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Electronic Supplementary Information for

Direct Hydroxylation of Benzene and Aromatics with H_2O_2 Catalyzed by a Self-Assembled Iron Complex: Evidence for a Metal-based Mechanism

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Table of Contents

Instruments and general methods

Oxidation products were identified by comparison of their GC retention times, GC/MS and ^{1}H NMR spectra with those of authentic compounds. GC analyses were carried out on a gas chromatograph equipped with a capillary methylsilicone column (30 m x 0.25 mm x 25 μm) Chrompack CP-Sil 5 CB. GC-MS analyses were performed with a mass detector (EI at 70eV) coupled with a gas chromatograph equipped with a melted silica capillary column (30 m x 0.2 mm x 25 μm) covered with a methylsilicone film (5% phenylsilicone, OV5). NMR spectra were recorded on a BrukerDPX300 spectrometer and were internally referenced to the residual proton solvent signal.

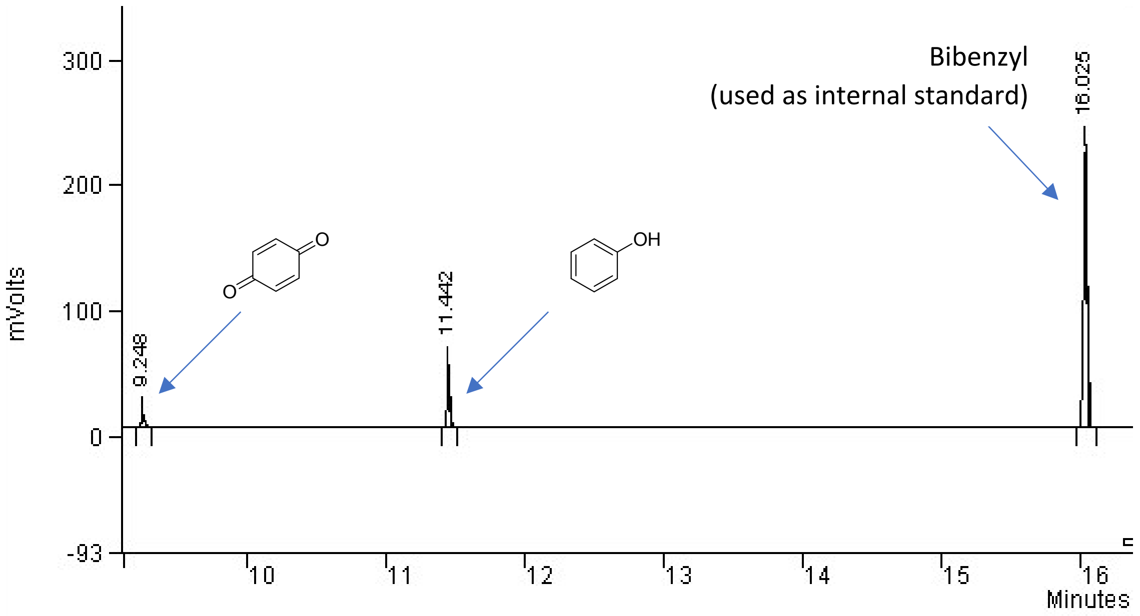
Materials

All reagents and solvents were purchased at the highest commercial quality and were used without further purification unless otherwise stated. $Fe(OTf)_2{\bullet}2CH_3CN$ (or $Fe(CF_3SO_3)_2{\bullet}2CH_3CN$) was prepared according to a literature procedure[1] from Fe(II) chloride (Sigma Aldrich). Solvents were purchased from Sigma Aldrich and used as received.

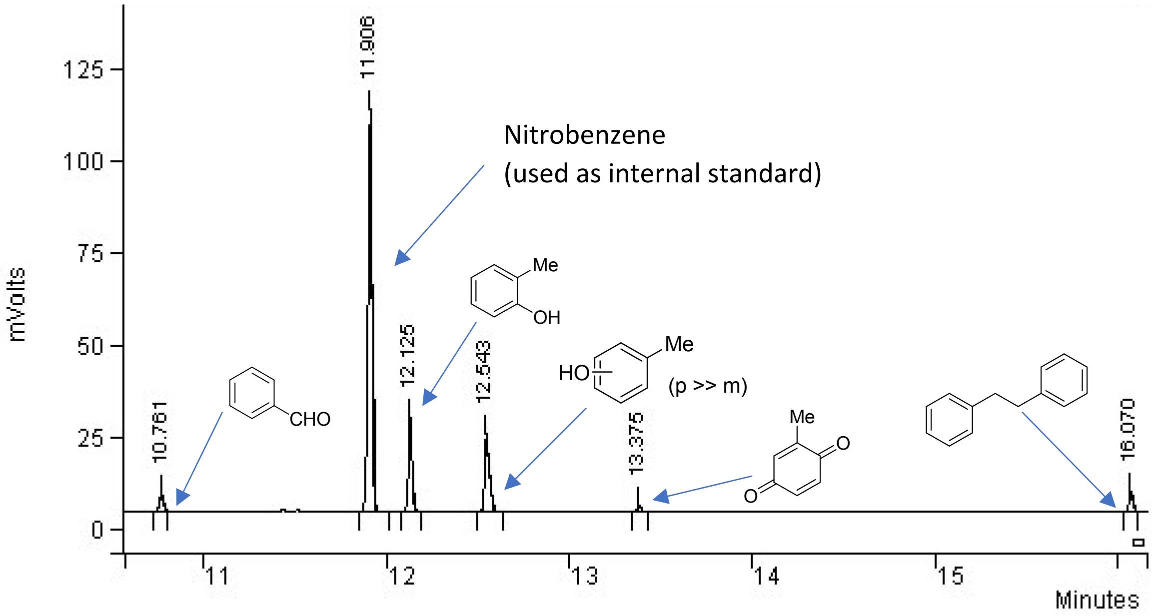
[1] A. Diebold, A. Elbouadili and K. S. Hagen, *Inorg. Chem.* 2000, **39**, 3915–3923.

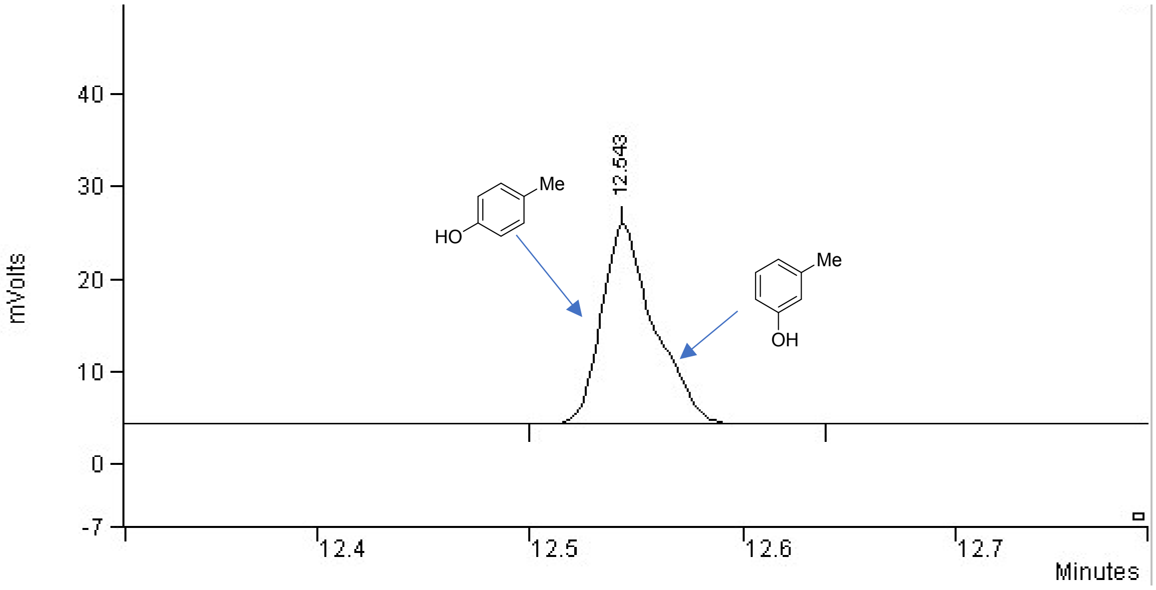
*Selected examples of **1** catalyzed H_2O_2 oxidation of aromatic compounds*

Benzene (optimized conditions, one of the runs for entry 15 of Table 1)



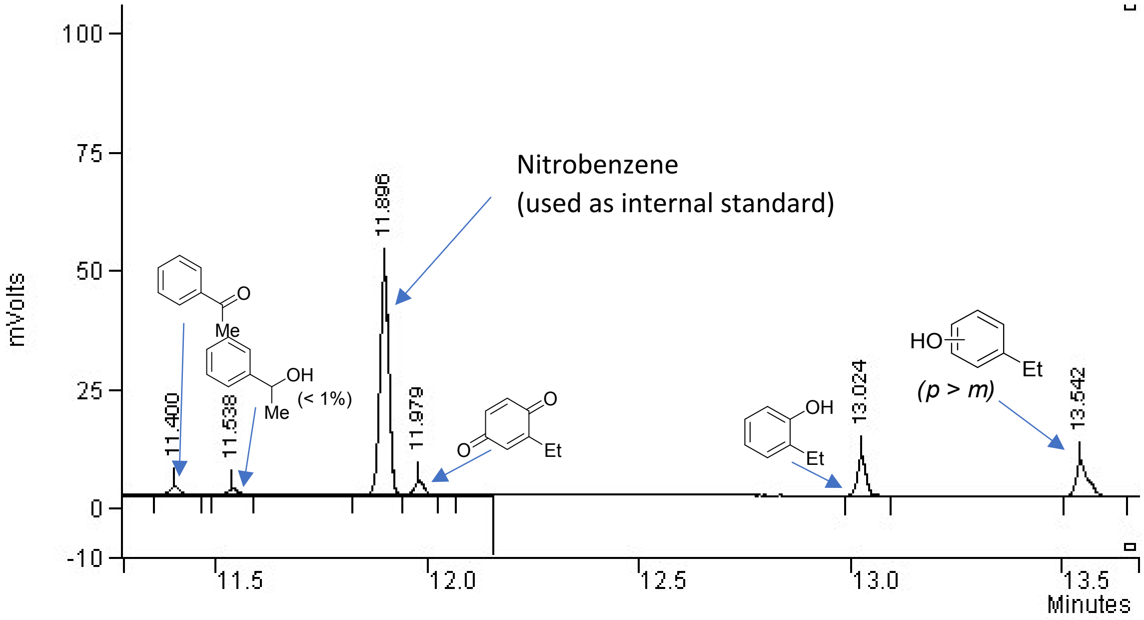
Toluene (one of the runs of toluene oxidation reported in Table 2)

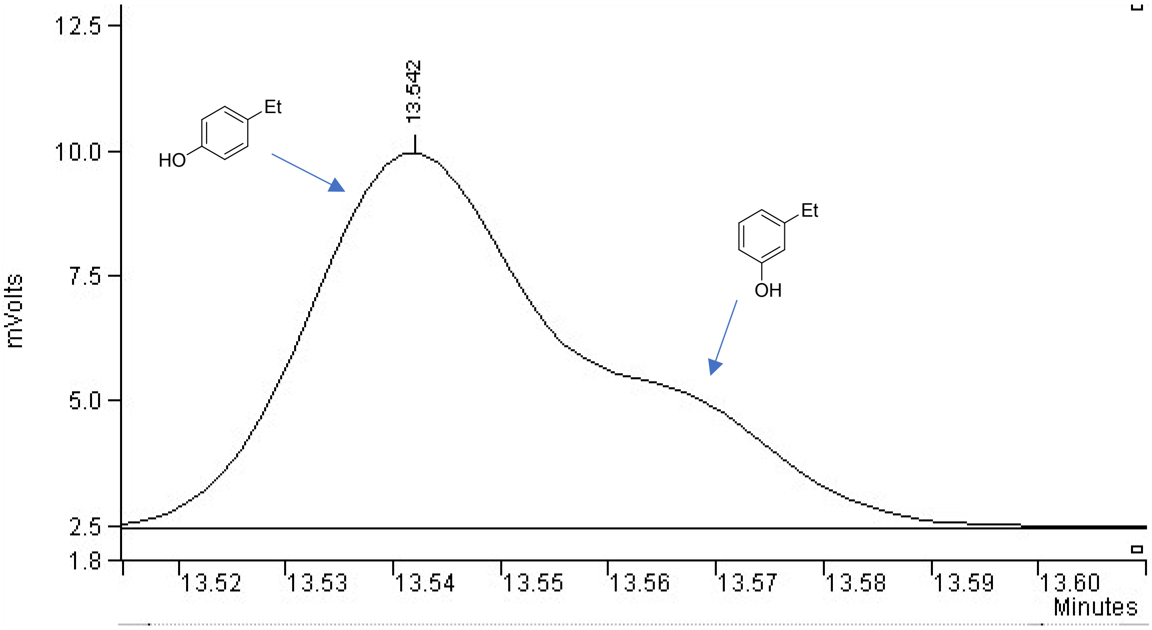




Toluene oxidation (zoom on the *p*+*m* cresols peak showing a 3:1 ratio).

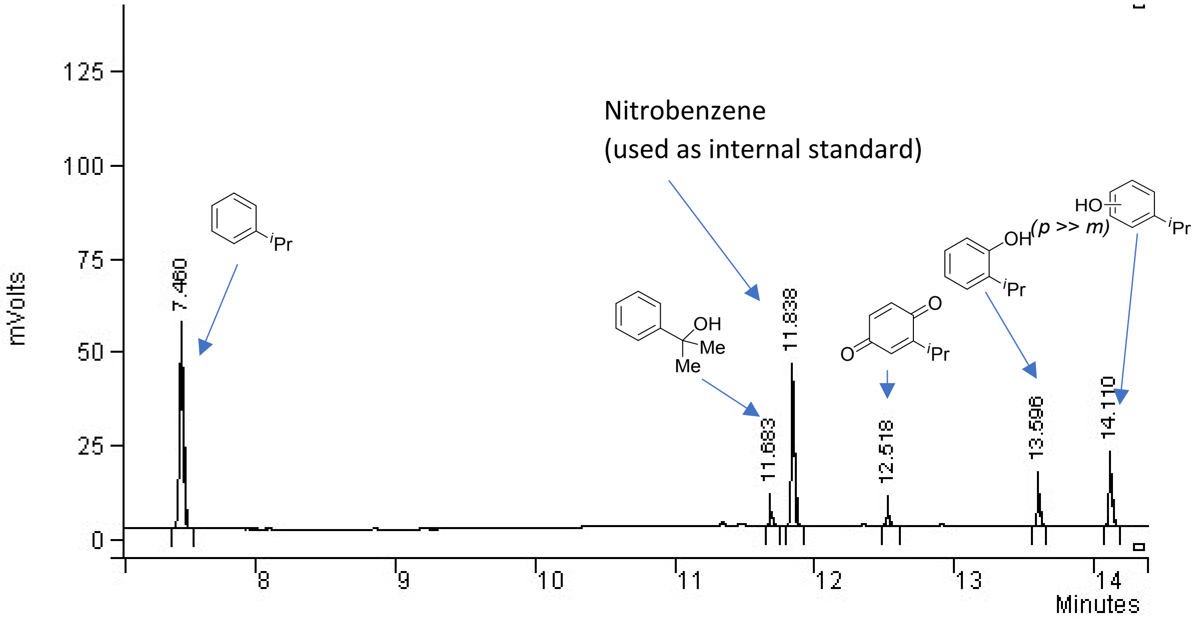
Ethylbenzene (one of the runs of ethylbenzene oxidation reported in Table 2)

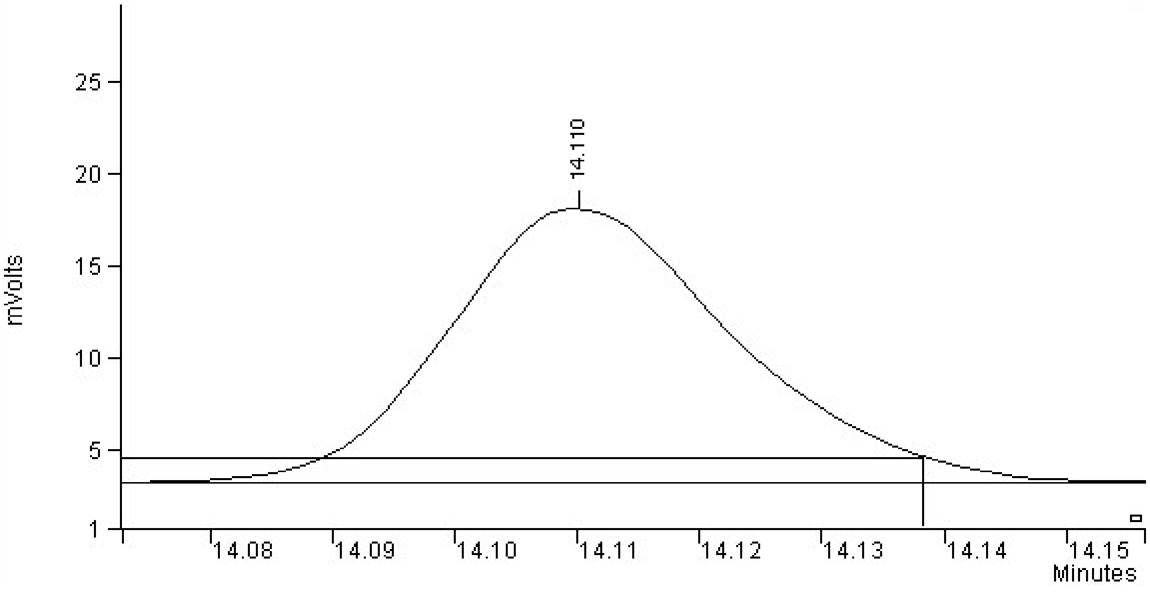




Ethylbenzene oxidation (zoom on the p+m ethylphenols peak showing a 2:1 ratio)

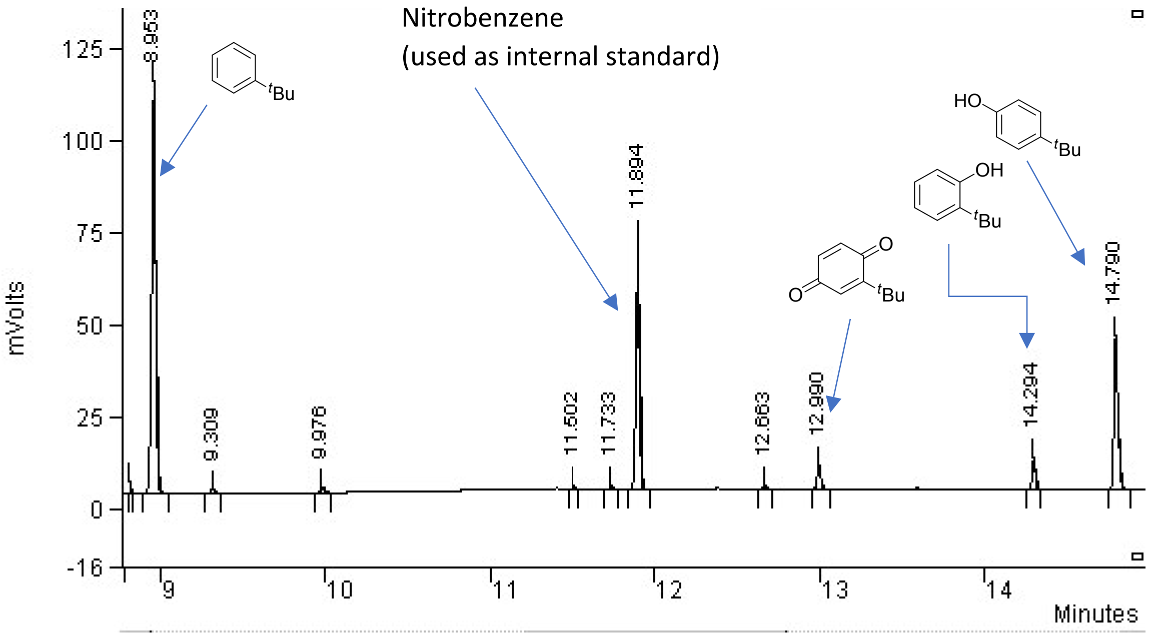
Cumene (one of the runs of cumene oxidation reported in Table 2)

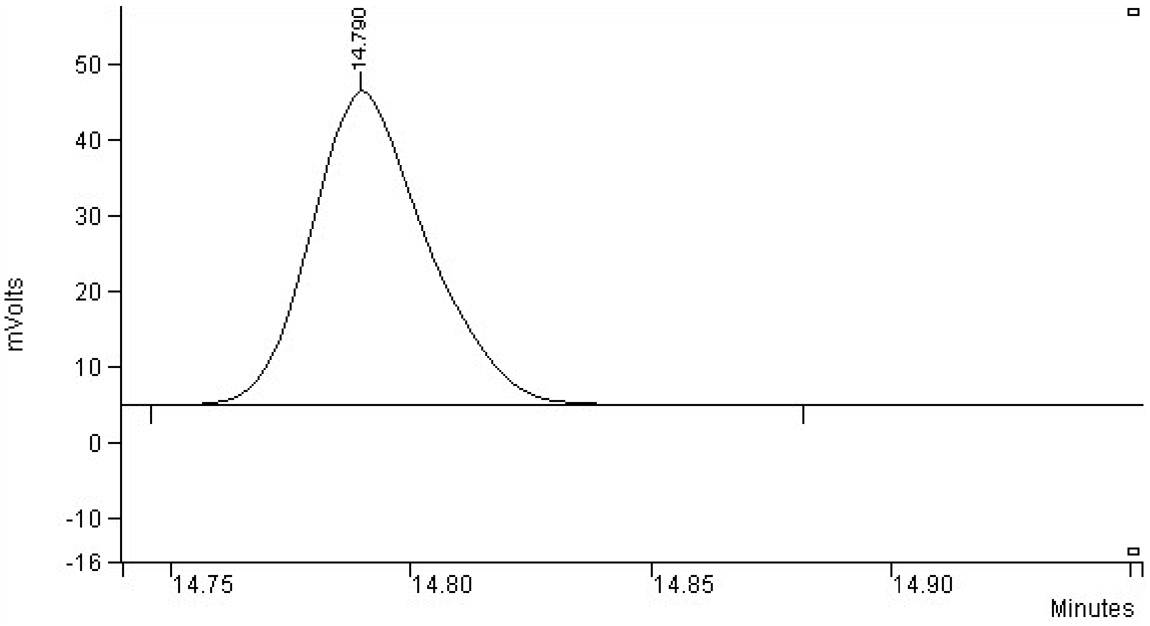




Cumene oxidation (zoom on the *p*-isopropylphenol peak showing a single maximum with no visible contibution from the *meta* isomer)

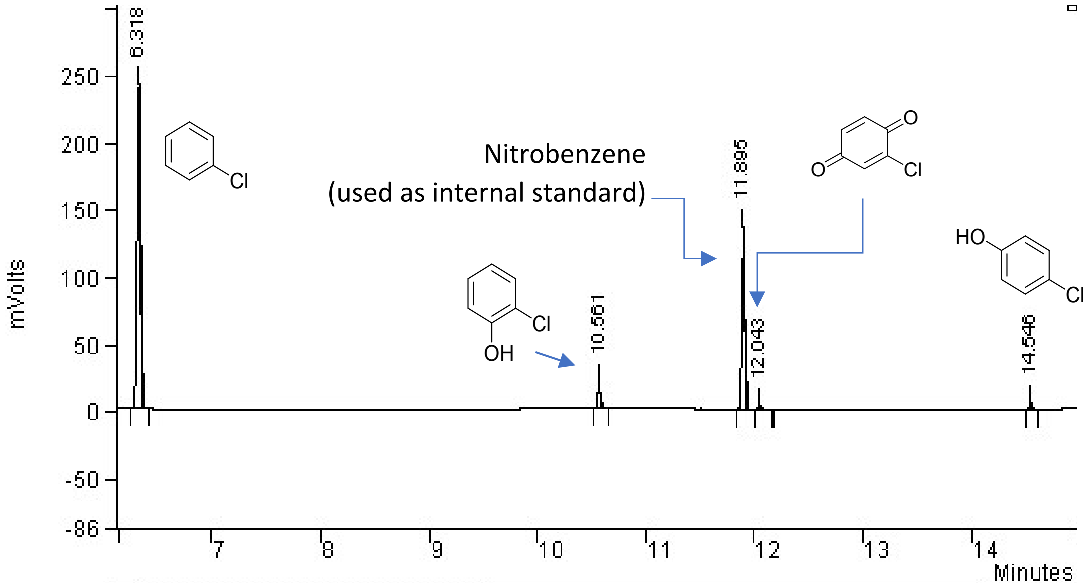
tert-butylbenzene (one of the runs of _tert_-butylbenzene oxidation reported in Table 2)



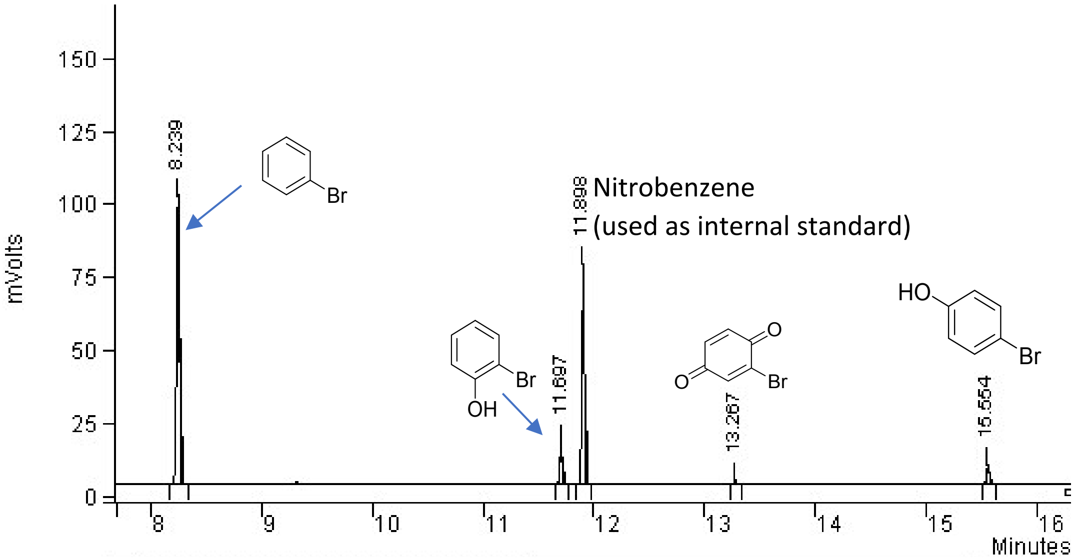


tert-butylbenzene oxidation (zoom on the p-*tert*-butylphenol peak showing a single maximum with no visible contibution from the meta isomer)

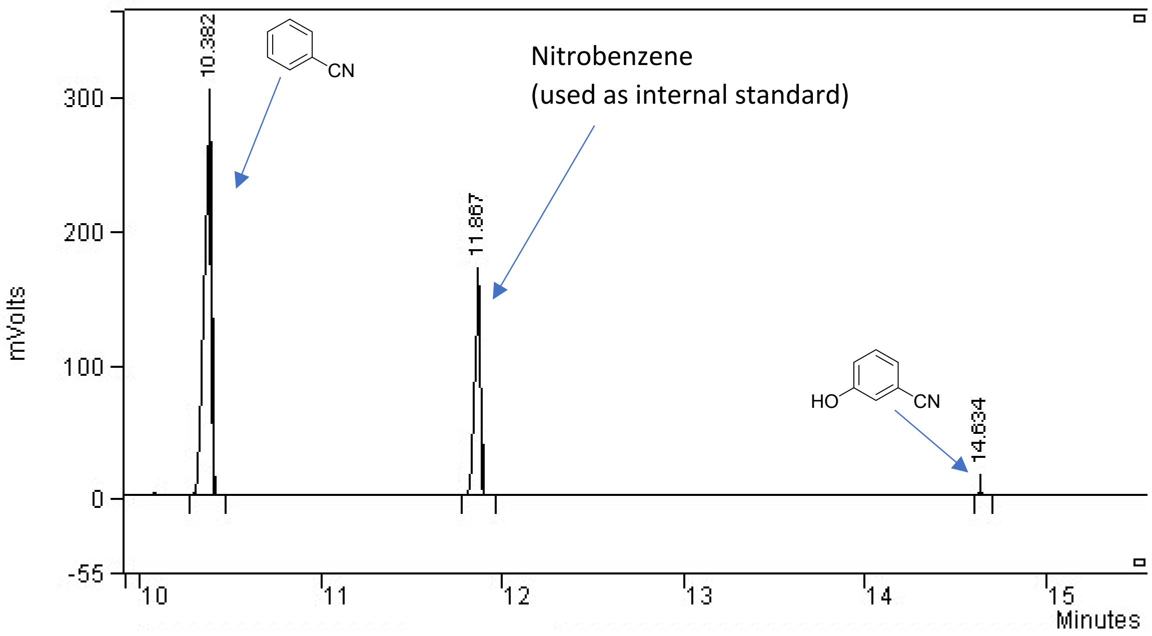
Chlorobenzene (one of the runs of chlorobenzene oxidation reported in Table 2)



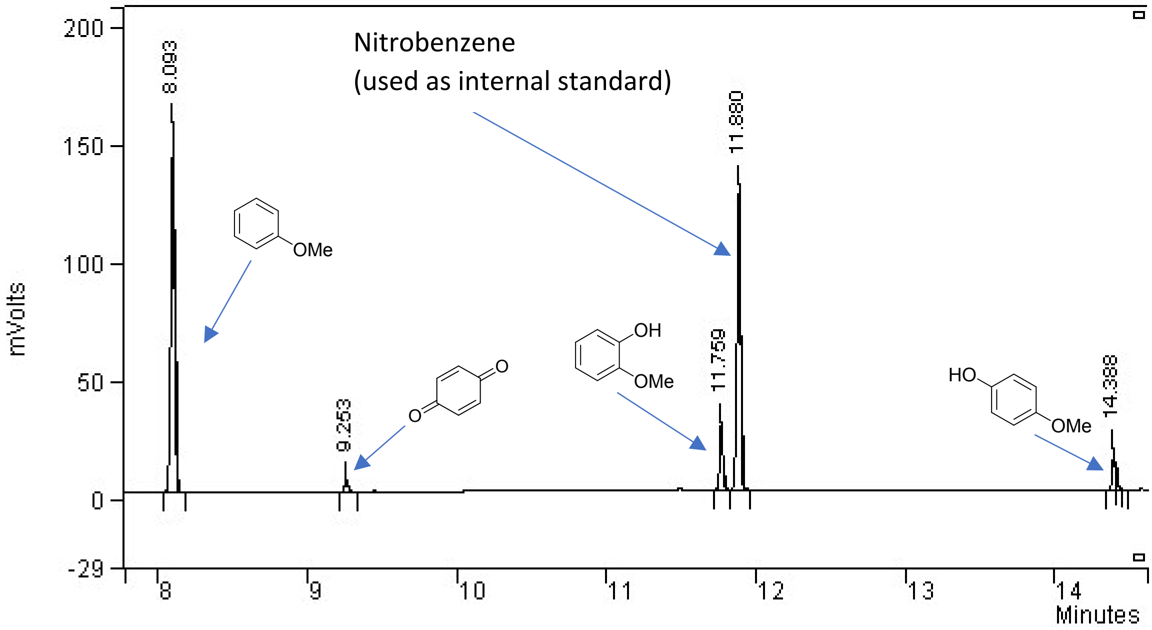
Bromobenzene (one of the runs of bromobenzene oxidation reported in Table 2)



Benzonitrile (one of the runs of benzonitrile oxidation reported in Table 2)



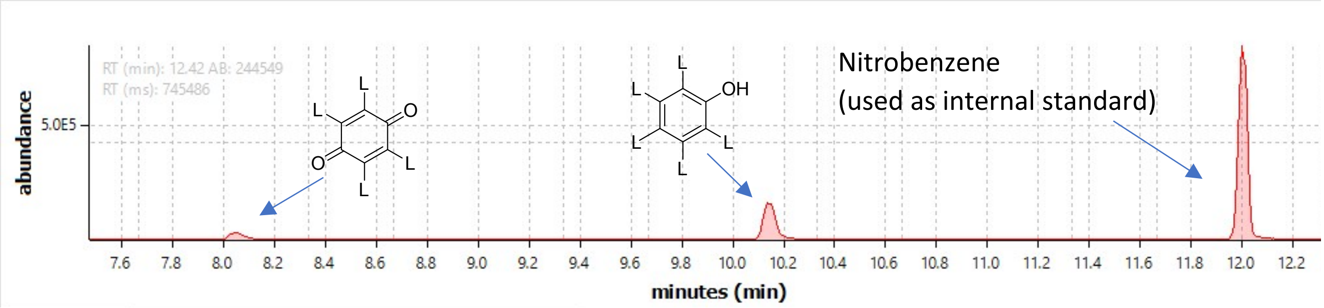
Anisole (one of the runs of anisole oxidation reported in Table 2)



Competitive oxidation between X-substituted benzenes and cyclohexane

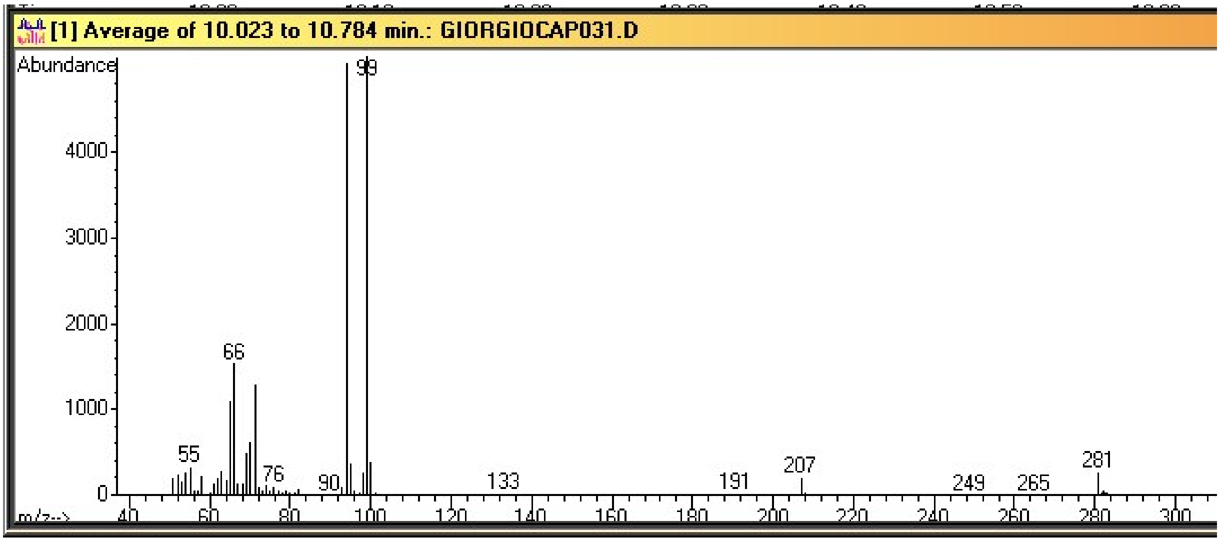
The reaction was carried out with limiting amount of hydrogen peroxide and half of the arene (in moles) was replaced with cyclohexane. The final ratio is catalyst **1**:ArX:CyH:H_2O_2 1:50:50:100. The products were identified by comparison of their retention times with authentic samples and quantified by internal standard.

Competitive oxidation between benzene and d_6 benzene (measure of KIE)



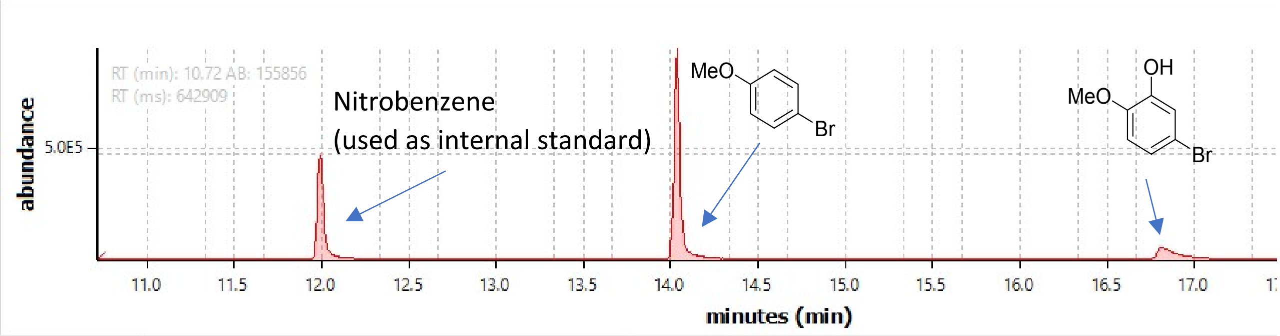
d_6-benzene and benzene competitive oxidation (L = H or D)

For the run shown, mean abundances for ions with m/z = 94 and 99 over the phenol peak (RT(min)=10.023-10.784) were respectively 5039 and 5122 which translates to a KIE of 0.98.

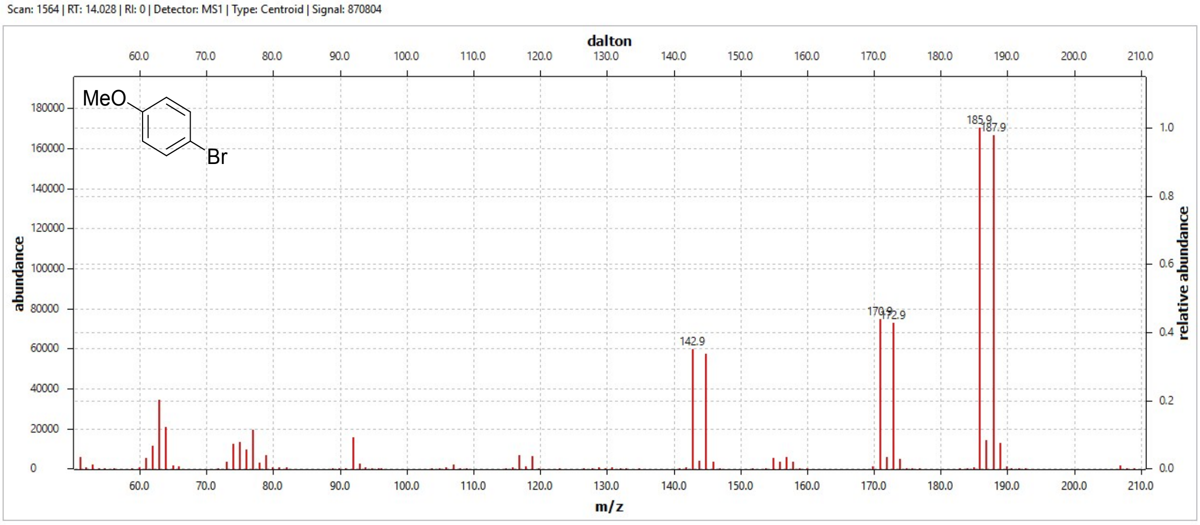


Oxidation of p-bromoanisole

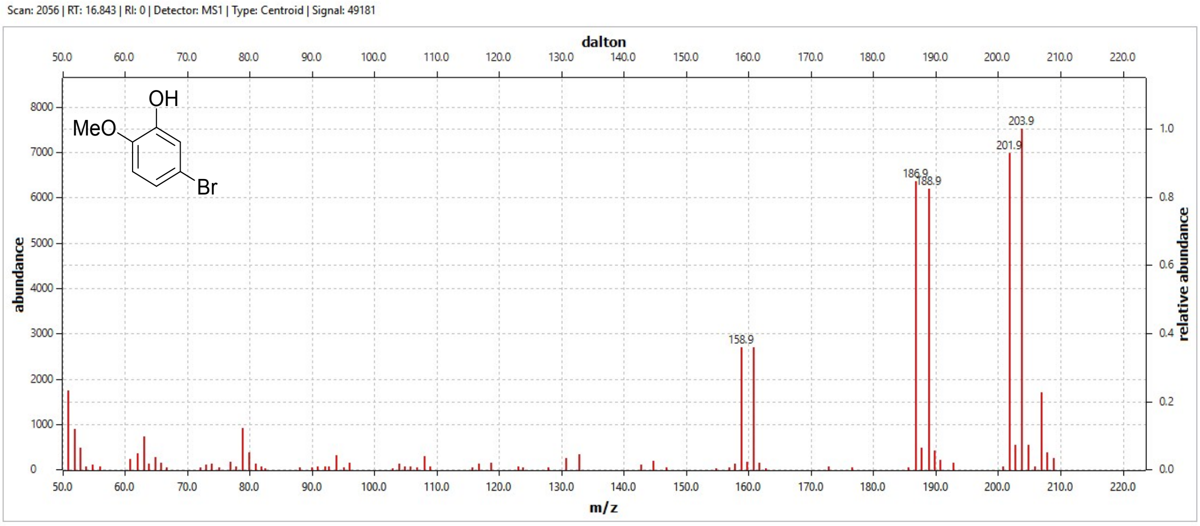
In order to evaluate the relative activation properties of bromo- and methoxy- substituents on the aromatic ring, we carried out the **1** catalyzed oxidation of *p*-bromoanisole with H_2O_2. The only detectable phenol product present in the crude mixture was found to be 5-bromo-2-methoxyphenol (identified by MS and ^{1}H-NMR).



Chromatogram of crude mixture of p-bromoanisole oxidation



EI mass spectrum of p-bromoanisole (peak at RT(min)=14.028)



EI mass spectrum of 5-bromo-2-methoxyphenol, the only phenol product detected in the oxidation crude from the p-bromoanisole reaction (peak at RT(min)=16.843)

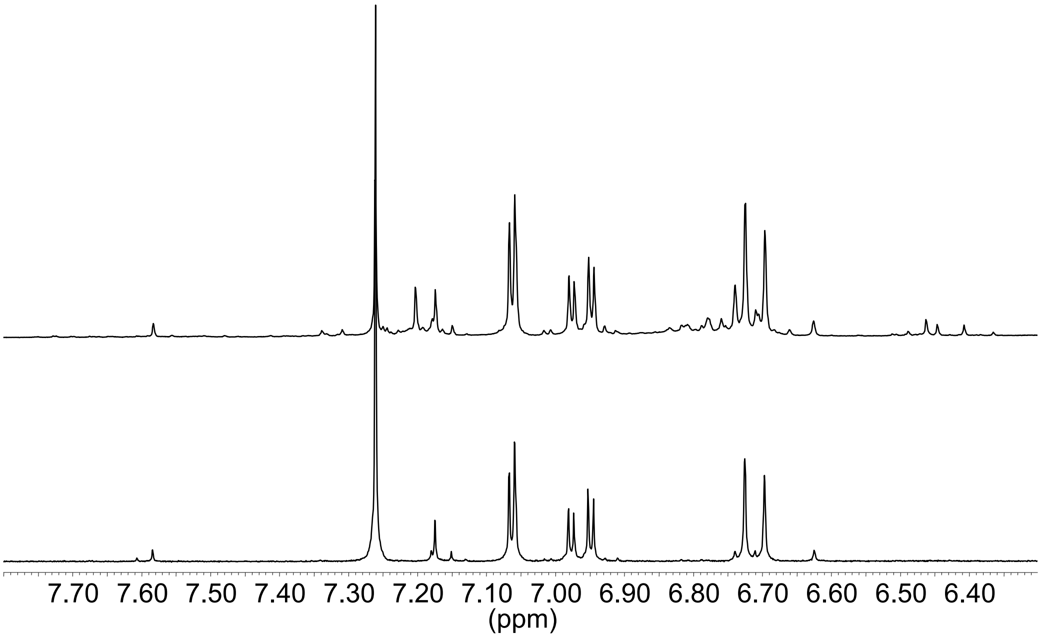
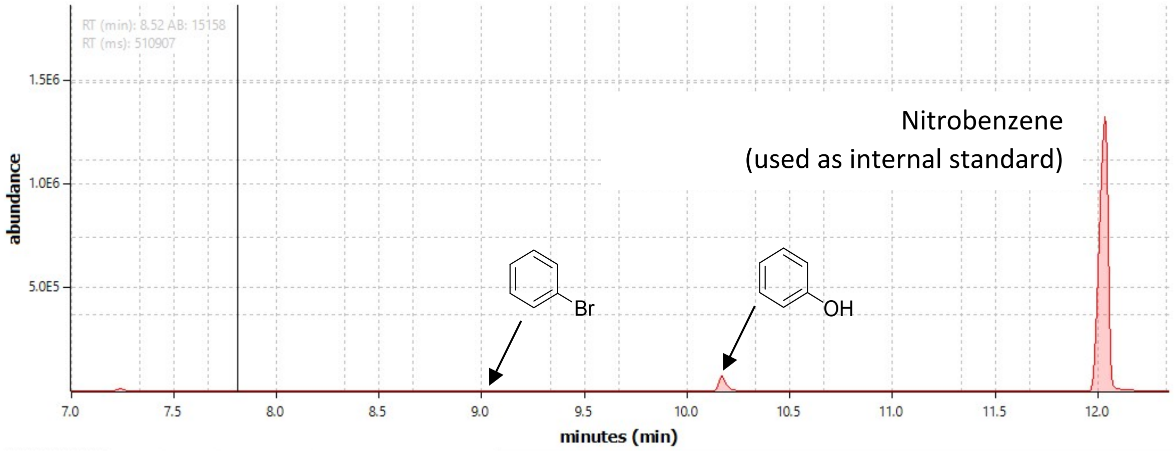


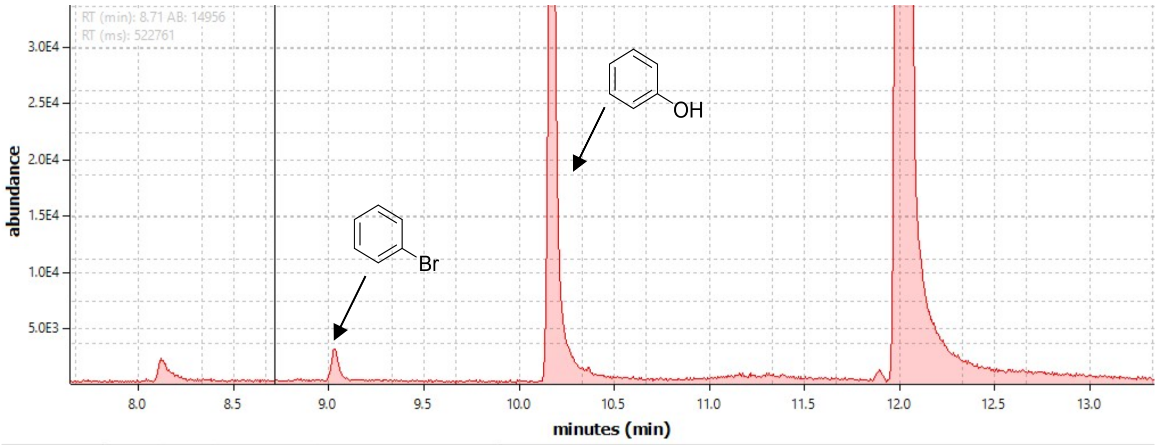
Figure S1. ^{1}H NMR spectrum (aromatic region) of reaction crude obtained from the **1** catalyzed H_2O_2 oxidation of 4-bromoanisole (top), and of 5-bromo-2-methoxyphenol (bottom) obtained by chromatography: ($CDCl_3$, 300 MHz) δ (ppm) 7.06 (d, J = 2.4 Hz, 1H), 6.96 (dd, J = 8.6 and 2.4 Hz, 1H), 6.71 (d, J = 8.6 Hz, 1H), 3.87 (not shown) (s, 3H). the signals are perfectly coincident with those reported by N. Fujikawa, T. Ohta, T. Yamaguchi T. Fukuda, F. Ishibashi, M. Iwoo, *Tetrahedron* 2006, **62**, 594-604. No trace of signals related to 2-bromo-5-methoxyphenol are found in these spectra (for $CDCl_3$ ^{1}H NMR spectrum of 2-bromo-5-methoxyphenol see Y. Takashima, Y. Kaneko, Y. Kobayashi, *Tetrahedron* 2010, **66**, 197-207: ^{1}H NMR (300 MHz, $CDCl_3$) δ (ppm) 3.77 (s, 3H), 5.51 (s, 1H), **6.41** (dd, J = 9, 3 Hz, 1H), **6.60** (d, J = 3 Hz, 1H), **7.31** (d, J = 9 Hz, 1H)).

Oxidation in presence of a radical trap (bromotrichloromethane)

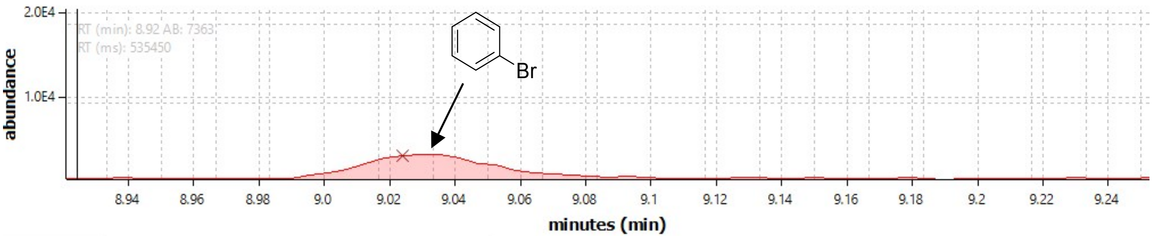
Oxidation of benzene under Gif conditions (in the presence of sole $Fe(OTf)_2$)



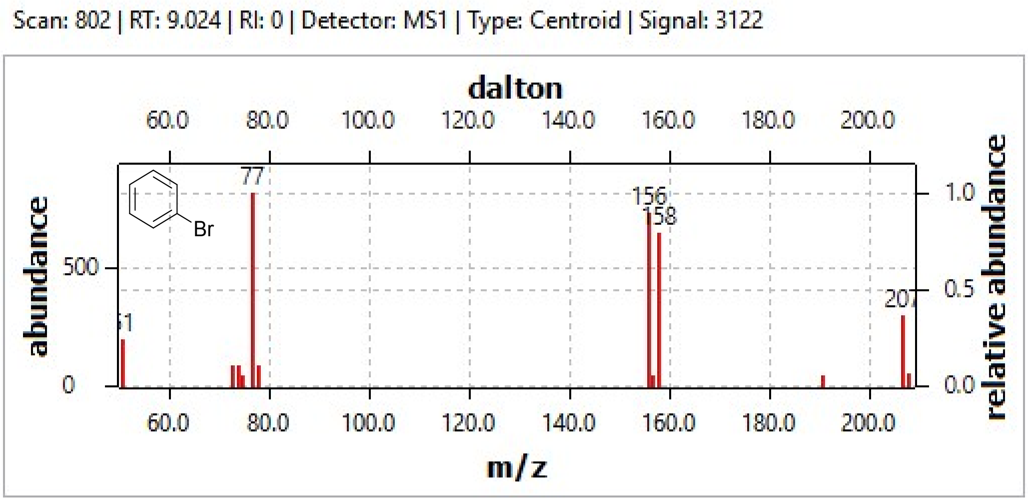
Oxidation of benzene under Fenton-type conditions ($Fe(CF_3SO_3)_2(CH_3CN)_2$ as catalyst) in the presence of bromotrichloromethane.



Oxidation of benzene under Gif conditions in the presence of bromotrichloromethane (zoom). Peak at 8.1 min is due to 1,4 quinone.

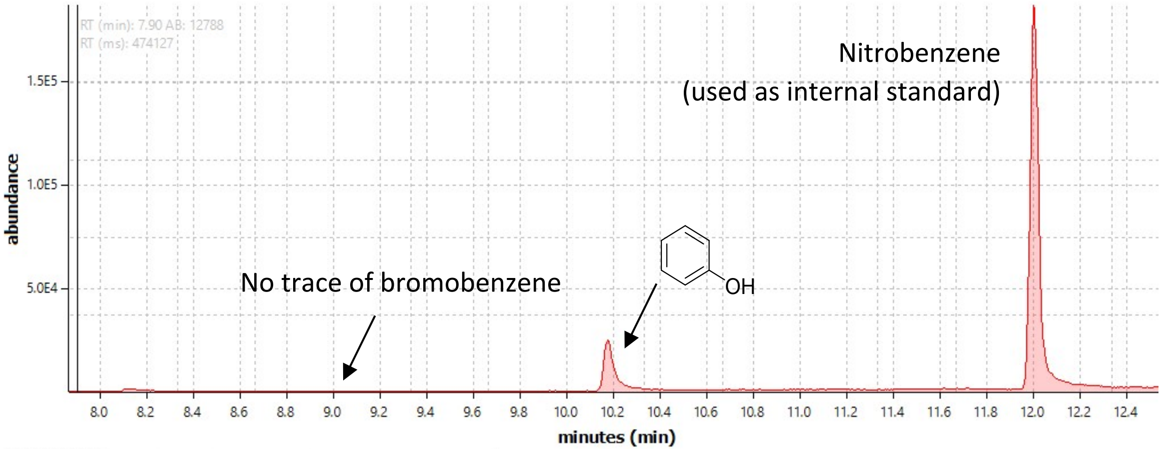


Oxidation of benzene under Fenton-type conditions ($Fe(CF_3SO_3)_2(CH_3CN)_2$ as catalyst) conditions in the presence of bromotrichloromethane (zoom on the bromobenzene peak at RT(min) = 9.024)

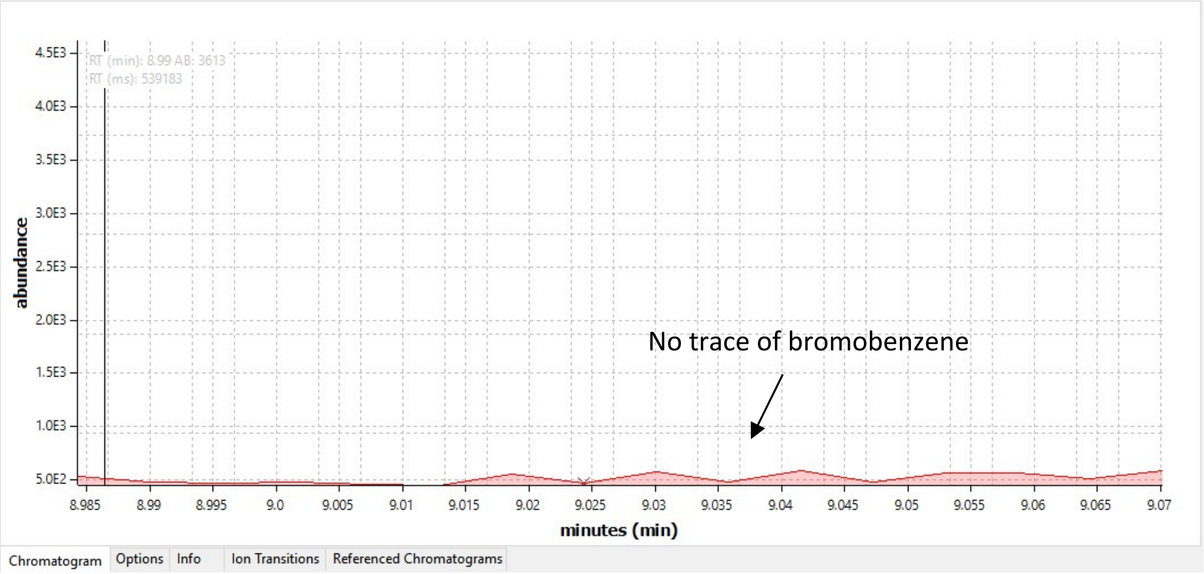


EI mass spectrum of bromobenzene at RT(min) = 9.024 generated during the oxidation of benzene under Gif conditions in the presence of bromotrichlorometane

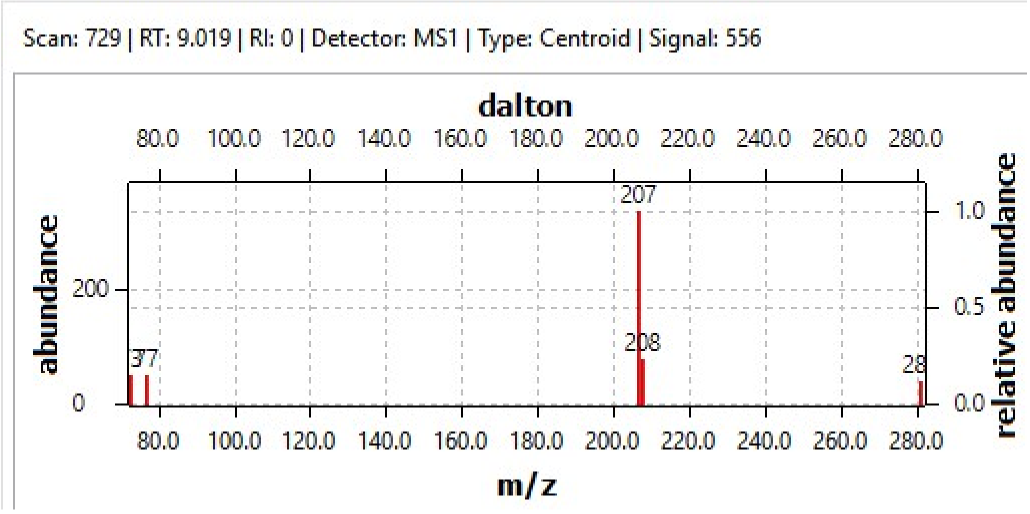
Oxidation of benzene in the presence of catalyst **1**.



Oxidation of benzene catalysed by complex **1** in the presence of bromotrichloromethane



Oxidation of benzene catalysed by complex **1** in the presence of bromotrichloromethane (zoom on the area around RT(min) = 9.024: no peaks emerge from the background noise)

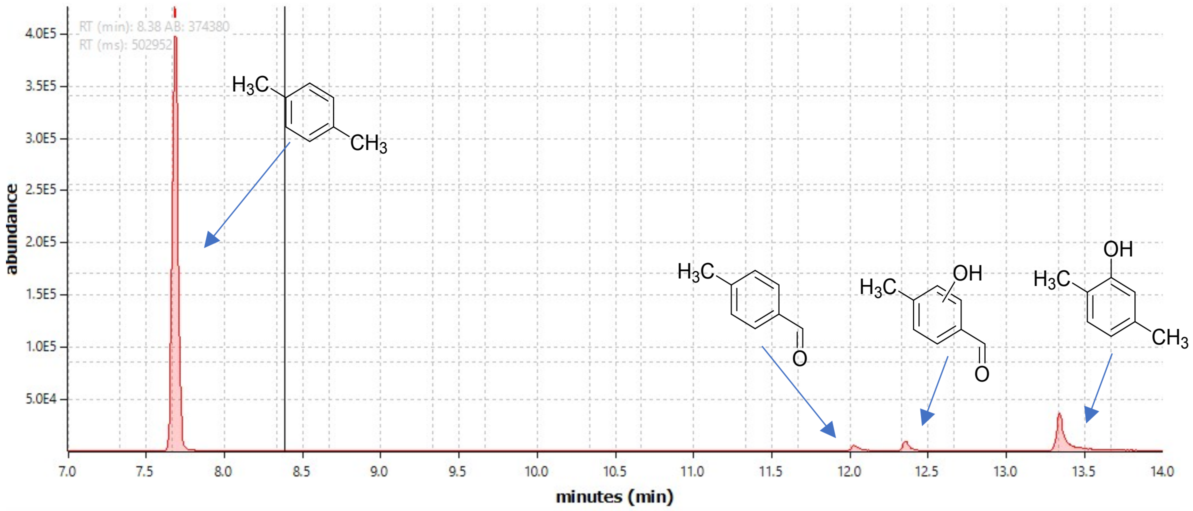


Scan: 729 | RT: 9.019 | RI: 0 | Detector: MS1 | Type: Centroid | Signal: 556

EI mass spectrum for RT (min) = 9.019: the spectrum shows no trace of bromobenzene

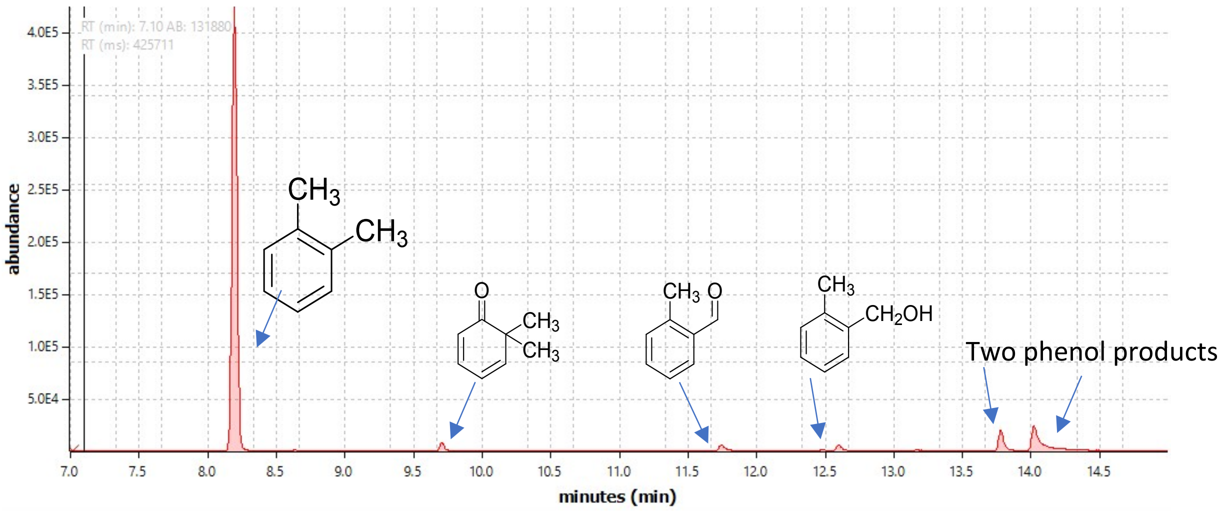
Rearrangement experiments

Oxidation of *p*-xylene (one of the runs of *p*-xylene oxidation)



Chromatogram of crude mixture from the *p*-xylene oxidation

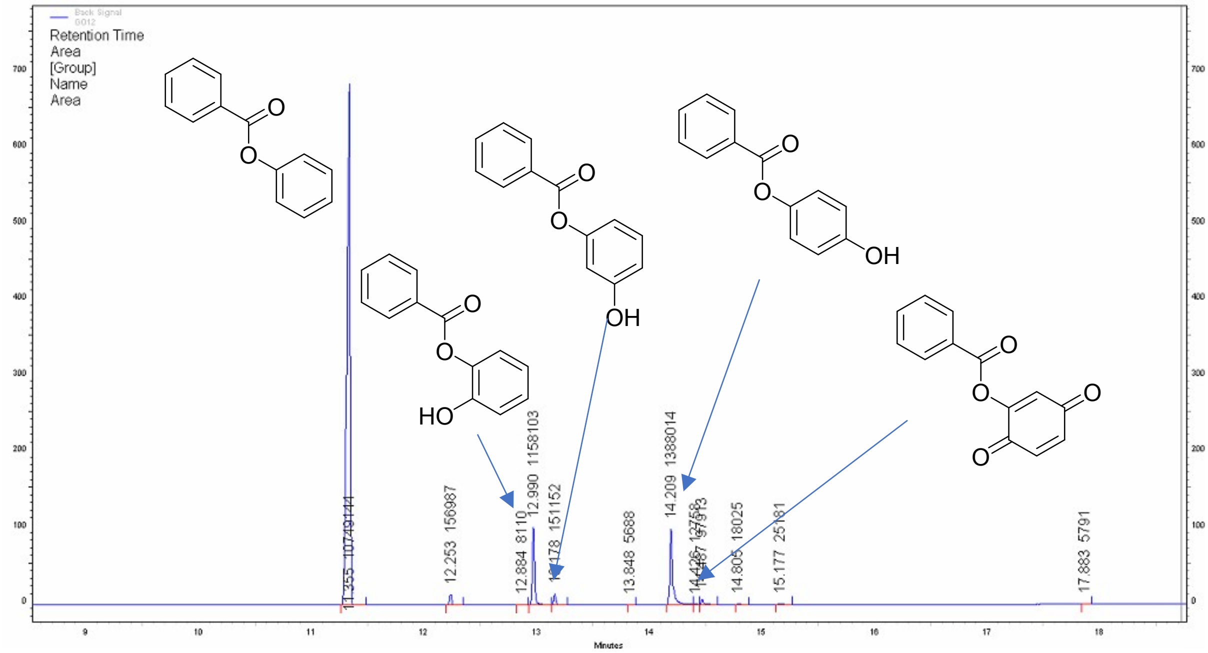
Oxidation of *o*-xylene (one of the runs of *o*-xylene oxidation)



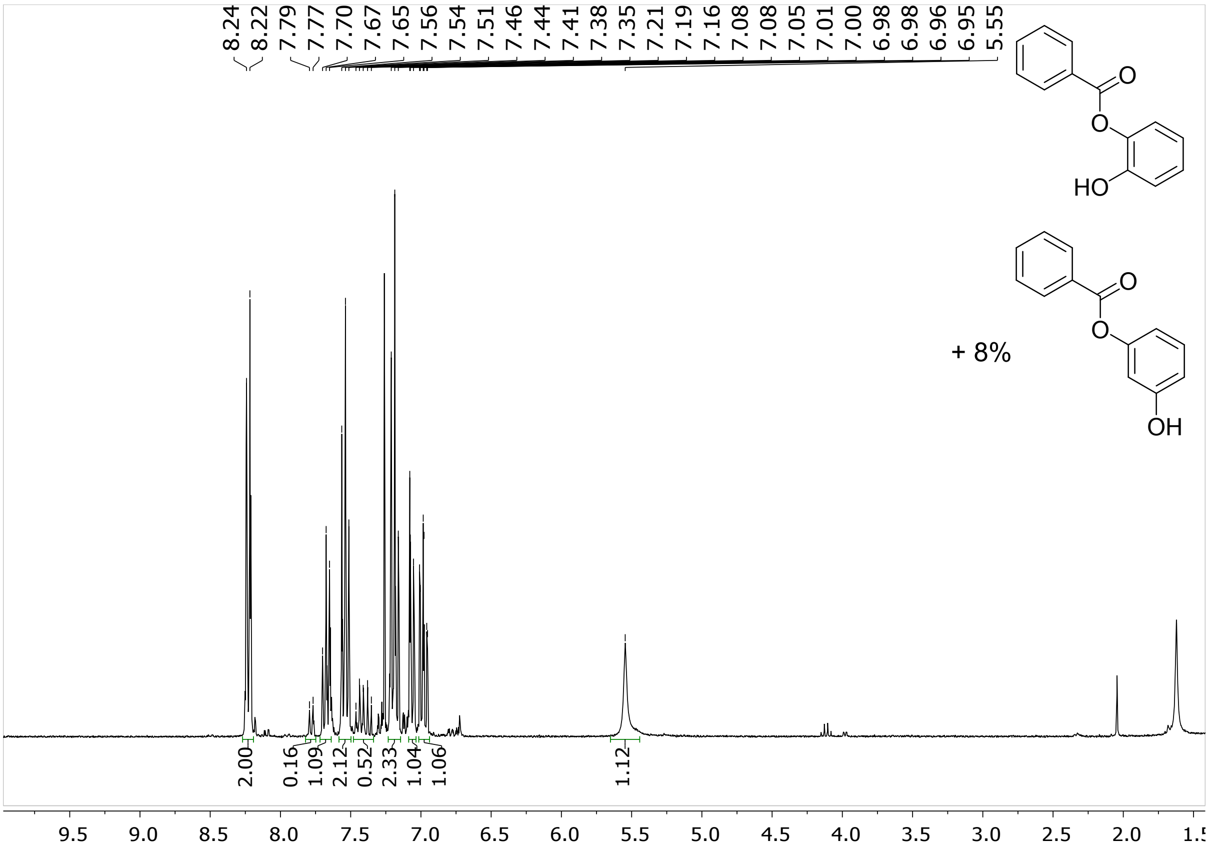
Chromatogram of crude mixture from the *o*-xylene oxidation

Oxidation of phenyl benzoate

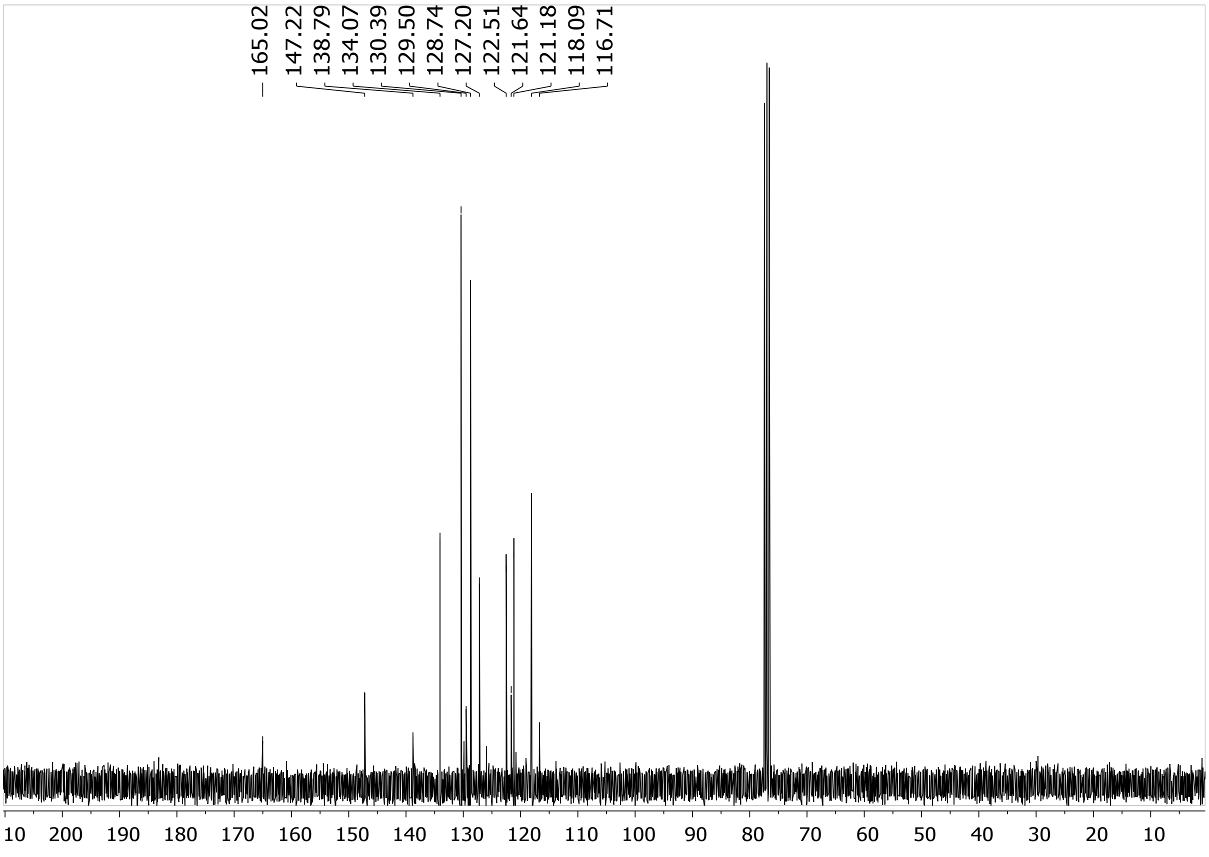
The reaction was performed as described in typical oxidation conditions, with 2.50 µmol of in situ generated **1**, and 49.5 mg, 250 µmol of phenyl benzoate. After the reaction, solvent was removed by rotatory evaporation and column chromatography (SiO_2, AcOEt:Hex 1:1, MeOH 1%) afforded substrate (24 mg, 121 µmol, 48%), *ortho*-phenol along with traces of *meta*-phenol (12 mg, 56 µmol, 22% yield, 12:1 ratio o/m) and *para*-phenol along with traces of *p*-benzoquinone (14 mg, 65 µmol, 26% yield, 9:1 ratio). *Ortho* + *meta* phenols ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 8.23 (dt, $^2J = 6$ Hz, $^3J = 3$ Hz, 2H), 7.78 (dt, J = 6 Hz, 0.16 H), 7.67 (tt, $^2J = 9$ Hz, $^3J = 3$ Hz, 1H), 7.54 (t, J = 9 Hz, 2H), 7.40 (m, 0.52 H), 7.19 (td, $^2J = 6$ Hz, $^3J = 2$ Hz, 2H), 7.06 (dt, $^2J = 9$ Hz, $^3J = 2$ Hz, 1H), 6.98 (td, $^2J = 9$ Hz, $^3J = 2$ Hz, 1H), 5.55 (s, 1H). ^{13}C-NMR (300 MHz, $CDCl_3$) δ:165.0, 147,2, 138.8, 134.1, 130.4, 129.5, 128.7, 127.2, 122.5, 121.6, 121.2, 118.1, 116.7. HRMS ($C_{13}H_{10}O_3 + H^+$): calcd 215.0703, found 215.0698. *para*-phenol and *p*-benzoquinone: ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 8.20 (dt, $^2J = 3$ Hz, $^3J = 3$ Hz, 2H), 8.10 (dt, J = 9 Hz, 0.25 H), 7.64 (tt, $^2J = 9$ Hz, $^3J = 3$ Hz, 1H), 7.51 (tt, $^2J = 9$ Hz, $^3J = 3$ Hz, 2H), 7.40 (m, 0.25 H), 7.20 (m, 0.4 H), 7.05 (dd, $^2J = 9$ Hz, $^3J = 2$ Hz, 2H), 6.88 (m, 0.30 H), 6.82 (dd, $^2J = 9$ Hz, $^3J = 2$ Hz, 2H), 5.47 (s, 1H). ^{13}C-NMR (300 MHz, $CDCl_3$) δ:166.0, 153.50, 144.2, 133.6, 130.2, 129.4, 128.6, 122.5, 121.8, 116.1, 115.4. HRMS ($C_{13}H_{10}O_3 + H^+$): calcd 215.0703, found 215.0695.



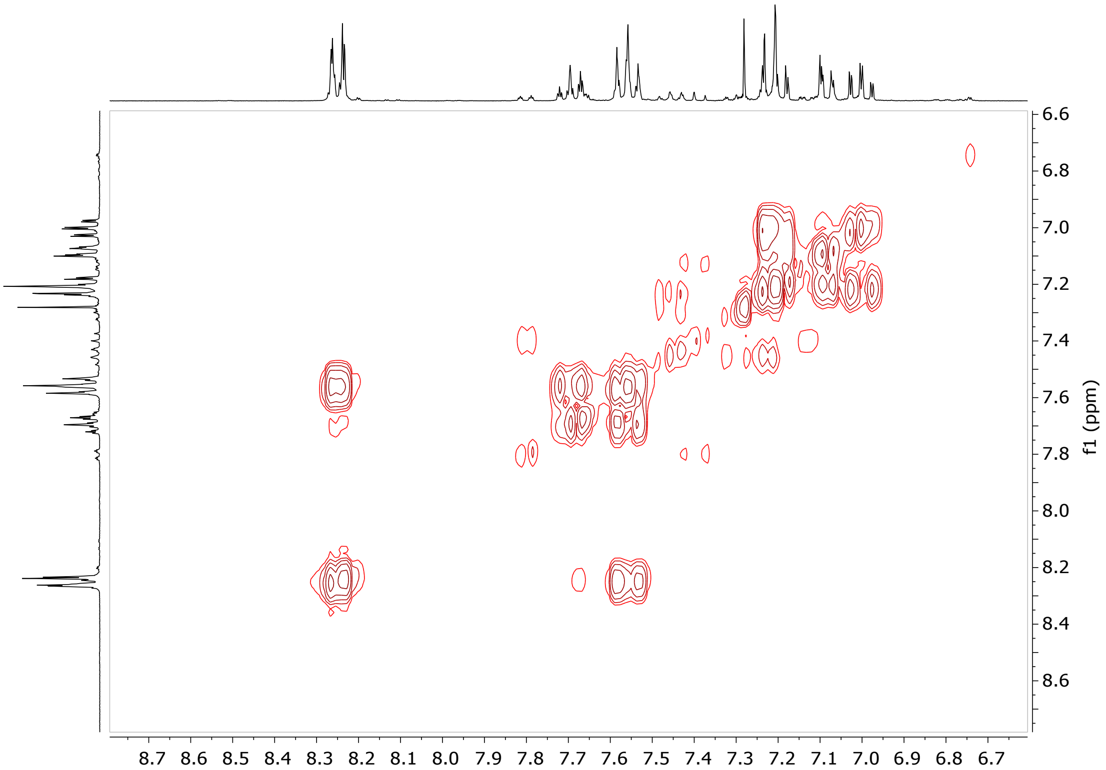
GC chromatogram of phenylbenzoate oxidation catalysed by **1**.



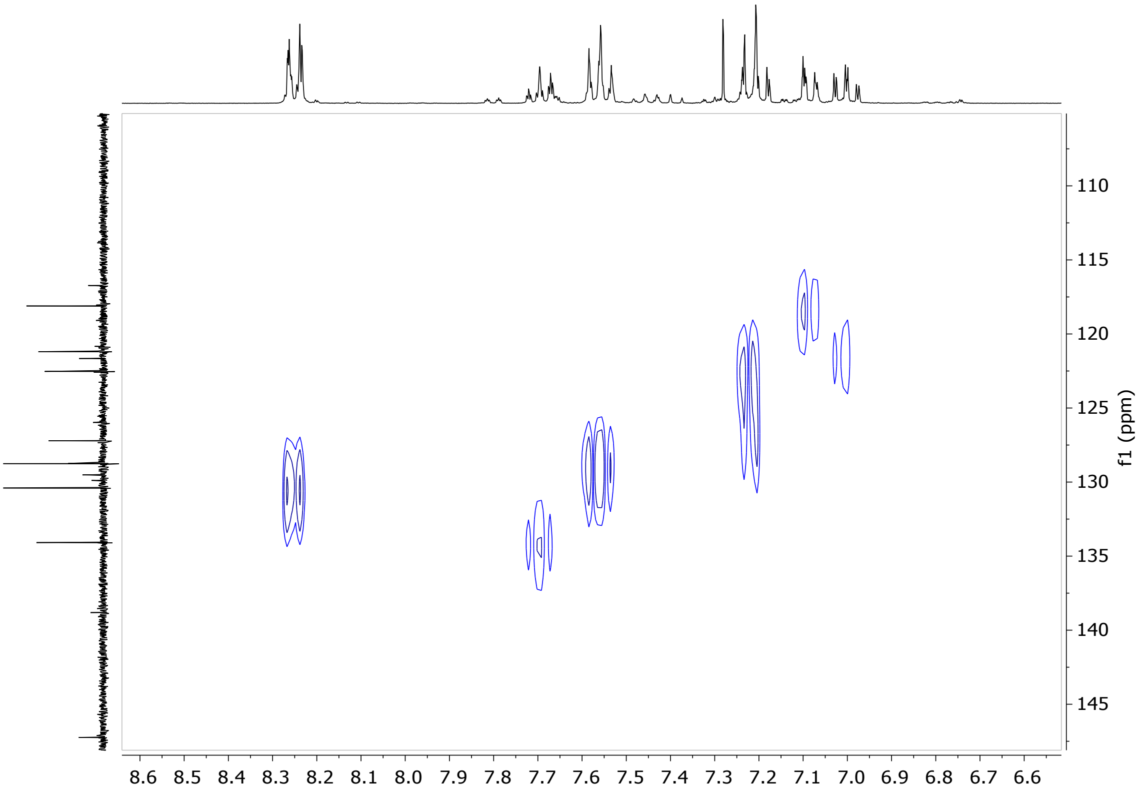
^{1}H-NMR of *ortho* + *meta* phenols



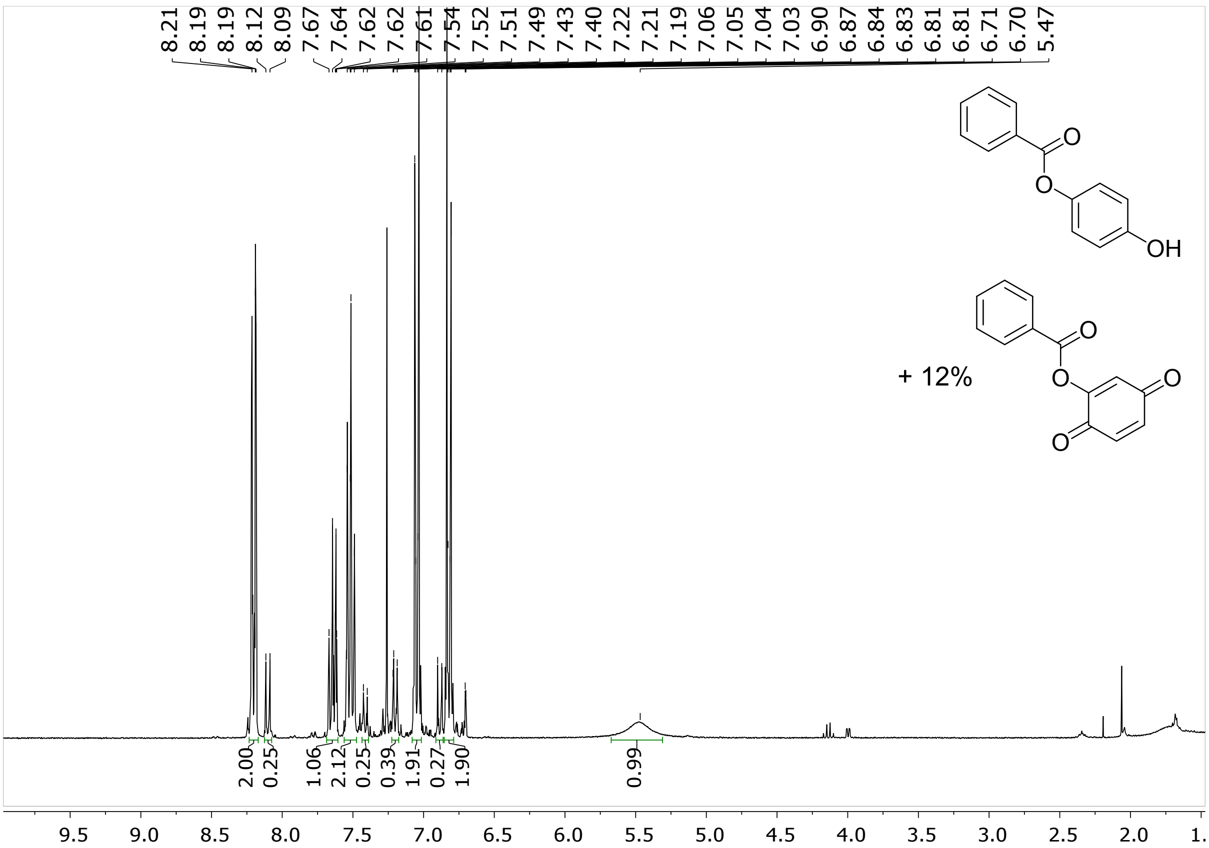
^{13}C-NMR of *ortho* + *meta* phenols



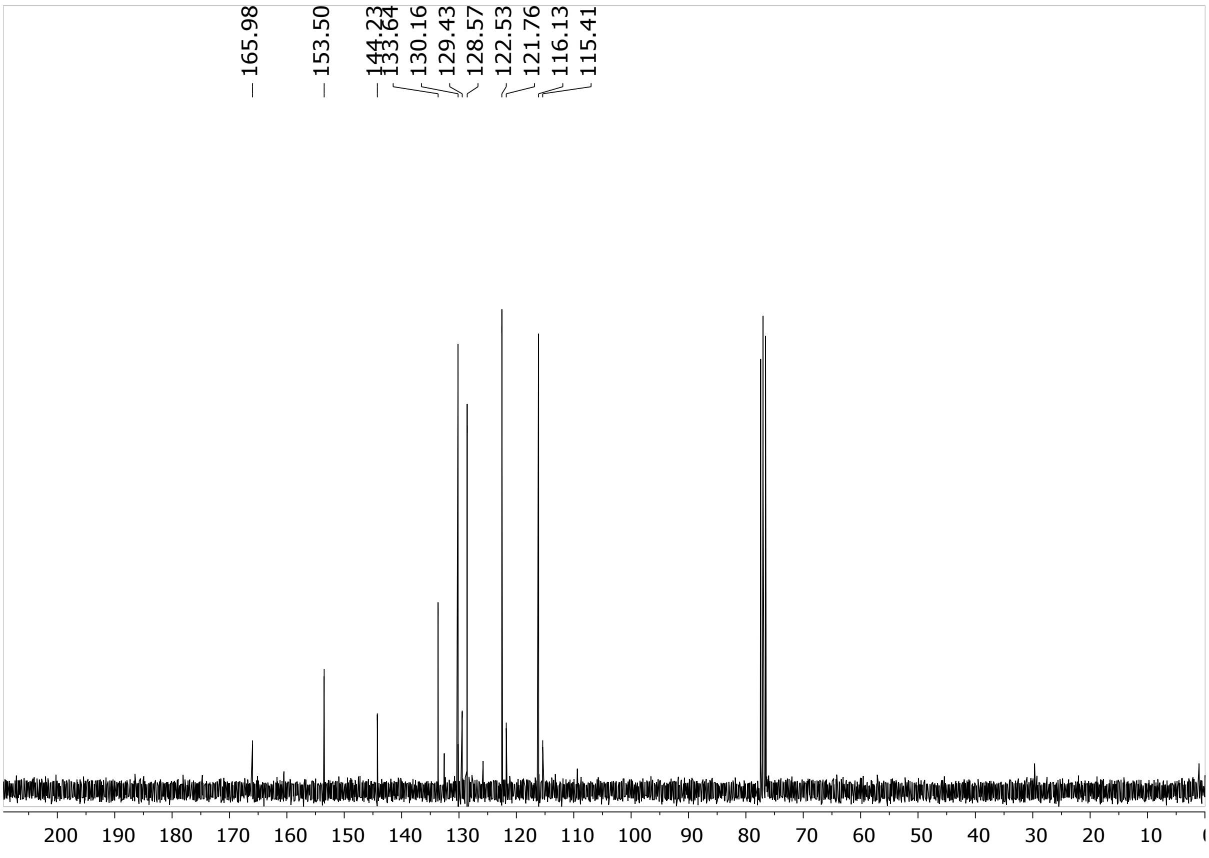
COSY of *ortho* + *meta* phenols (aromatic region)



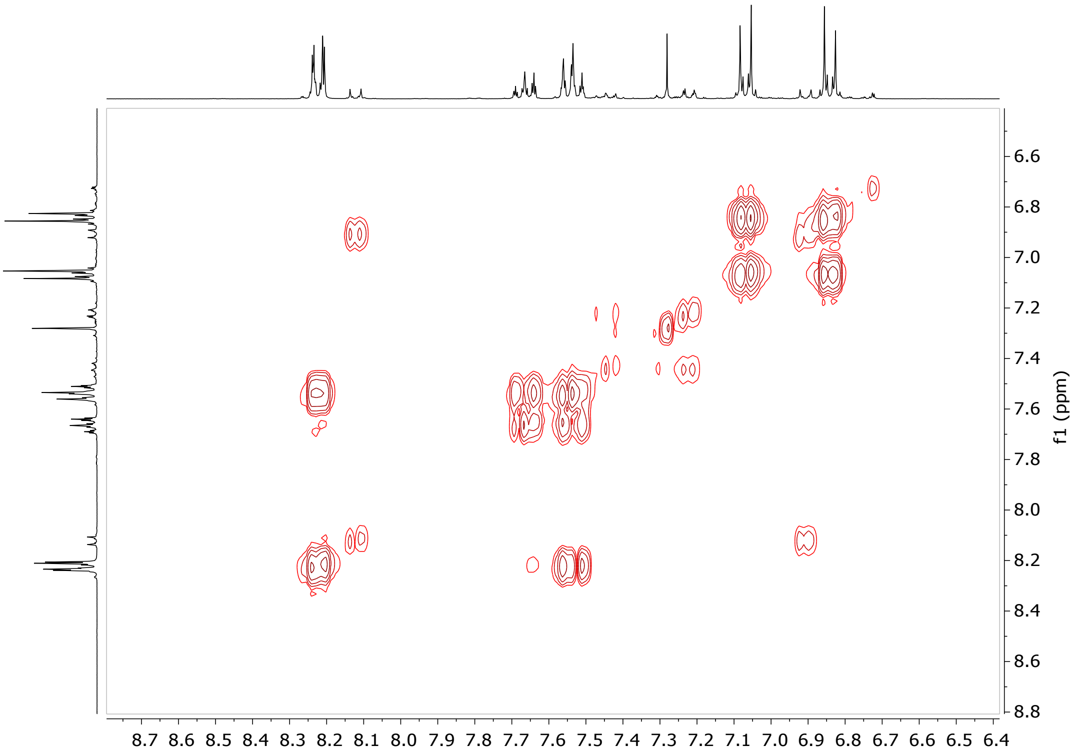
HSQC of *ortho* + *meta* phenols (aromatic region)



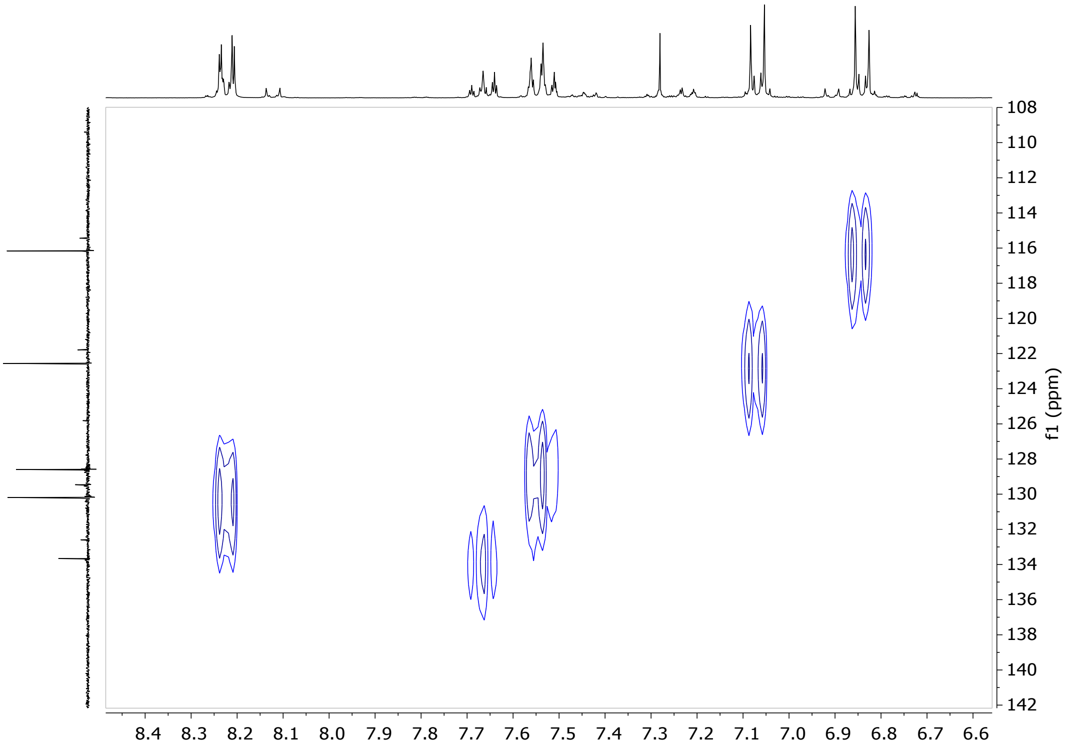
^{1}H-NMR of *para*-phenol and *p*-benzoquinone



^{13}C-NMR of *para*-phenol and *p*-benzoquinone



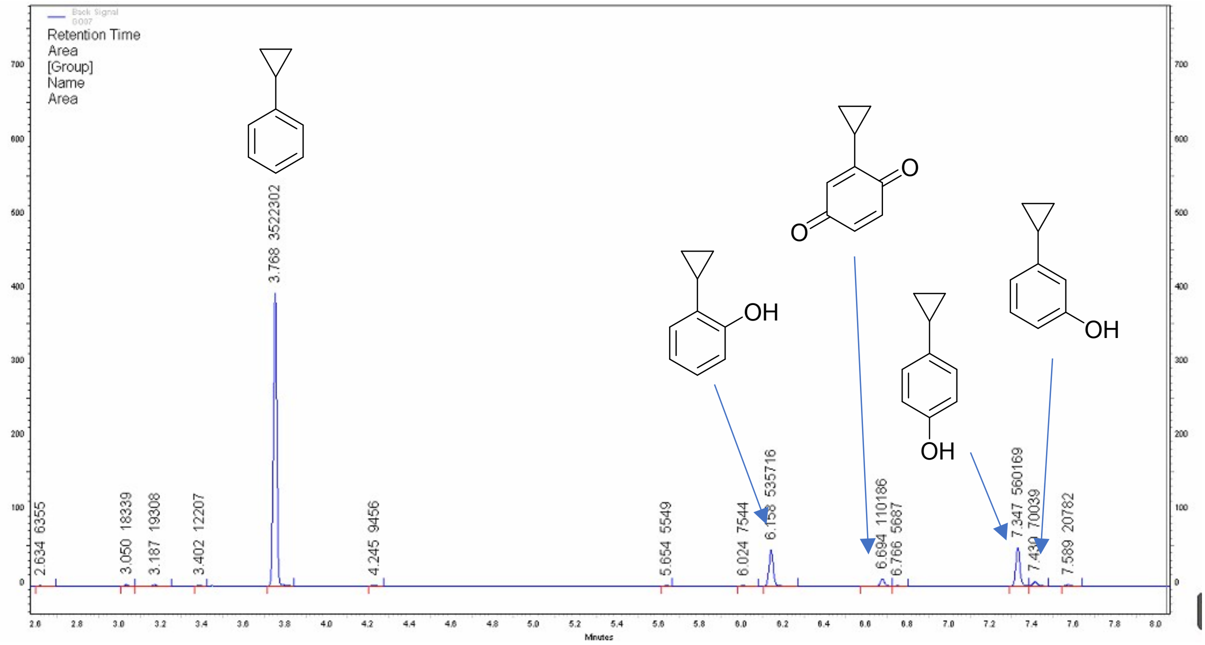
COSY of *para*-phenol and *p*-benzoquinone (aromatic region)



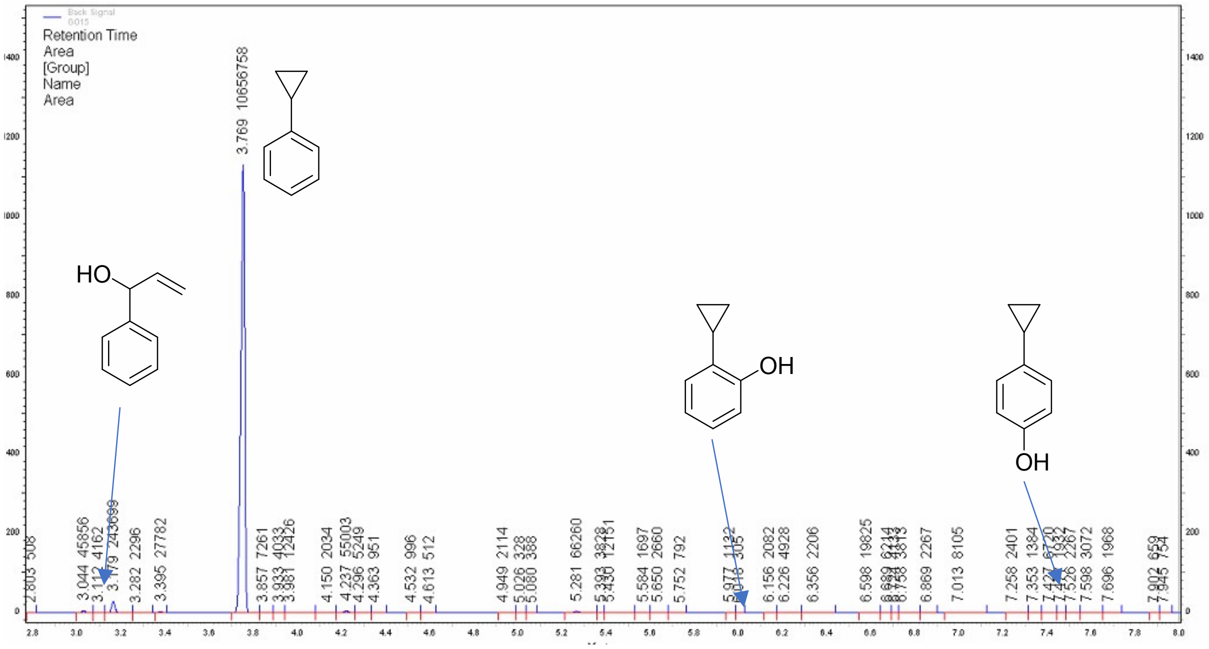
HSQC of *para*-phenol and *p*-benzoquinone (aromatic region)

Oxidation of cyclopropylbenzene

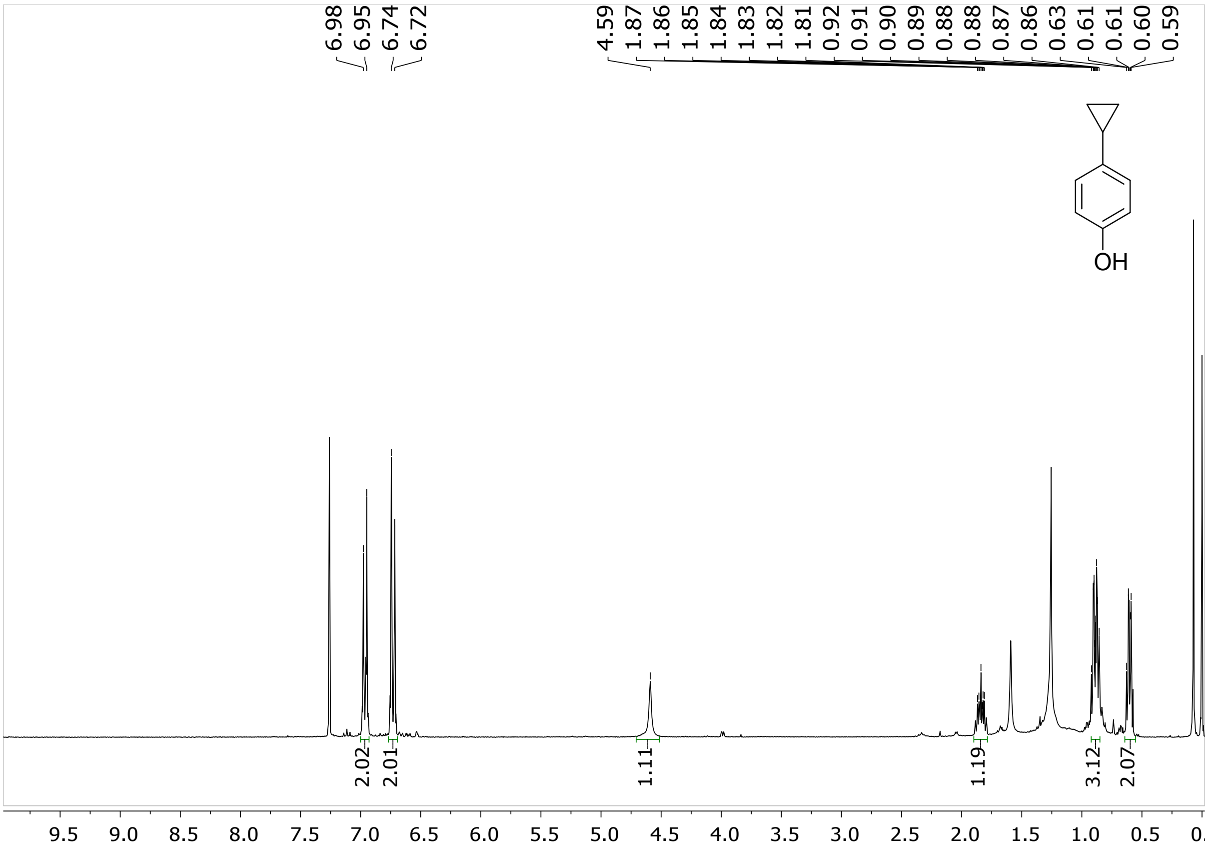
The reaction was performed as described in typical oxidation conditions, with 2.50 µmol of in situ generated **1**, and 29.5 mg, 250 µmol of cyclopropylbenzene. After the reaction, solvent was removed by rotatory evaporation and column chromatography (SiO_2, AcOEt:Hex 1:2, MeOH 1%) afforded substrate (18 mg, 152 µmol, 58%), *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone (7.0 mg, 52 µmol, 21% yield, 8:1:1 ratio o/m/quinone) and *para*-phenol (5.9 mg, 44 µmol, 18% yield). *Ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 8.56 (dst, ^2J = 3 Hz, ^3J = 1.5 Hz, 0.21 H), 7.89 (dt, J = 6 Hz, 0.25 H), 7.64 (t, J = 3 Hz, 0.26H), 7.24 (m, 0.24 H), 7.10 (dt, ^2J = 8 Hz, ^3J = 6 Hz, 2H), 6.86 (d, J = 8 Hz, 2 H), 6.79 (m, 0.41 H), 6.70 (m, 0.18 H), 6.15 (m, 0.26 H), 2.06 (m, 0.47 H), 1.82 (m, 1 H), 1.12 (qq, 0.97 H), 0.97 (qq, ^2J = 6 Hz, ^3J = 3 Hz, 2H), 0.76 (qq, ^2J = 6 Hz, ^3J = 3 Hz, 0.77H), 0.65 (qq, ^2J = 6 Hz, ^3J = 3 Hz, 2H). ^{13}C-NMR (300 MHz, $CDCl_3$) δ: 136.5, 136.3, 128.6, 127.7, 126.3, 121.3, 120.3, 114.5, 32.7, 29.7, 11.2, 9.23, 5.37. *Para*-phenol ^{1}H-NMR (300 MHz, $CDCl_3$) δ: 6.97 (d, J = 6 Hz, 2H), 6.73 (d, J = 6 Hz, 2 H), 4.59 (s, 1H), 1.84 (m, 1H), 0.88 (qq, ^2J = 9 Hz, ^3J = 2 Hz, 2H), 0.64 (qq, ^2J = 9 Hz, ^3J = 2 Hz, 2H). ^{13}C-NMR (300 MHz, $CDCl_3$) δ:153.3, 136.0, 127.0, 115.1, 14.6, 8.50. HRMS ($C_9H_{10}O + H^+$): calcd 135.0804, found 135.0800.



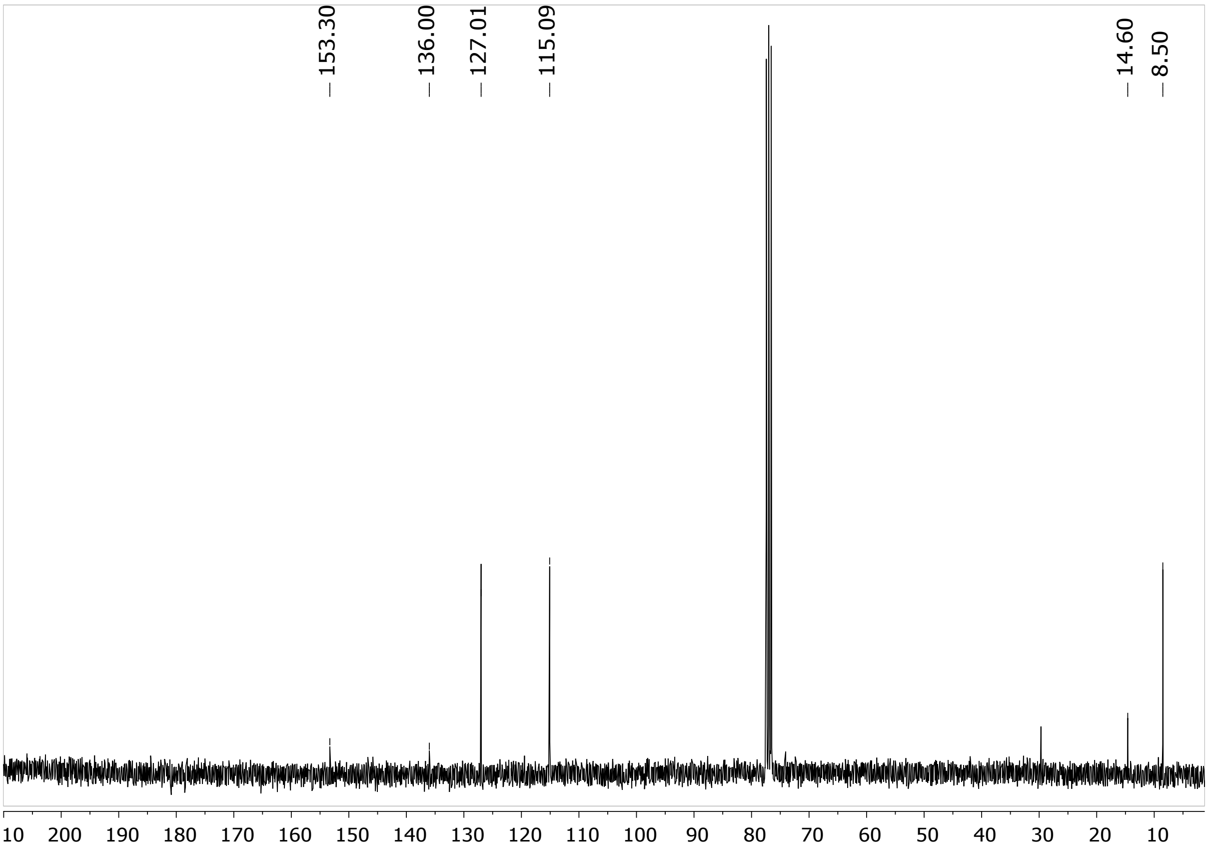
GC chromatogram of cyclopropylbenzene oxidation catalysed by **1**.



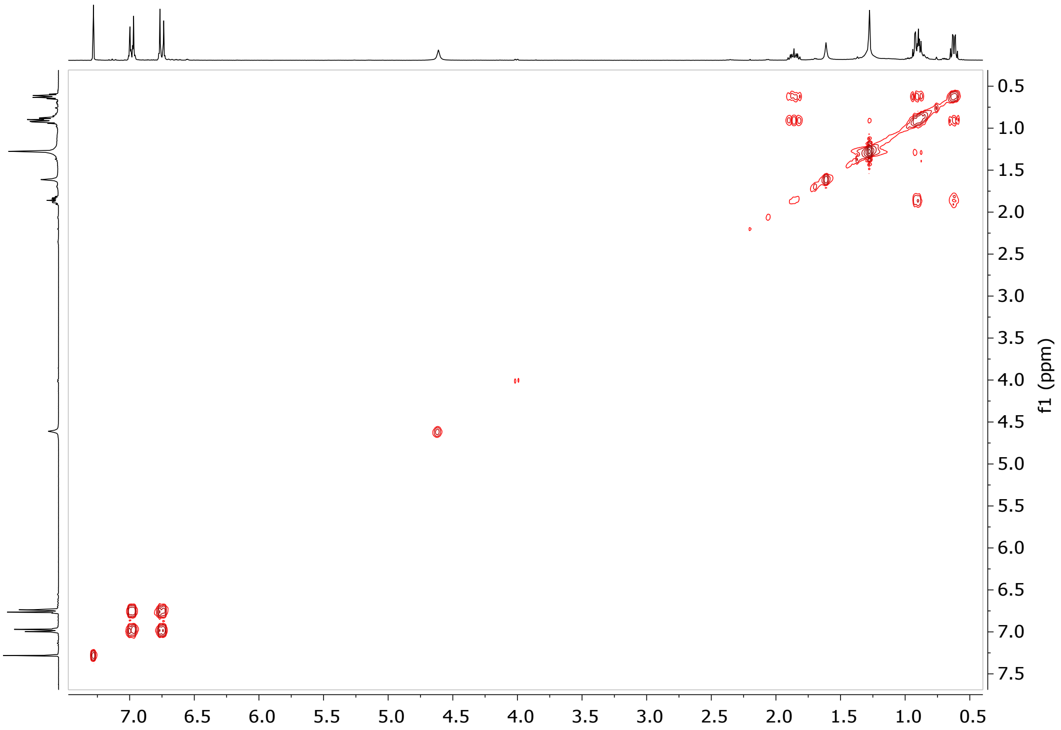
GC chromatogram of cyclopropylbenzene oxidation catalysed by $Fe(CF_3SO_3)_2(CH_3CN)_2$ (Fenton-type conditions)



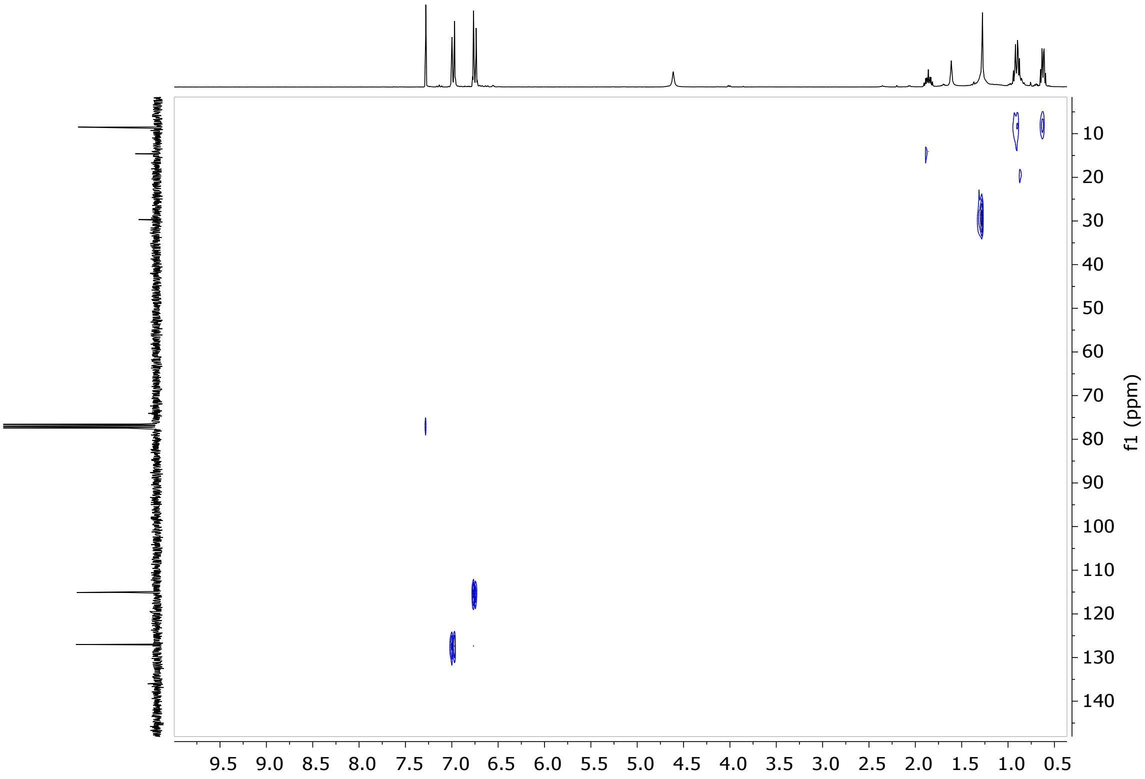
^{1}H-NMR of *para*-phenol



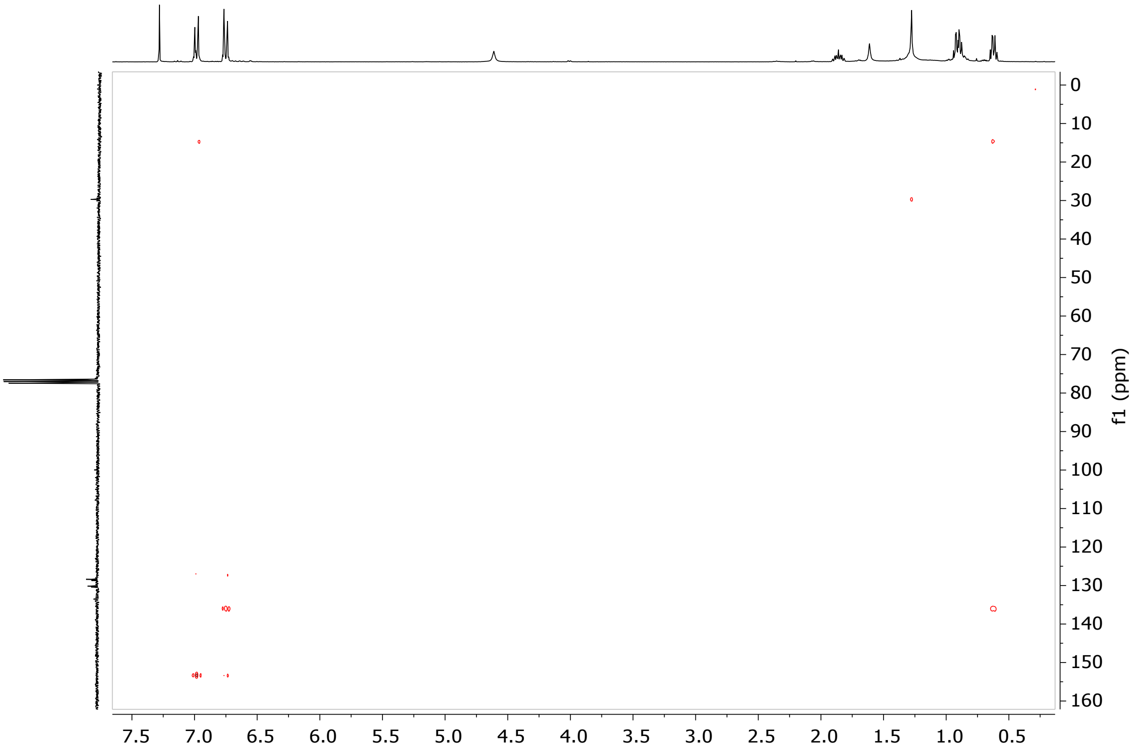
^{13}C-NMR of *para*-phenol



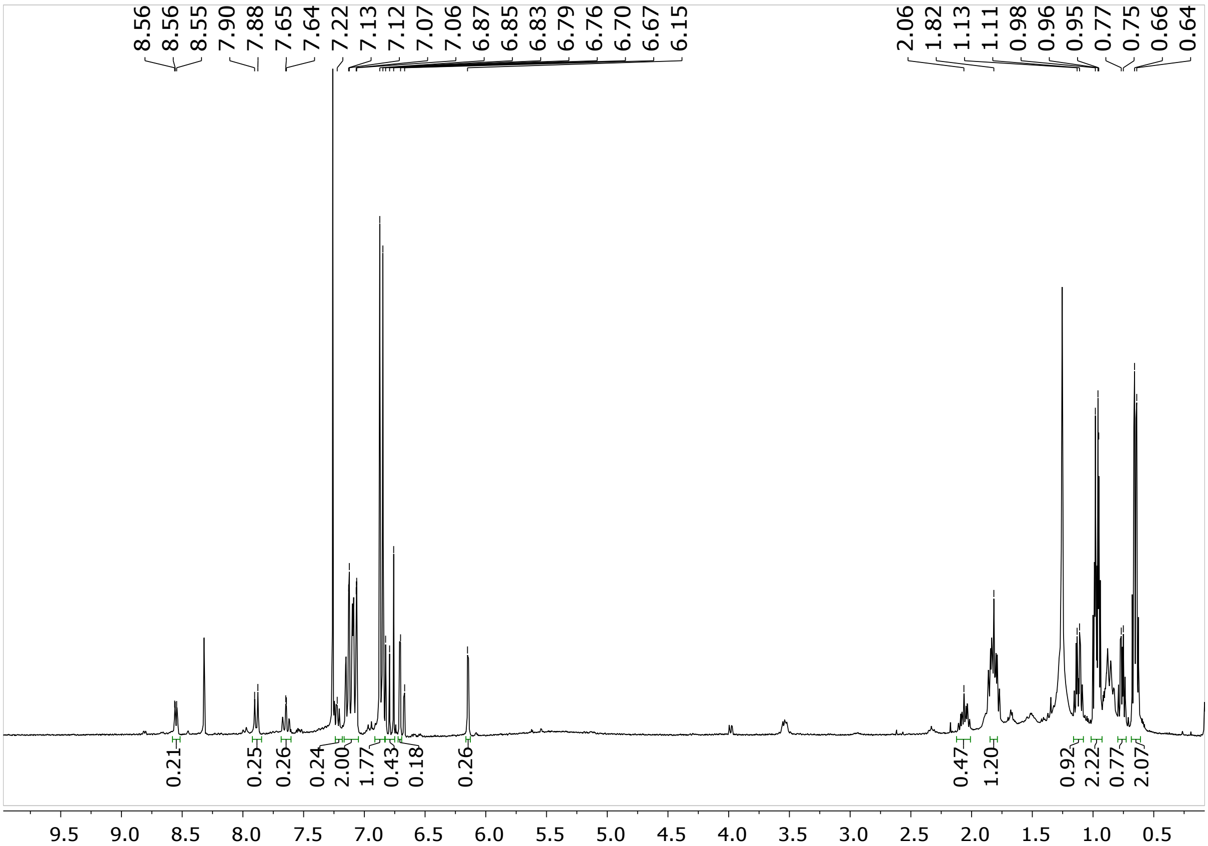
COSY of *para*-phenol



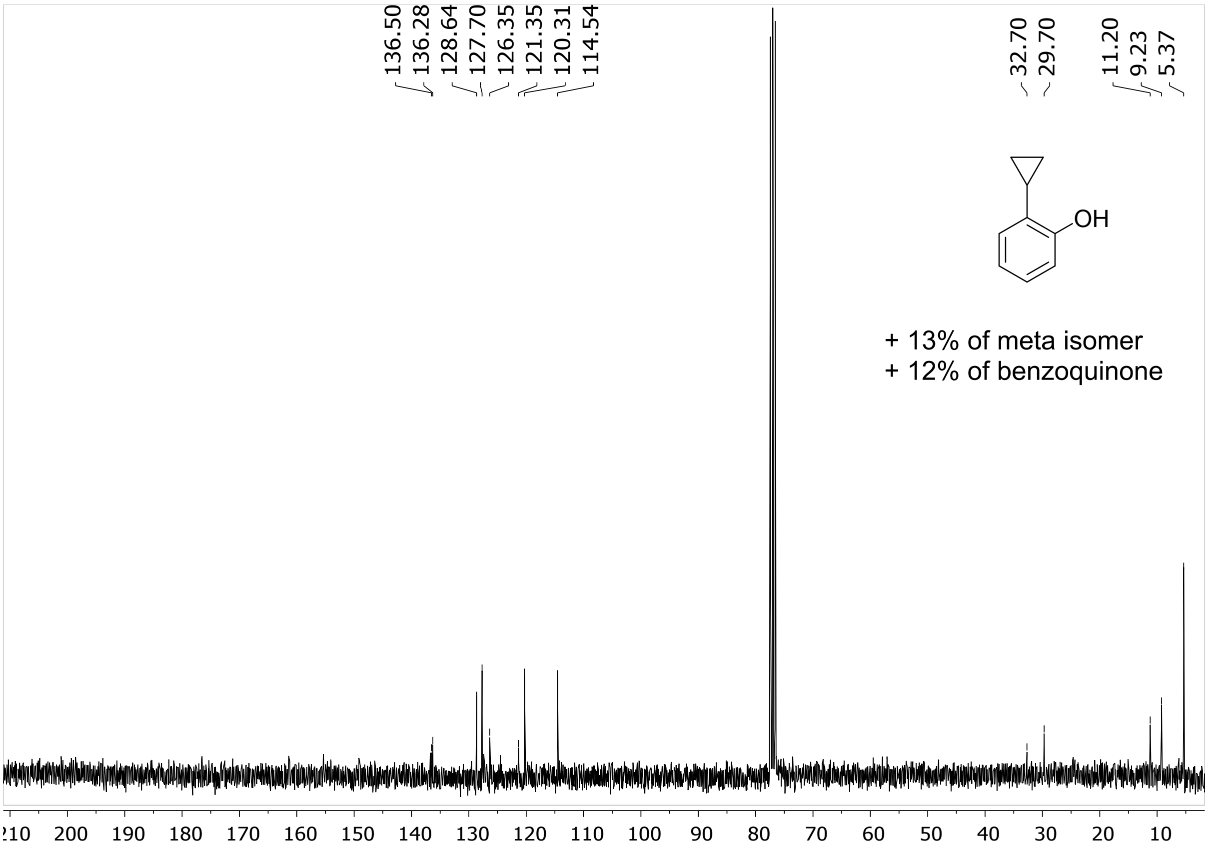
HSQC of *para*-phenol



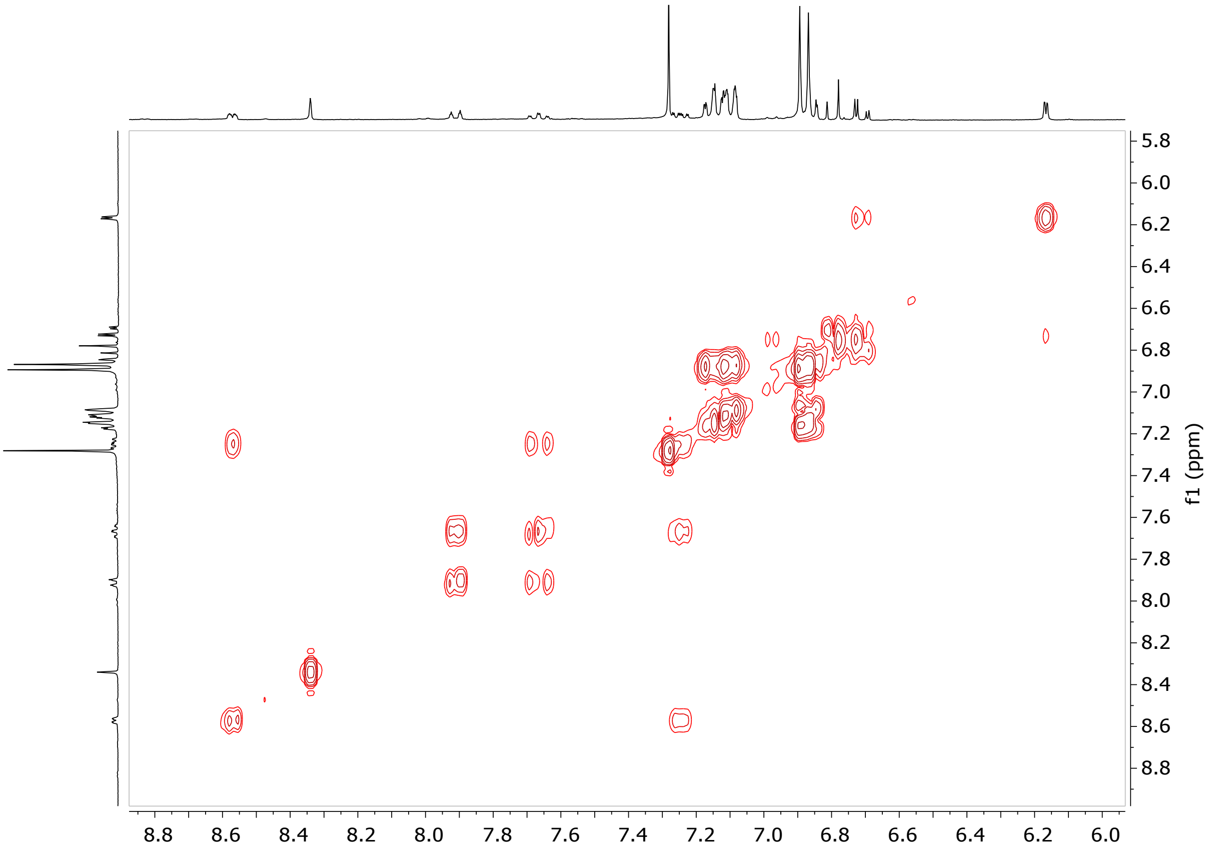
HMBC of *para*-phenol



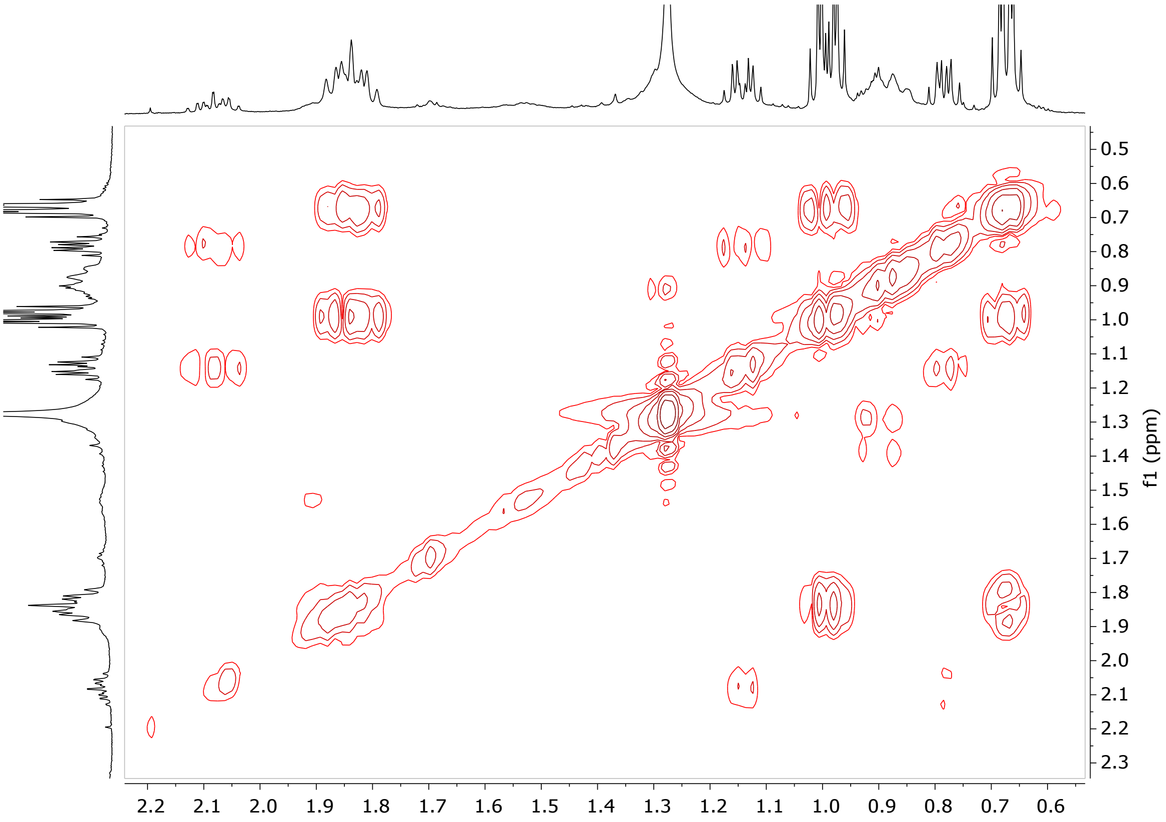
^{1}H-NMR of *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone



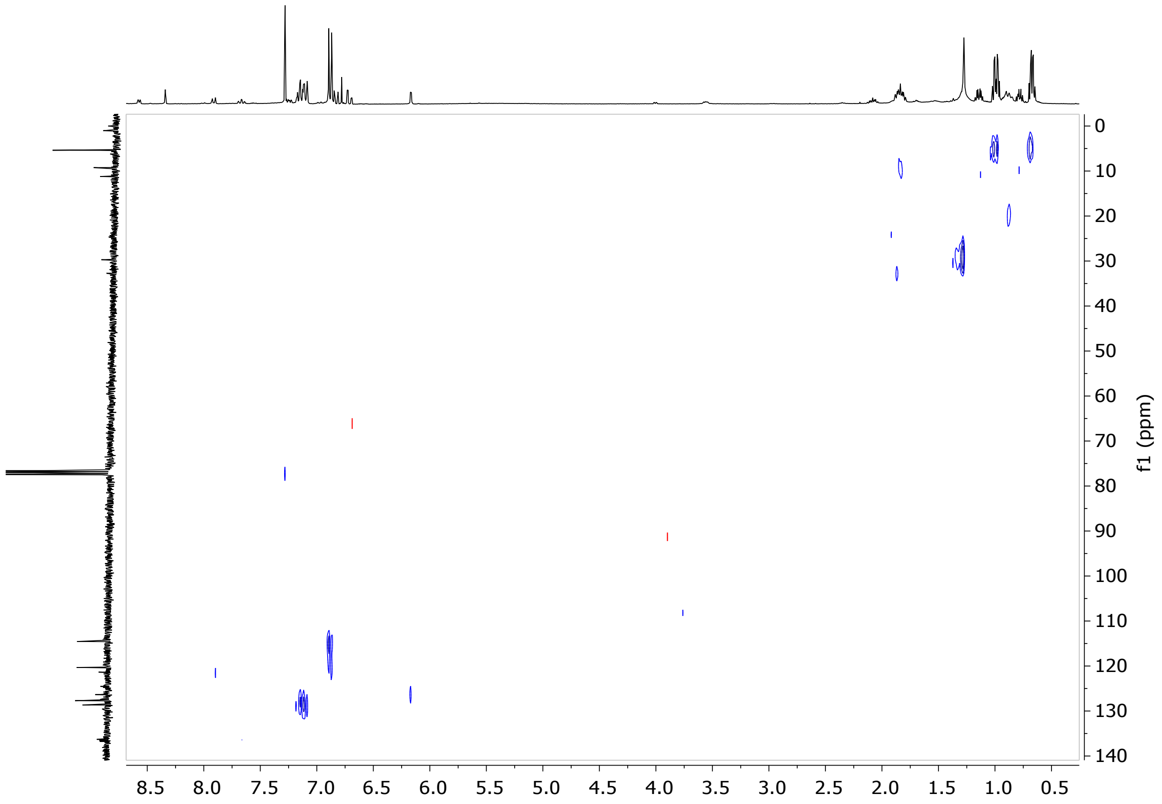
^{13}C-NMR of *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone



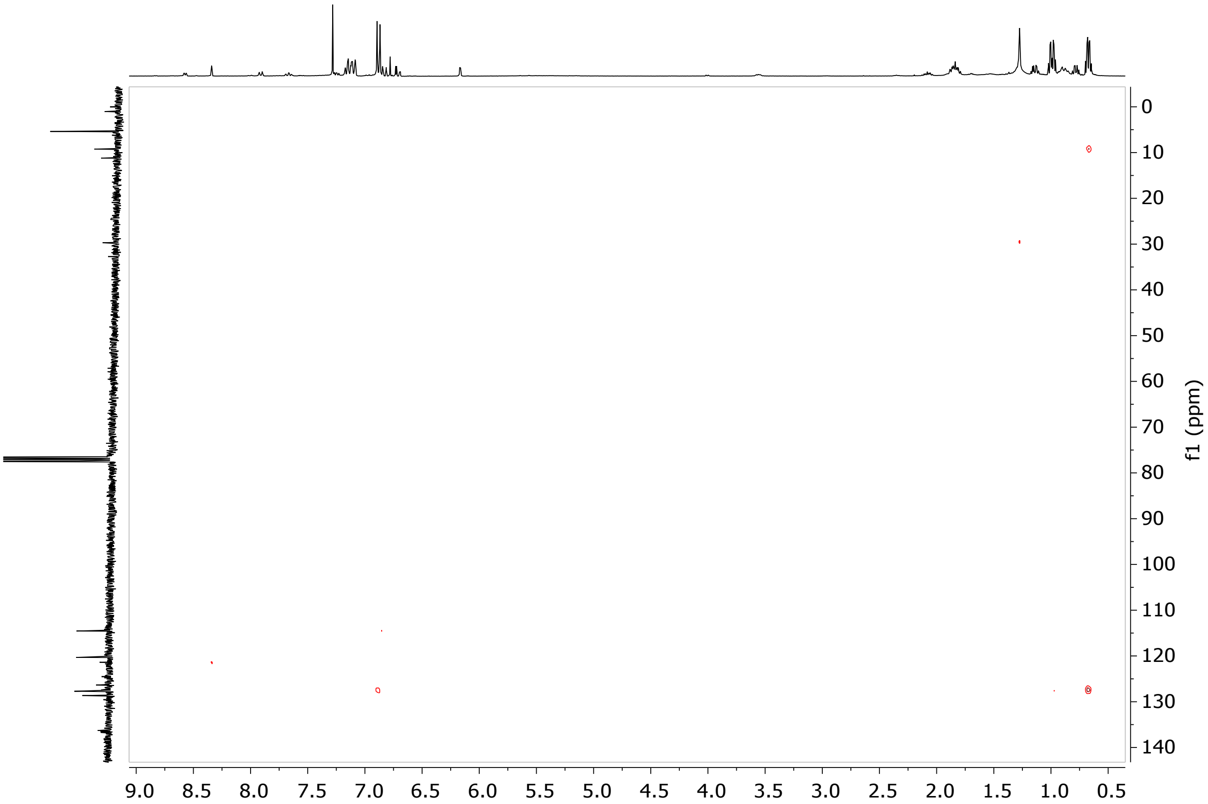
COSY of *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone (aromatic region)



COSY of *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone (aliphatic region)



HSQC of *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone (aromatic region)



HMBC of *ortho*-phenol and *meta*-phenol with traces of *p*-benzoquinone (aromatic region)