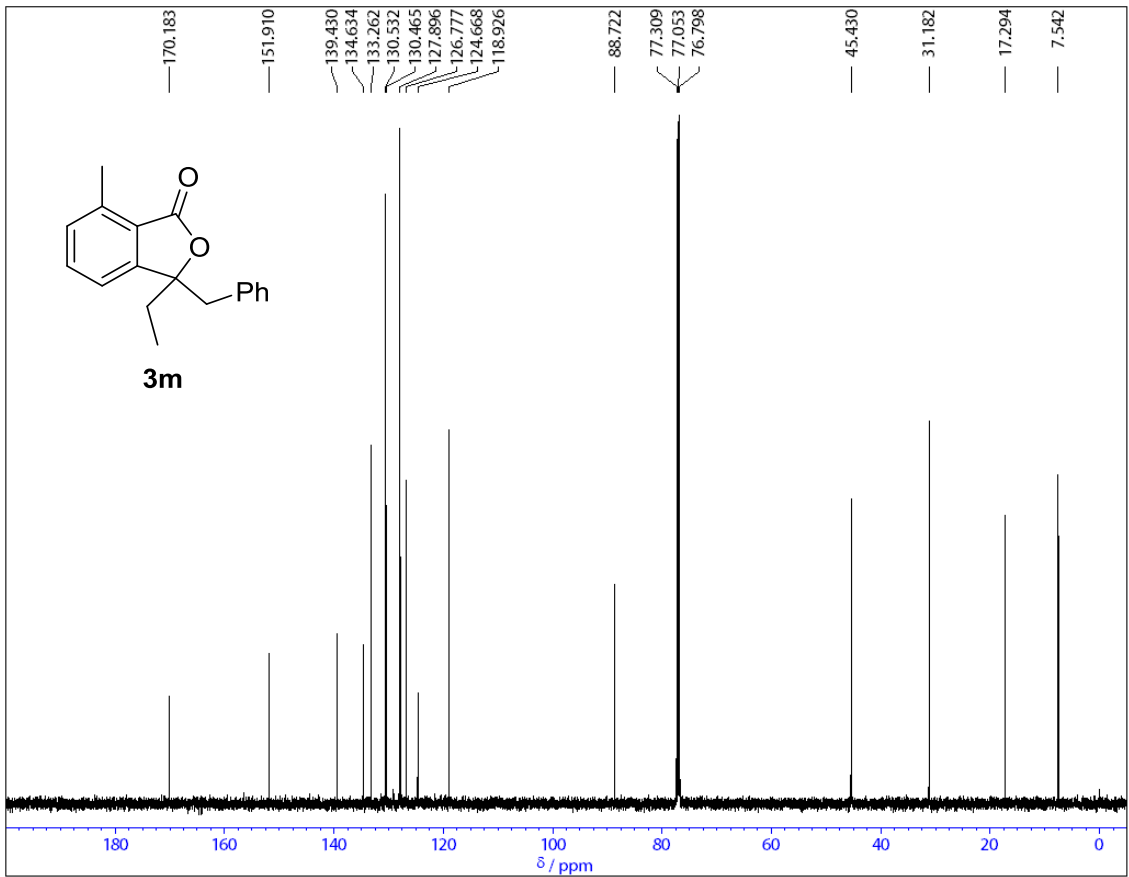
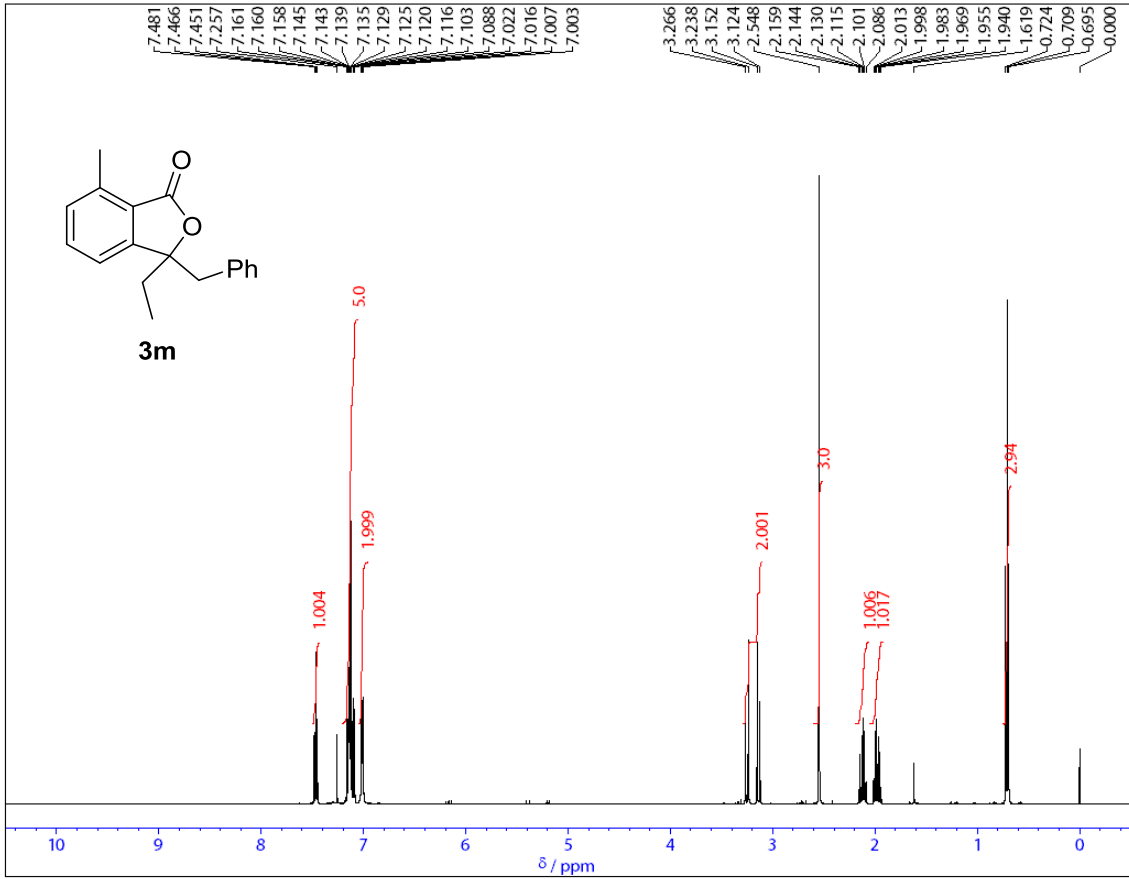


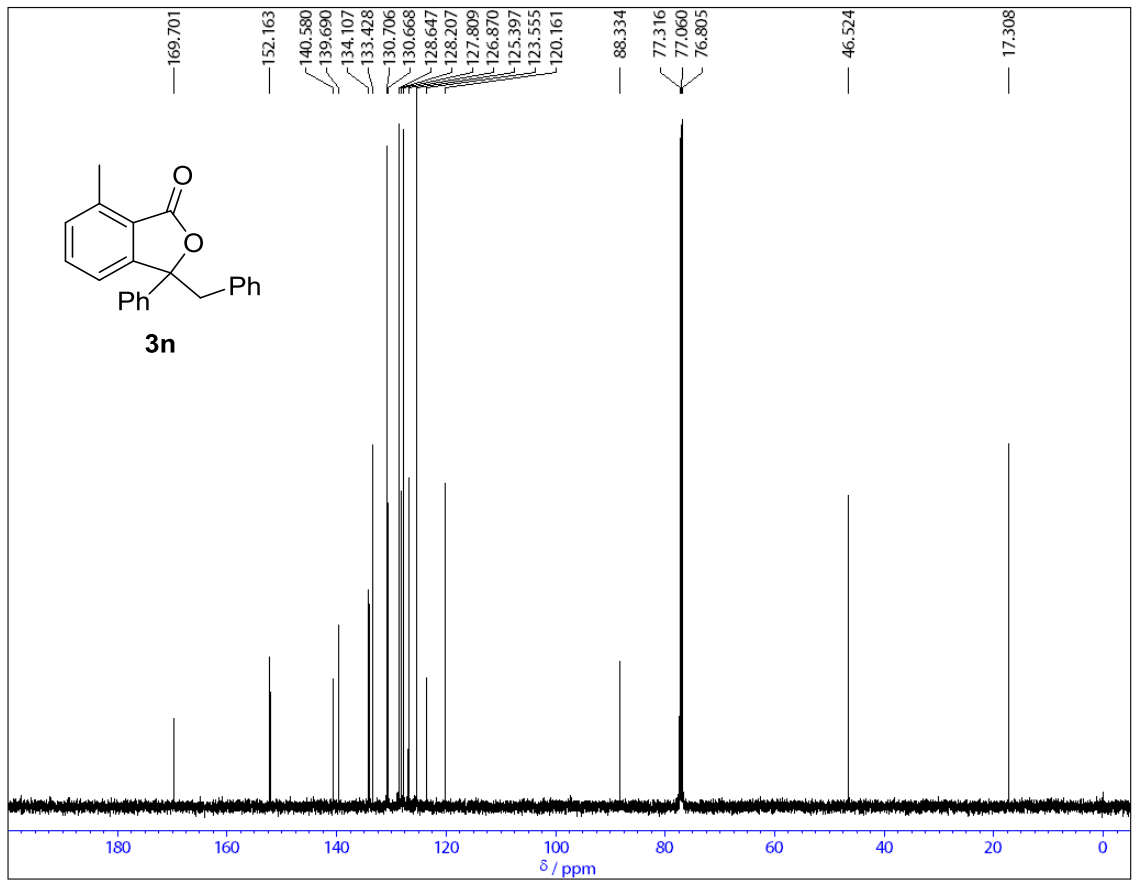
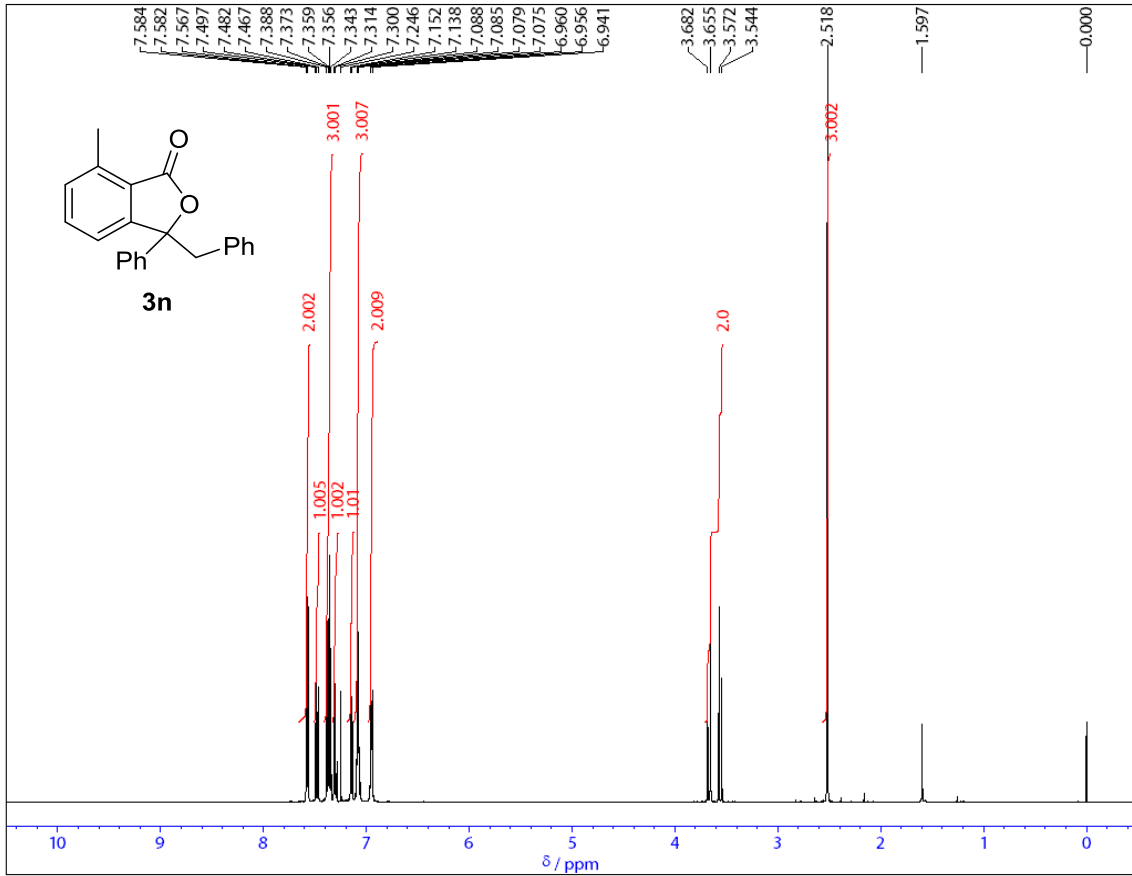


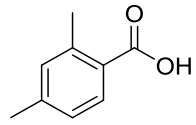




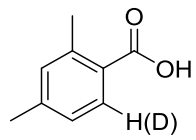
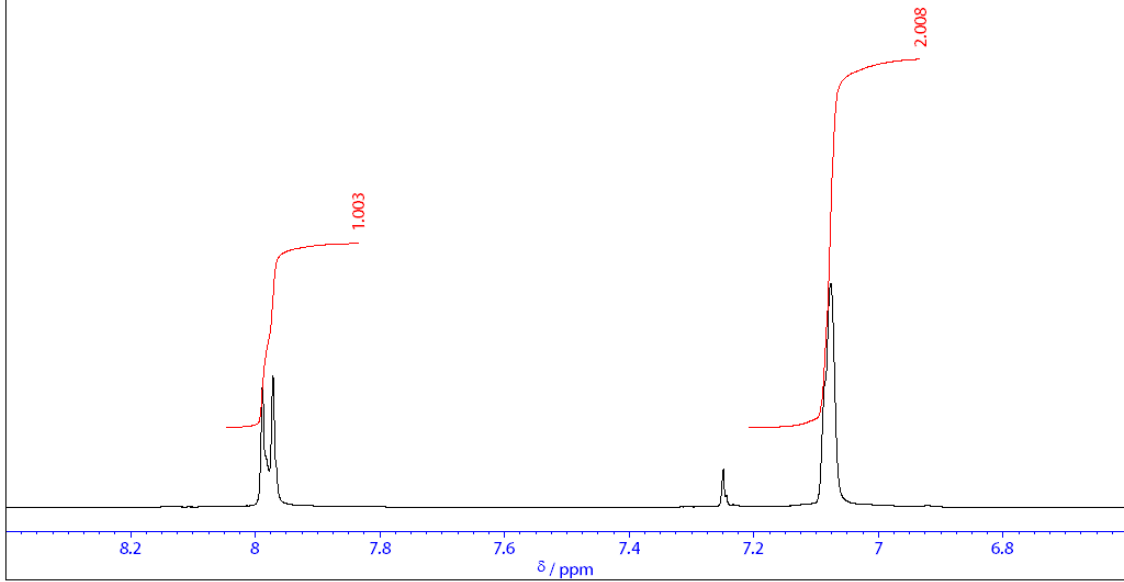








1b



d-1b

