

Novel triarylimidazole redox catalysts: synthesis, electrochemical properties and applicability to electrooxidative C-H activation

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Table of contents for the supporting information

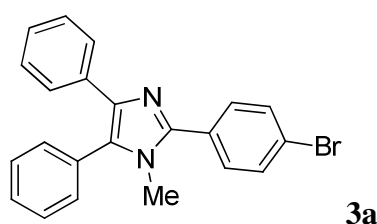
1. General information
2. General procedure for the synthesis of triarylimidazoles
3. Cyclic voltammetry measurement of redox catalyst **3** and substrates **4**, **6**
4. Typical CV of redox catalyst **3a** and its quasi-reversible first oxidation peak
5. Illustration of the first 5 cycles of the CV for **3a**
6. Synthesis of substrate benzyl ethers **6**
7. The general procedure for the preparative scale electrolysis of **4**
8. The general procedure for the preparative scale electrolysis of benzyl ethers
9. Photograph of preparative scale electrolysis
10. Spectra of redox catalyst **3b** and **3c**

1. General information

All solvents were of commercial quality and were dried and purified by conventional methods. Melting points (m.p.) were determined on XT4A Electrothermal apparatus equipped with a microscope and were uncorrected. Infrared spectra (IR) were recorded as thin films on KBr plates with a Bruker IR spectrophotometer and are expressed in ν (cm^{-1}). The ^1H NMR and ^{13}C NMR spectra were obtained using an AV 400 M Bruker spectrometer in solvent (CDCl_3 or $\text{DMSO}-d_6$) with TMS as internal reference. 4-Methoxybenzyl acetate¹ was synthesized as previously described and all spectroscopic data were consistent with those reported for this compound.

2. General procedure for the synthesis of triarylimidazoles.

A mixture of the benzil of choice (5 mmol), methylamine (5 mmol), aldehyde (5 mmol), ammonium acetate (5 mmol) and NaH_2PO_4 (1.5 mmol) was added to a thick-walled test-tube with a screw-on Teflon top. The reaction mixture was heated to $150\text{ }^\circ\text{C}$ and maintained at the temperature for 2-5 hours; the reaction mixture was stirred throughout. Then the reaction mixture was cooled to room temperature. Acetone was added to dissolve the mixture and the undissolved residue was removed by filtration. After evaporation of the solvent under reduced pressure, the resulting solid residue was recrystallized from acetone–water to obtain pure products **3**.

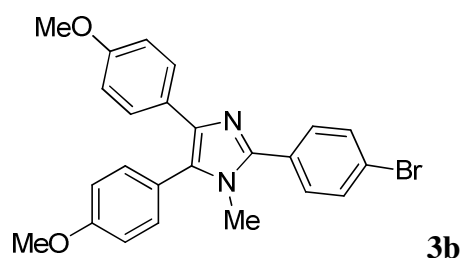


2-(4-Bromophenyl)-1-methyl-4,5-diphenyl-1H-imidazole (3a)² Yield: 92%; Yellow needle, m.p.: $201\text{--}202\text{ }^\circ\text{C}$; ^1H NMR (400 MHz, CDCl_3): δ 3.50 (s, 3H, CH_3), 7.16 (t, 1H, $J = 7.2\text{ Hz}$, Ar-H), 7.22 (t, 2H, $J = 7.2\text{ Hz}$, Ar-H), 7.39–7.41 (m, 2H, Ar-H), 7.45–7.48 (m, 3H, Ar-H), 7.52–7.54 (m, 2H, Ar-H), 7.63 (d, 2H, $J = 8.8\text{ Hz}$, Ar-H),

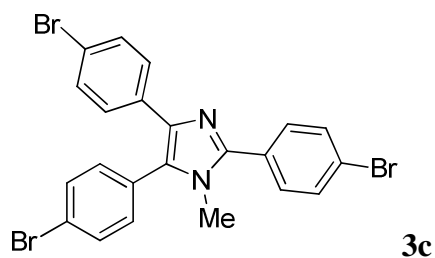
¹ (a) Ardeshtir, K.; Amin, R.; Fatemeh, M. *Chin. Chem. Lett.* **2010**, 21, 1430. (b) Hilborn, J. W.; MacKnight, E.; Pincock, J. A.; Wedge, P. J. *J. Am. Chem. Soc.* **1994**, 116, 3337.

² Alireza, E.; Abdolkarim, Z.; Mohsen, S.; Javad, A.R. *J. Comb. Chem.* **2010**, 12, 844.

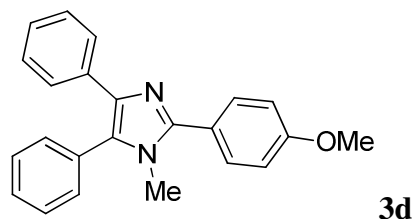
7.65 (d, 2H, $J = 8.8$ Hz, Ar-H).



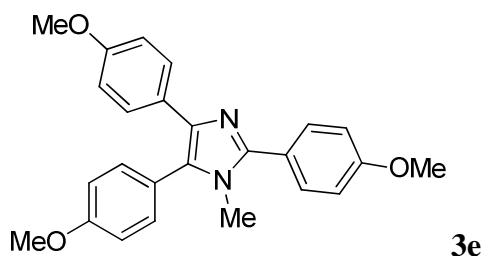
2-(4-Bromophenyl)-4,5-bis(4-methoxyphenyl)-1-methyl-1H-imidazole (3b) Yield: 87%; Yellow needle, m.p.: 169-171 °C; IR: 3430, 2949, 2831, 1614, 1464, 1105, 1010, 834; ^1H NMR (400 MHz, CDCl_3): δ 3.49 (s, 3H, CH_3), 3.77 (s, 3H, OCH_3), 3.88 (s, 3H, OCH_3), 6.78 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.00 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.30 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.48 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.62 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.65 (d, 2H, $J = 8.8$ Hz, Ar-H); ^{13}C NMR (100 MHz, CDCl_3): δ 33.1, 55.1, 55.3, 113.5, 114.5, 122.9, 123.1, 127.3, 128.0, 129.8, 130.0, 130.4, 131.8, 132.1, 137.6, 146.3, 158.2, 159.8. HRMS (+ESI/TOF) m/z calculated for $\text{C}_{24}\text{H}_{22}\text{N}_2\text{O}_2\text{Br}$ $[\text{M}+\text{H}]^+$ 449.0865; found 449.0850.



2,4,5-Tris(4-bromophenyl)-1-methyl-1H-imidazole (3c) Yield: 86%; Yellow needle, m.p.: 229-231 °C; IR: 3432, 2918, 1475, 1009, 834; ^1H NMR (400 MHz, $\text{DMSO}-d_6$): δ 3.49 (s, 3H, CH_3), 7.36 (d, 2H, $J = 8.4$ Hz, Ar-H), 7.42 (d, 2H, $J = 8.4$ Hz, Ar-H), 7.47 (d, 2H, $J = 8.4$ Hz, Ar-H), 7.75-7.76 (m, 6H, Ar-H); ^{13}C NMR (100 MHz, CDCl_3): δ 33.3, 120.6, 123.3, 123.4, 128.5, 129.4, 129.5, 129.8, 130.5, 131.4, 131.9, 132.3, 132.6, 133.1, 137.3, 147.3. HRMS (+ESI/TOF) m/z calculated for $\text{C}_{22}\text{H}_{16}\text{N}_2\text{Br}_3$ $[\text{M}+\text{H}]^+$ 544.8864; found 544.8845.



2-(4-Methoxyphenyl)-1-methyl-4,5-diphenyl-1H-imidazole (3d)³ Yield: 88%; White needle, m.p.: 166-167 °C; ¹H NMR (400 MHz, CDCl₃): δ 3.48 (s, 3H), 3.87 (s, 3H), 7.02 (d, J = 8.8 Hz, 2H), 7.14 (t, J = 7.2 Hz, 1H), 7.21 (t, J = 7.2 Hz, 2H), 7.40-7.42 (m, 2H), 7.44-7.48 (m, 3H), 7.54-7.56 (m, 2H), 7.68 (d, J = 8.8 Hz, 2H).



2,4,5-Tris(4-methoxyphenyl)-1-methyl-1H-imidazole (3e)⁴ Yield: 85%; White needle, m.p.: 116-118 °C; ¹H NMR (400 MHz, CDCl₃): δ 3.45 (s, 3H), 3.77 (s, 3H), 3.87 (s, 3H), 3.88 (s, 3H), 6.77 (d, J = 8.8 Hz, 2H), 6.99-7.02 (m, 4H), 7.31 (d, J = 8.8 Hz, 2H), 7.49 (d, J = 8.8 Hz, 2H), 7.66 (d, J = 8.8 Hz, 2H).

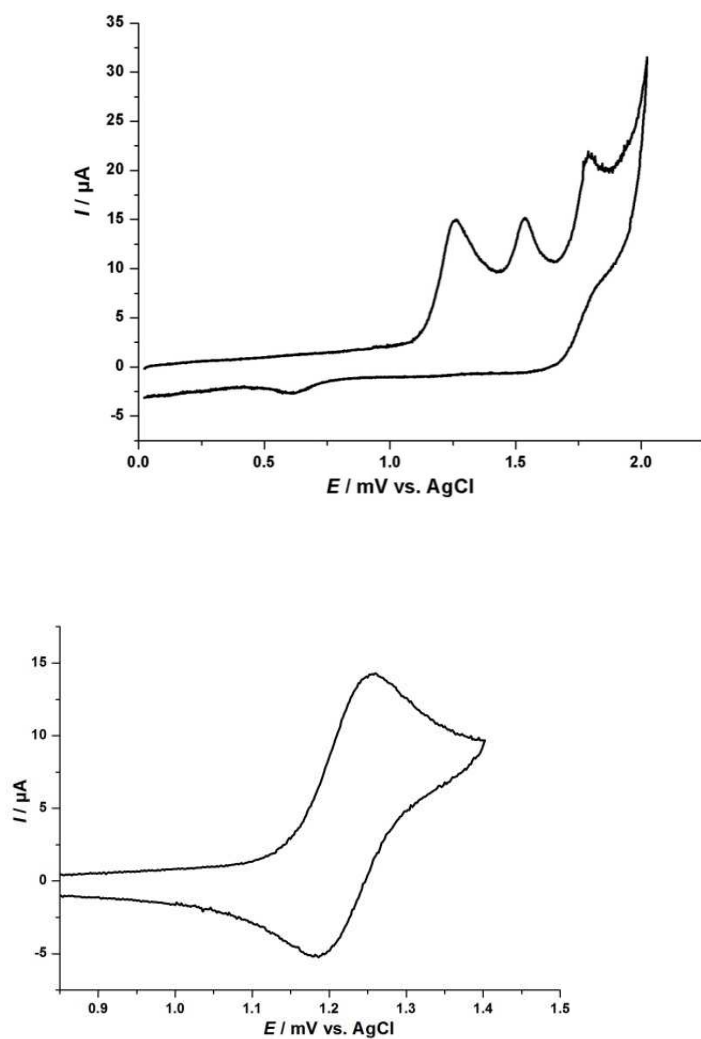
3. Cyclic voltammetry measurement of redox catalyst 3 and substrates 4 and 6

Cyclic voltammograms were measured using a 273A Potentiostat/Galvanostat (Princeton Applied Research) equipped with an electrochemical analysis software, using a conventional three-electrode cell. The working electrode was a glassy carbon disk electrode (ca. ϕ = 3 mm). The auxiliary and reference electrodes in these studies were Pt wire and Ag/AgCl (in 3 M KCl), respectively. LiClO₄ (0.2 mol L⁻¹) in mixed solution of acetonitrile and dichloromethane (V:V = 4:1) was used as supporting electrolyte system. The concentration of each triarylimidazole was 1 mmol L⁻¹.

³ Zoltan, M.; Csaba, H.; Jozsef, N.; Jeno, F.; Maria, K. P.; Jozsef, N. *ACH - Models Chem.* **1999**, 136, 393.

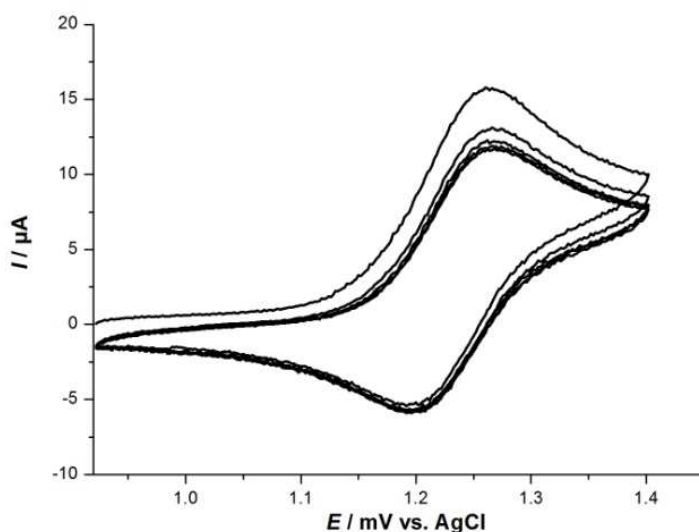
⁴ Fumitoshi, S.; Eiji, Y.; Toshiaki, M. *J. Org. Chem.* **2011**, 76, 2680.

4. Typical CV of redox catalyst 3a and its quasi-reversible first oxidation peak



Conditions: Glassy carbon working electrode, platinum wire counter, and Ag/AgCl reference electrodes, in 0.2 M of $\text{LiClO}_4/\text{CH}_3\text{CN}/\text{CH}_2\text{Cl}_2$, scan rate: 0.1 V/s.

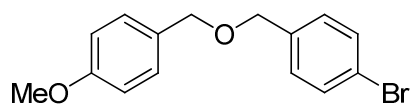
5. 20 cyclic scans of 3a (the first 5 cycles are illustrated)



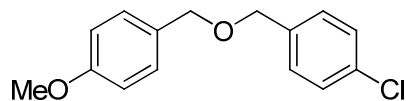
Condition: Glassy carbon working electrode, platinum wire counter, and Ag/AgCl reference electrodes, in 0.2 M of LiClO₄/ CH₃CN/CH₂Cl₂, scan rate: 0.1 V/s.

6. Synthesis of substrate benzyl ethers

The synthesis of each benzyl ether follows a known procedure.⁵



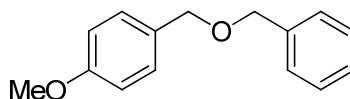
1-Bromo-4-((4-methoxybenzyloxy)methyl)benzene (5a)⁶ White solid, m.p.: 32-33 °C; ¹H NMR (400 MHz, CDCl₃): δ 3.81 (s, 3H, OCH₃), 4.47 (s, 2H, OCH₂), 4.48 (s, 2H, OCH₂), 6.89 (d, 2H, J = 8.8 Hz, Ar-H), 7.23 (d, 2H, J = 8.0 Hz, Ar-H), 7.28 (d, 2H, J = 8.8 Hz, Ar-H), 7.70 (d, 2H, J = 8.0 Hz, Ar-H).



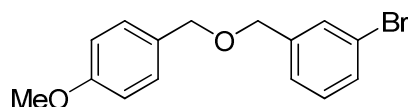
⁵ Chakraborti, A. K.; Chankeshwara, S. V. *J. Org. Chem.* **2009**, 74, 1367.

⁶ Donde, Y.; Nguyen, J. H. PCT Int. Appl., 2006063179, 15 Jun 2006.

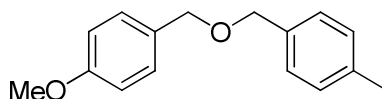
1-Chloro-4-((4-methoxybenzyloxy)methyl)benzene (5b)⁷ Yellow oil, ¹H NMR (400 MHz, CDCl₃): δ 3.79 (s, 3H, OCH₃), 4.47 (s, 2H, OCH₂), 4.48 (s, 2H, OCH₂), 6.88 (d, 2H, *J* = 8.8 Hz, Ar-H), 7.13-7.32 (m, 6H, Ar-H).



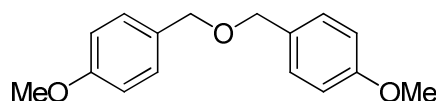
1-(Benzyloxymethyl)-4-methoxybenzene (5c)⁸ Yellow oil, ¹H NMR (400 MHz, CDCl₃): δ 3.81 (s, 3H, OCH₃), 4.49 (s, 2H, OCH₂), 4.53 (s, 2H, OCH₂), 6.89 (d, 2H, *J* = 8.4 Hz, Ar-H), 7.28-7.30 (m, 3H, Ar-H) 7.35-7.36 (m, 4H, Ar-H).



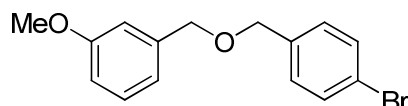
1-Bromo-3-((4-methoxybenzyloxy)methyl)benzene (5d) (CAS No.: 1274038-52-6) Yellow oil, ¹H NMR (400 MHz, CDCl₃): δ 3.82 (s, 3H, OCH₃), 4.49 (s, 2H, OCH₂), 4.50 (s, 2H, OCH₂), 6.90 (d, 2H, *J* = 8.4 Hz, Ar-H), 7.21 (t, 1H, *J* = 7.6 Hz, Ar-H), 7.29 (d, 2H, *J* = 8.4 Hz, Ar-H) 7.41 (d, 1H, *J* = 8.0 Hz, Ar-H), 7.52 (s, 1H, Ar-H).



1-Methoxy-4-((4-methylbenzyloxy)methyl)benzene (5e)⁷ (CAS No.: 7500-74-5) Yellow oil, ¹H NMR (400 MHz, CDCl₃): δ 2.38 (s, 3H, CH₃), 3.84 (s, 3H, OCH₃), 4.50 (s, 2H, OCH₂), 4.52 (s, 2H, OCH₂), 6.92 (d, 2H, *J* = 8.8 Hz, Ar-H), 7.19 (d, 2H, *J* = 7.6 Hz, Ar-H), 7.27-7.33 (m, 4H, Ar-H).



4,4'-Oxybis(methylene)bis(methoxybenzene) (5f)⁸ White solid, m.p.: 37-38 °C; ¹H NMR (400 MHz, CDCl₃): δ 3.81 (s, 6H, OCH₃), 4.46 (s, 4H, OCH₂), 6.89 (d, 4H, *J* = 8.4 Hz, Ar-H), 7.29 (d, 4H, *J* = 8.0 Hz, Ar-H)

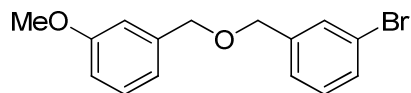


1-((4-Bromobenzyloxy)methyl)-3-methoxybenzene (5g) (CAS No.: 1275106-87-0)

⁷ Pratt, E. F.; Erickson, P. W. *J. Am. Chem. Soc.* **1956**, 78, 76.

⁸ Molander, G. A.; Canturk, B. *Org. Lett.* **2008**, 10, 2135.

Yellow oil, ^1H NMR (400 MHz, CDCl_3): δ 3.81 (s, 3H, OCH_3), 4.50 (s, 2H, OCH_2), 4.53 (s, 2H, OCH_2), 6.83-6.94 (m, 3H, Ar-H), , 7.23-7.29 (m, 3H, Ar-H), 7.47-7.49 (m, 2H, Ar-H).



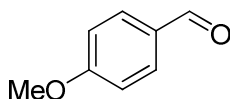
1-Bromo-3-((3-methoxybenzyloxy)methyl)benzene (5h) (CAS No.: 1274037-93-2)

Yellow oil, ^1H NMR (400 MHz, CDCl_3): δ 3.81 (s, 3H, OCH_3), 4.51 (s, 2H, OCH_2), 4.54 (s, 2H, OCH_2), 6.84-7.53 (m, 8H, Ar-H)

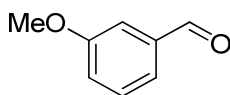
7. The general procedure for the preparative scale electrolysis of **4**

The preparative scale electrolytic setup consists of a 100 mL H-type cell equipped with a medium glass frit as a membrane. The anode compartment is fitted with a platinum mesh (2×3 cm) as the anode and a polished silver wire as the quasi-reference electrode, immersed in electrolyte solution in a glass cylinder with a fine glass frit at its end. A platinum plate (1×2 cm) served as the counter electrode and resides in the cathode compartment.

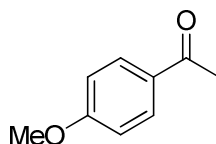
To the anode and cathode compartments of the H-type cell was added, respectively, 30 mL and 10 mL of 0.2 M LiClO_4 supporting electrolyte in $\text{CH}_3\text{CN}/\text{CH}_2\text{Cl}_2$ (V:V = 4:1) mixed solution. Then redox catalyst **3a** (0.1 mmol), substrate **4** (1 mmol) and 2,6-lutidine (5 mmol) were added to the anode compartment and electrolysis was performed at potential 1.26 V (vs. Ag/AgCl , 1.06 V vs Ag wire) controlled by the 273A Potentiostat/Galvanostat. During electrolysis, the mixture was stirred using a magnetic stirrer. The electrolysis was terminated when the current decreased to less than 1 mA. After electrolysis, the anolyte solution was removed under reduced pressure. The residue was dissolved in ethyl acetate and washed twice with water (2×20 mL). The organic layer was dried over MgSO_4 . Pure product was isolated by flash chromatography eluted with a mixture of ethyl acetate and petroleum ether.



4-Methoxybenzaldehyde⁹ Clear oil, ¹H NMR (400 MHz, CDCl₃): δ 3.89 (s, 3H, OCH₃), 7.01 (d, 2H, J = 8.8 Hz, Ar-H), 7.85 (d, 2H, J = 8.8 Hz, Ar-H), 9.89 (s, 1H, CHO).



3-Methoxybenzaldehyde⁹ Clear oil, ¹H NMR (400 MHz, CDCl₃): δ 3.88 (s, 3H, OCH₃), 7.18-7.56 (m, 4H), 10.00 (s, 1H, CHO).



1-(4-Methoxyphenyl)ethanone¹⁰ Clear oil, ¹H NMR (400 MHz, CDCl₃): δ 2.56 (s, 3H, CH₃), 3.87 (s, 3H, OCH₃), 6.93 (d, 2H, J = 8.8 Hz, Ar-H), 7.94 (d, 2H, J = 8.8 Hz, Ar-H).

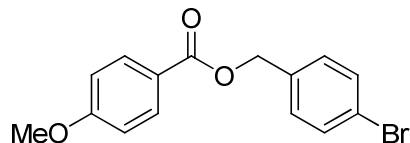
8. The general procedure for the preparative scale of electrolysis of benzyl ethers

To the anode and cathode compartments of the H-type cell was added, respectively, 30 mL and 10 mL of 0.2 M LiClO₄ supporting electrolyte in moist (0.1 mL of water was added to the anode compartment) CH₃CN/CH₂Cl₂ (V:V = 4:1) mixed solution. Then redox catalyst **3a** (0.1 mmol), benzyl ether **6** (1 mmol) and 2,6-lutidine (5 mmol) were added to the anode compartment and electrolysis was performed at potential 1.26 V (vs. Ag/AgCl, 1.06 V vs Ag wire) controlled by the 273A Potentiostat/Galvanostat. During the electrolysis, a magnetic stirrer was used. The electrolysis was terminated when the current decreased to less than 1 mA. After electrolysis, the anolyte solution was removed under reduced pressure. The residue was dissolved in ethyl acetate and washed twice with water (2×20 mL). The organic

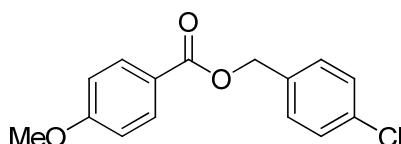
⁹ Miao, C. X.; He, L. N.; Wang, J. L.; Wu, F. *J. Org. Chem.* **2010**, 75, 257.

¹⁰ Liu, Y.; Yao, B.; Deng, C. L.; Tang, R. Y.; Zhang, X. G.; Li, J. H. *Org. Lett.* **2011**, 13, 2184.

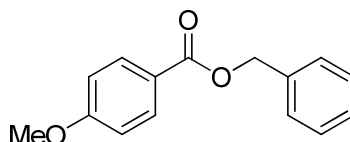
layer was dried over MgSO_4 . Pure product was isolated by flash chromatography eluted with a mixture of ethyl acetate and petroleum ether.



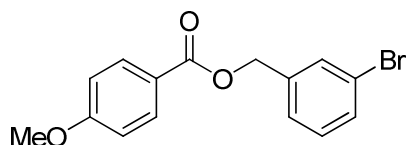
4-Bromobenzyl 4-methoxybenzoate (6a)¹¹ (CAS No.: 108939-27-1) White crystal, m.p.: 88-89 °C; ^1H NMR (400 MHz, CDCl_3): δ 3.86 (s, 3H, OCH_3), 5.28 (s, 2H, OCH_2), 6.92 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.31 (d, 2H, $J = 8.0$ Hz, Ar-H), 7.51 (d, 2H, $J = 8.0$ Hz, Ar-H), 8.01 (d, 2H, $J = 8.8$ Hz, Ar-H); ^{13}C NMR (100 MHz, CDCl_3): δ 55.5, 65.6, 113.7, 122.3, 128.9, 129.8, 130.9, 131.7, 135.3, 163.6, 166.1.



4-Chlorobenzyl 4-methoxybenzoate (6b)¹² White crystal, m.p.: 78-79 °C; ^1H NMR (400 MHz, CDCl_3): δ 3.86 (s, 3H, OCH_3), 5.29 (s, 2H, OCH_2), 6.92 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.34-7.39 (m, 4H, Ar-H), 8.02 (d, 2H, $J = 8.8$ Hz, Ar-H); ^{13}C NMR (100 MHz, CDCl_3): δ 55.5, 65.6, 113.6, 122.3, 128.7, 129.4, 131.7, 134.0, 134.8, 163.5, 166.0.



Benzyl 4-methoxybenzoate (6c)¹² Clear oil, ^1H NMR (400 MHz, CDCl_3): δ 3.86 (s, 3H, OCH_3), 5.34 (s, 2H, OCH_2), 6.91 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.34-7.45 (m, 5H, Ar-H), 8.04 (d, 2H, $J = 8.8$ Hz, Ar-H).

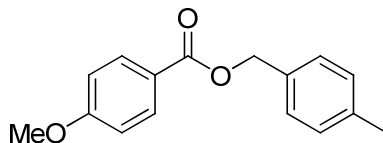


3-Bromobenzyl 4-methoxybenzoate (6d) (CAS No.: 671803-63-7) Clear oil, ^1H NMR (400 MHz, CDCl_3): δ 3.87 (s, 3H, OCH_3), 5.30 (s, 2H, OCH_2), 6.94 (d, 2H, $J = 8.8$ Hz, Ar-H), 7.24-7.71 (m, 4H, Ar-H), 8.04 (d, 2H, $J = 8.8$ Hz, Ar-H); ^{13}C NMR

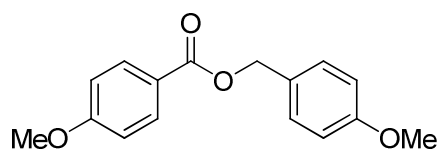
¹¹ Fiekers, B. A.; Di Geronimo, E. M. *J. Am. Chem. Soc.* **1948**, 70, 1654.

¹² Yamashita, M.; Ohishi, T. *Appl. Organomet. Chem.* **1993**, 7, 357.

(100 MHz, CDCl₃): δ 55.5, 65.6, 113.7, 122.2, 122.6, 126.6, 130.2, 131.0, 131.2, 131.8, 138.6, 163.6, 166.0.

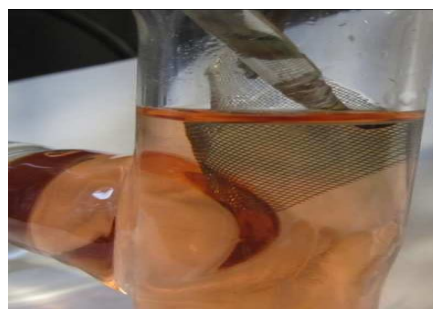
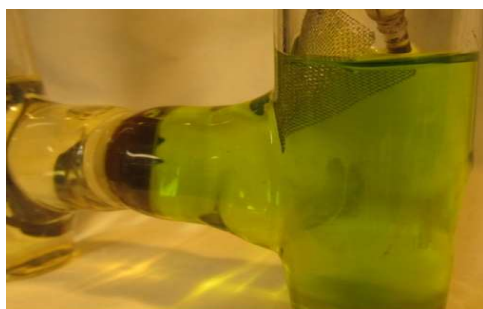


4-Methylbenzyl 4-methoxybenzoate (6e)¹³ Clear oil, ¹H NMR (400 MHz, CDCl₃): δ 2.35 (s, 3H, CH₃), 3.85 (s, 3H, OCH₃), 5.29 (s, 2H, OCH₂), 6.90 (d, 2H, J = 8.8 Hz, Ar-H), 7.19 (d, 2H, J = 8.0 Hz, Ar-H), 7.34 (d, 2H, J = 8.0 Hz, Ar-H), 8.02 (d, 2H, J = 8.8 Hz, Ar-H).



4-Methoxybenzyl 4-methoxybenzoate (6f)¹² Clear oil, ¹H NMR (400 MHz, CDCl₃): δ 3.82 (s, 3H, OCH₃), 3.85 (s, 3H, OCH₃), 5.27 (s, 2H, OCH₂), 6.88-6.92 (m, 4H, Ar-H), 7.38 (d, 2H, J = 8.4 Hz, Ar-H), 8.01 (d, 2H, J = 8.8 Hz, Ar-H).

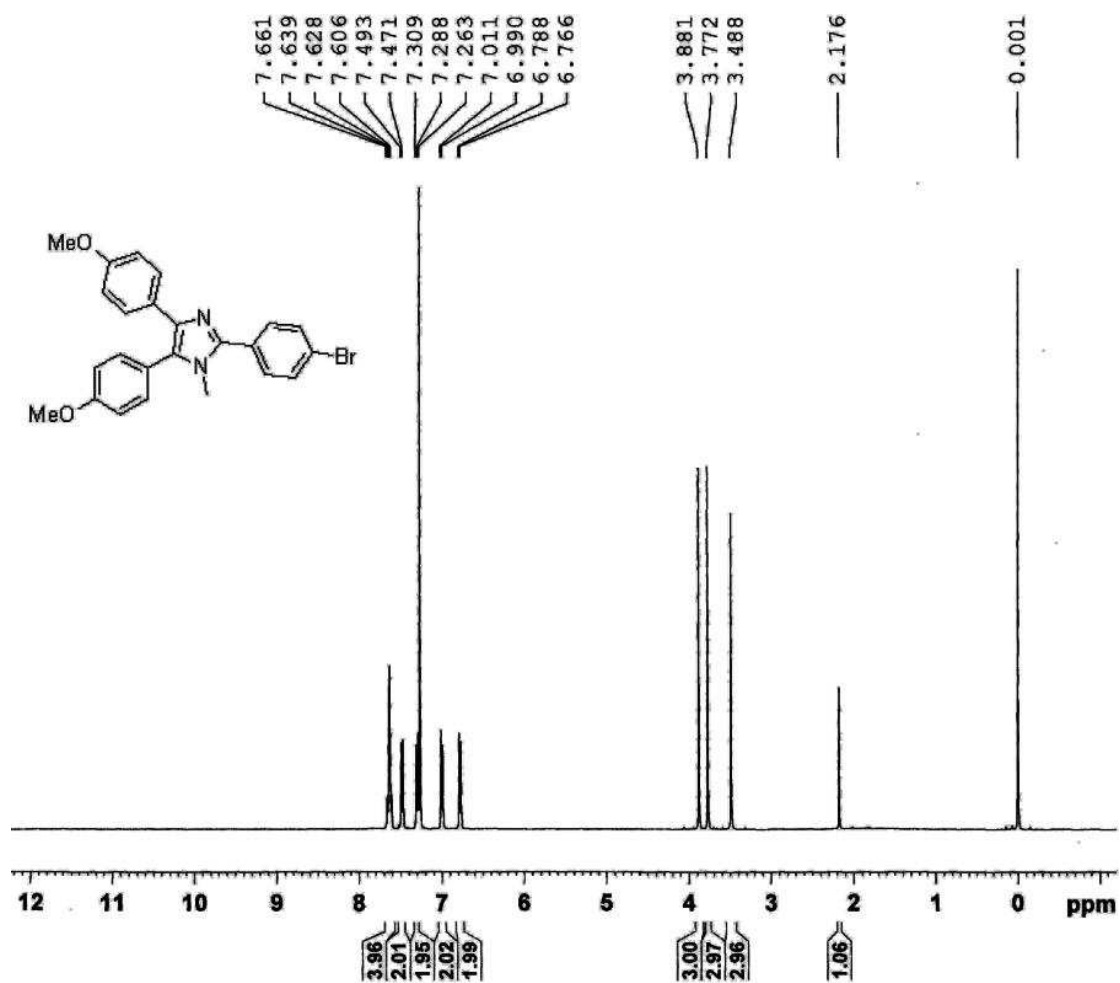
9. Photographs of preparative scale electrolysis



Electrolysis of a mixture of mediator **3a** (0.1 mmol) and lutidine (5 mmol) before (left photo) and after (right photo) an addition of substrate **4a** (1 mmol)

10. Spectra of redox catalyst **3b** and **3c**

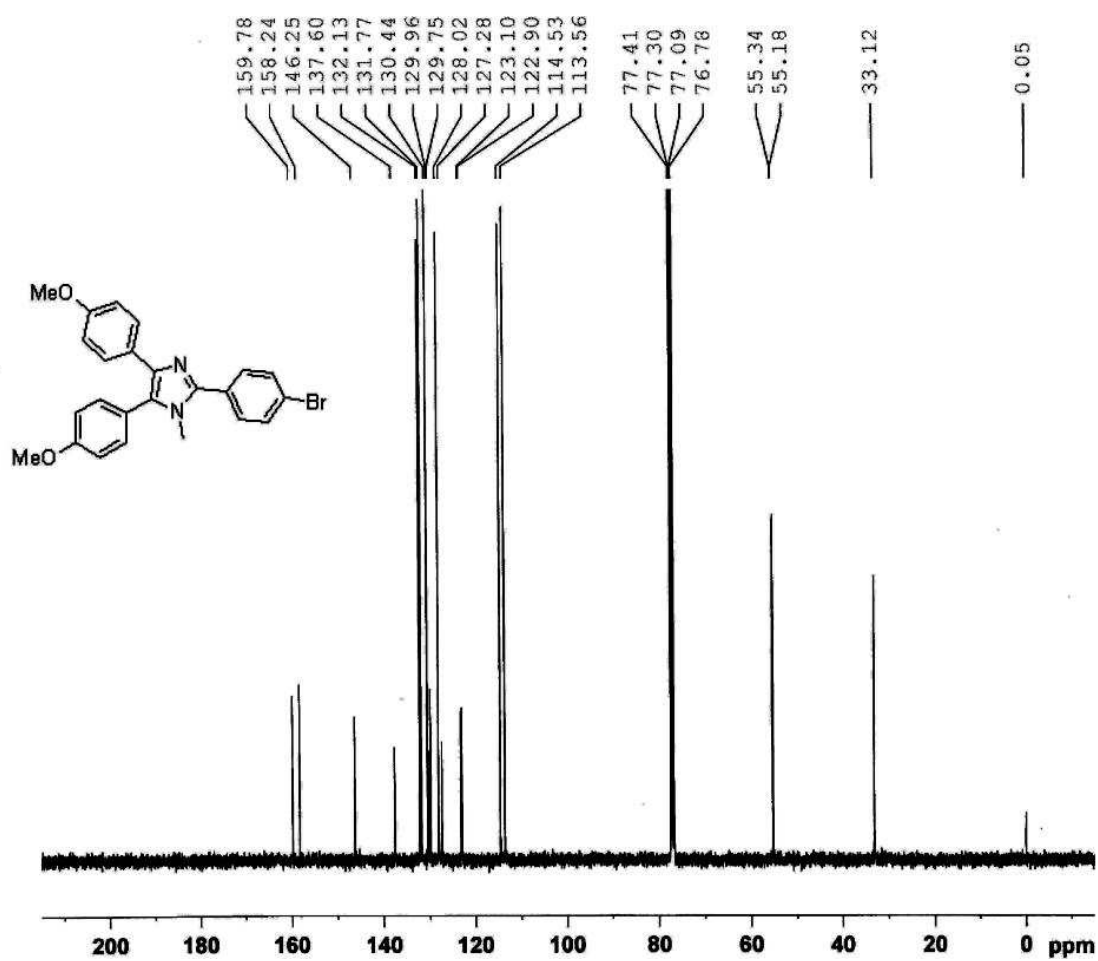
¹³ Corey, E. J.; Lazerwith, S. E. *J. Am. Chem. Soc.* **1998**, *120*, 12777.



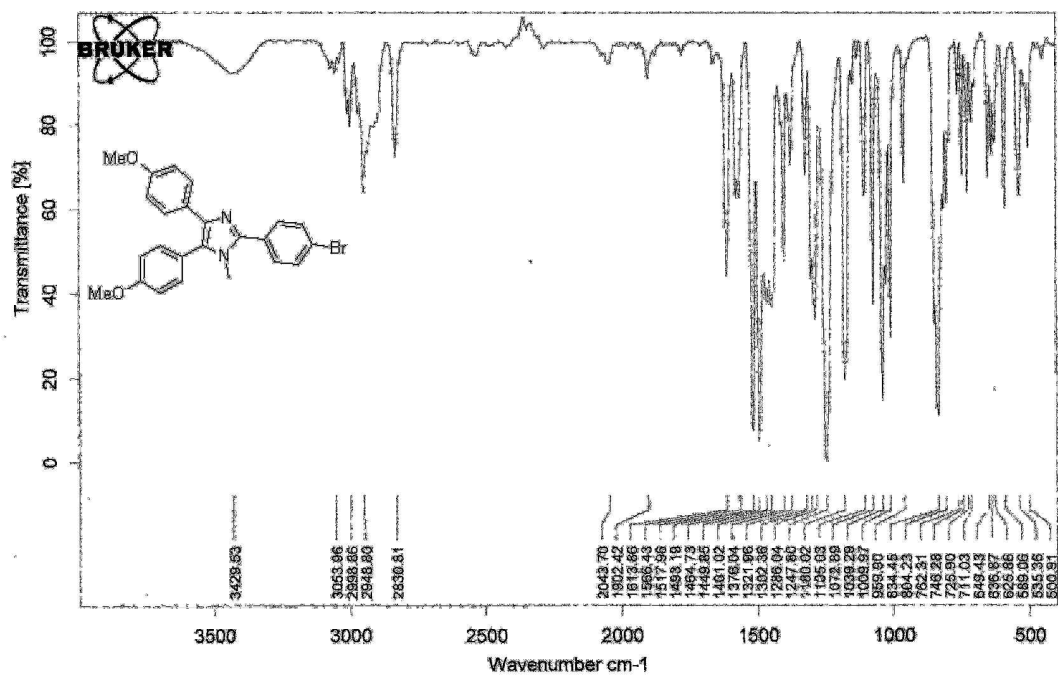
¹H NMR of redox catalyst **3b** (peak at ~2.1 is acetone; it was used in recrystallization)

HRMS (+ESI/TOF) m/z calculated for C₂₄H₂₂N₂O₂Br [M+H]⁺ 449.0865;

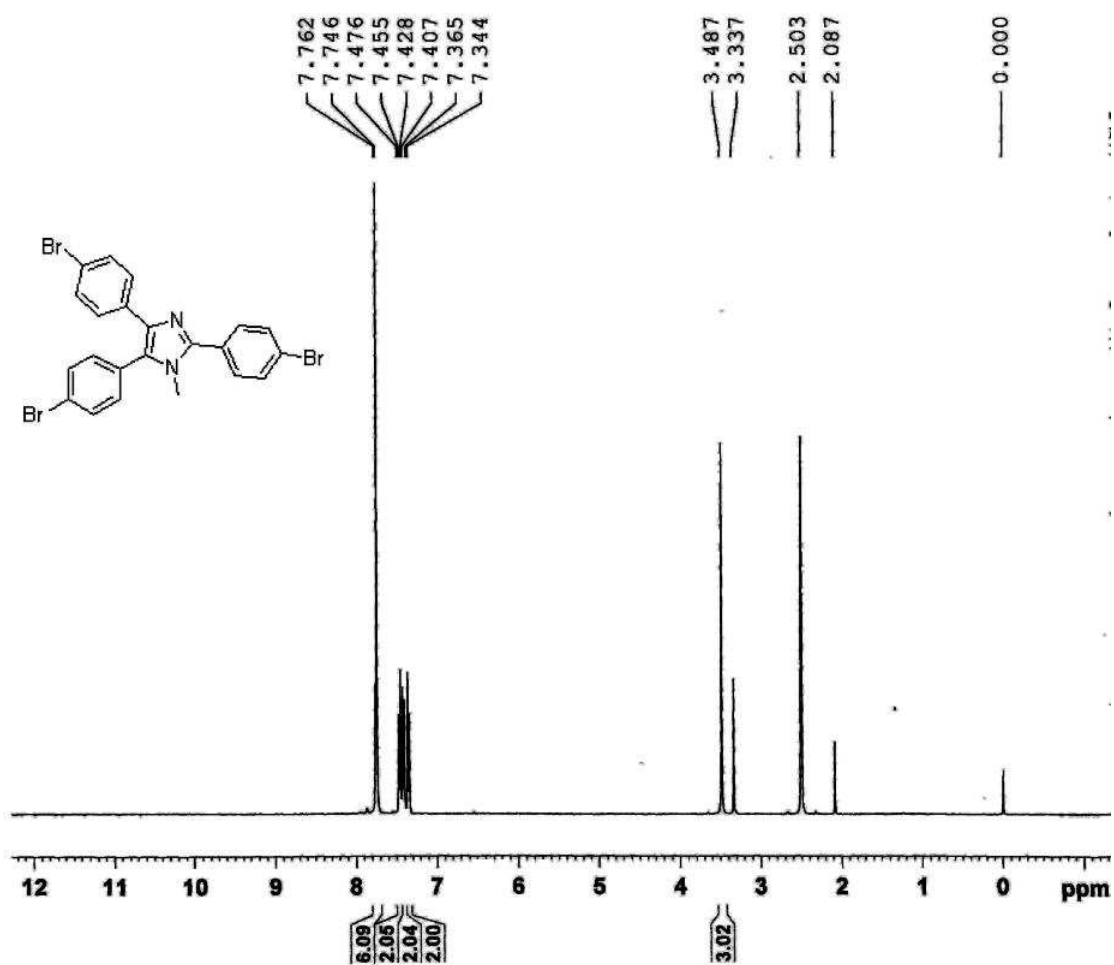
found 449.0850.



¹³C NMR of redox catalyst **3b**

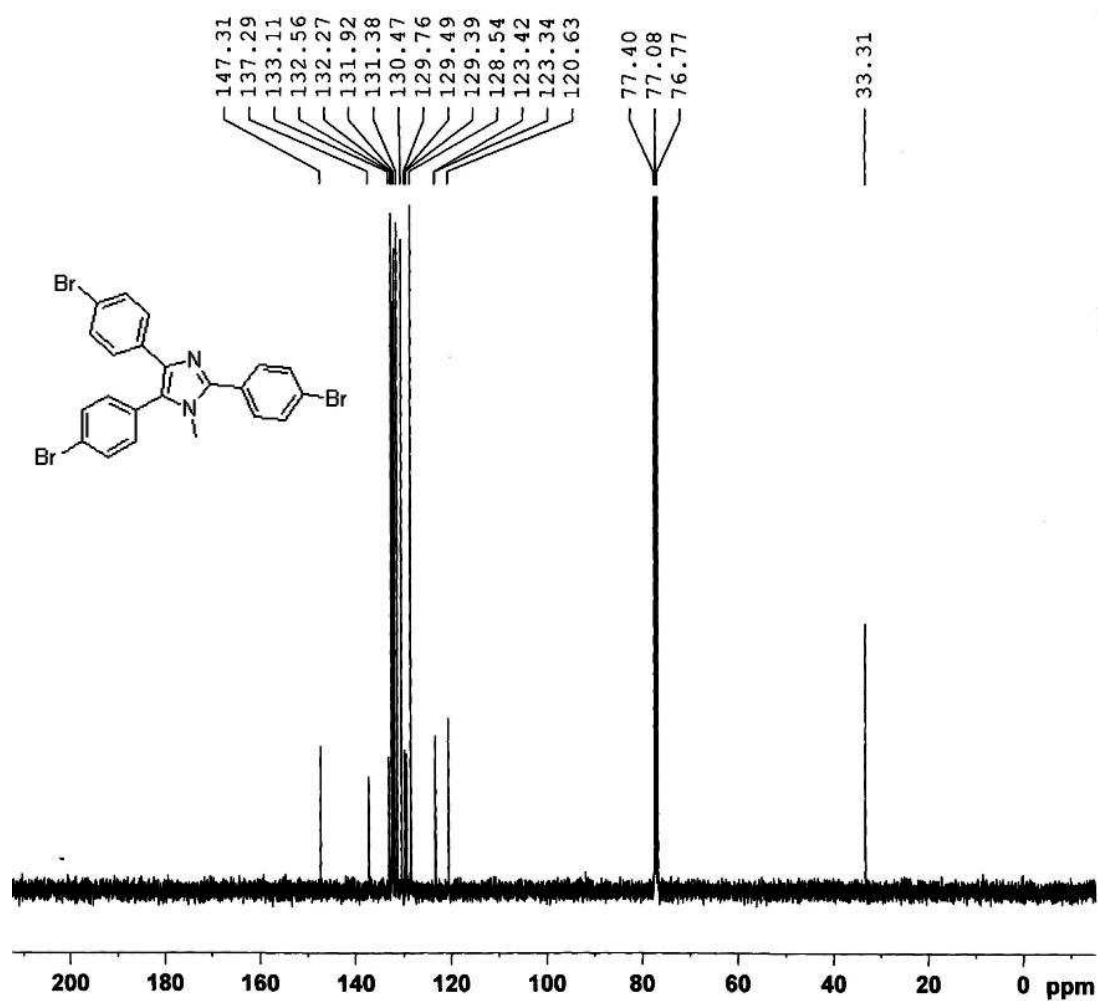


IR of redox catalyst **3b**

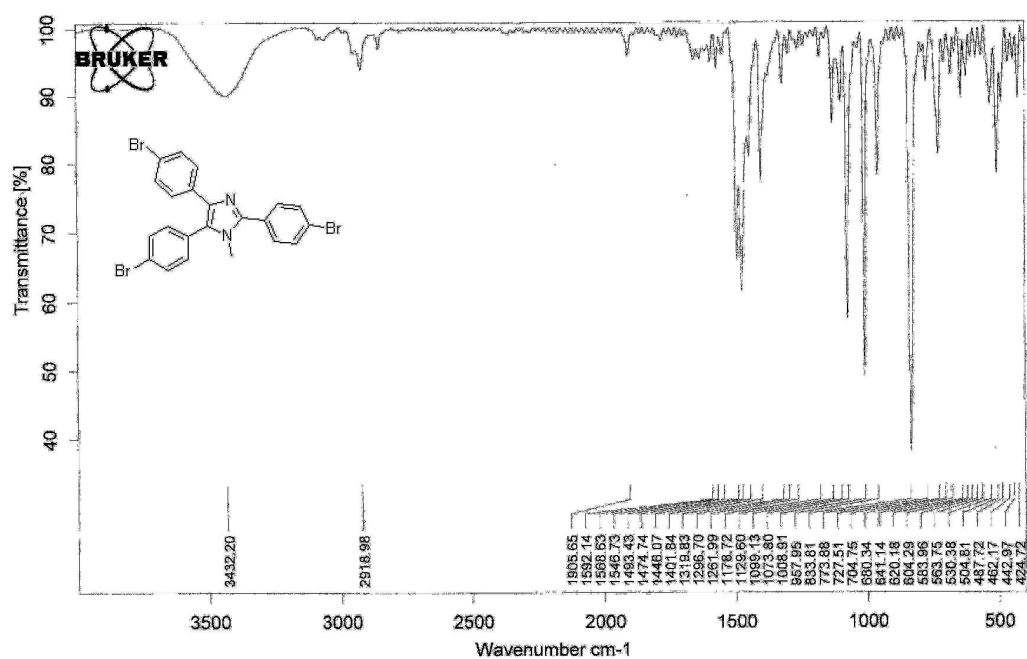


¹H NMR of redox catalyst **3c** (peak at ~2.1 is acetone, ~ 2.5 corresponds to incompletely deuterated DMSO-d₆, ~3.3 to water in the DMSO-d₆)

HRMS (+ESI/TOF) m/z calculated for C₂₂H₁₆N₂Br₃ [M+H]⁺ 544.8864; found 544.8845.



¹³C NMR of redox catalyst **3c**



IR of redox catalyst **3c**