Electronic Supplementary Information for

Proton Transfer Dynamics Dictate Quinone Speciation at Lipid-modified Electrodes

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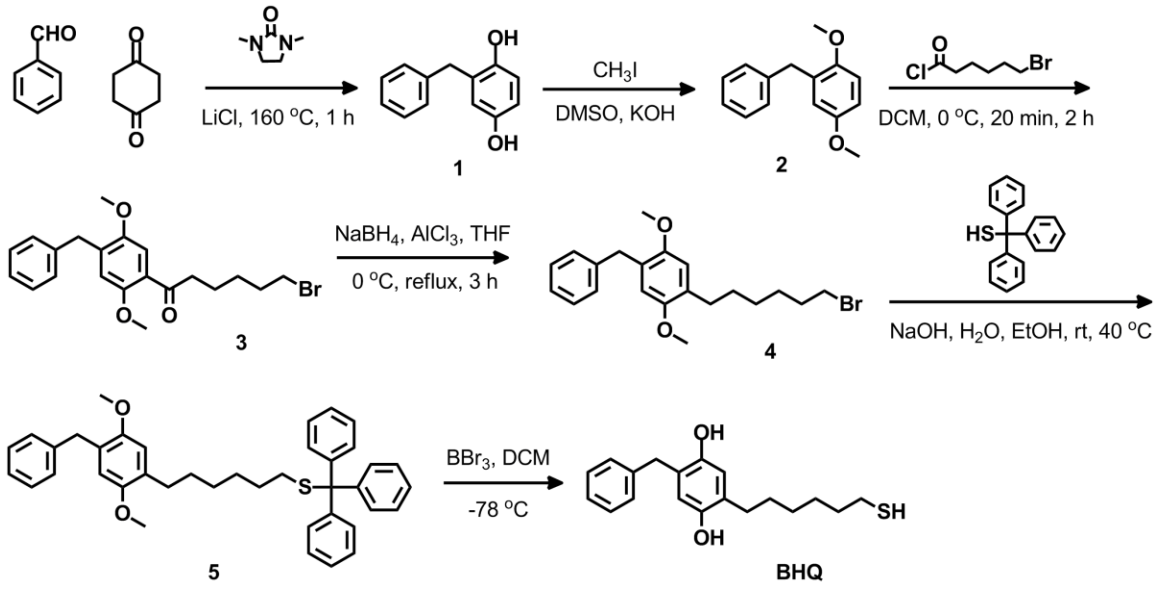
1. General methods

All reactions were carried out under a dry N_2 atmosphere. Chemicals were purchased from commercial sources and used without further purification. Dry dichloromethane (DCM), tetrahydrofuran (THF), and dimethyl sulfoxide (DMSO) were used directly from a solvent delivery system just prior to use. All other solvents, such as methanol (MeOH), ethyl acetate (EtOAc) and hexanes (Hx) were of reagent grade and used without further purification. Reported reaction temperatures refer to the temperature of the heating medium. The progress of reactions was monitored by silica gel thin layer chromatography (TLC) using 0.2 mm silica 60 coated, plastic plates with F254 indicator. Flash and gravity chromatography was performed using 230-400 mesh (40-63 μm) silica gel (SiO_2). Ratios of solvents for NMR solvents and flash chromatography are reported as volume ratios (v/v). NMR spectra were performed in $CDCl_3$ unless otherwise specified and acquired using a Varian Unity 500 MHz instrument (^1H, 500 MHz; ^{13}C, 125 MHz) in the VOICE laboratory, University of Illinois at Urbana–Champaign. Chemical shifts (δ) and coupling constants (J) are reported in parts per million (ppm) and hertz (Hz), respectively. For ^1H spectra, chemical shifts are referenced to the residual protio solvent peak: 7.26 ppm for $CDCl_3$. For ^{13}C spectra, chemical shifts are referenced to the solvent peak at 77.5 ppm in $CDCl_3$. Electrospray ionization mass spectrometry (ESI-MS) data were collected on a Quattro II instrument (Waters) at the University of Illinois at Urbana-Champaign.

2. Synthetic Procedures



Compound 1 was obtained according to a reported procedure.[1]

Compound 2 was prepared according to a previously reported procedure for a similar compound.[2] To 30 mL of DMSO, potassium hydroxide (6.4 g, 0.11 mol) was added. The mixture was stirred at room temperature for 10 min. To the suspension, **1** (3 g, 15 mmol) and methyl iodide (4 mL, 64 mmol) were added. The mixture was stirred at room temperature for 1 h, poured into 30 mL of water, and extracted twice with 50 mL of DCM. The organic layers were combined, dried with anhydrous Na_2SO_4, concentrated using a rotary evaporator to give an off-white solid (3.2 g, 93 %) as the product without further purification. ^{1}H NMR δ 7.27 (m, 2H), 7.19 (m, 3H), 6.80 (d, J = 8.5, 1H), 6.72 (dd, J = 8.5,3, 1H), 6.66 (d, J = 3, 1H), 3.95 (s, 2H), 3.78 (s, 3H), 3.72 (s, 3H).

Compound 3. A solution of **2** (1.7 g, 7.4 mmol) in 15 mL of DCM was cooled to 0 ˚C and $AlCl_3$ (1.34 g, 10 mmol) was added portion-wise over 20 min. To the mixture, 6-

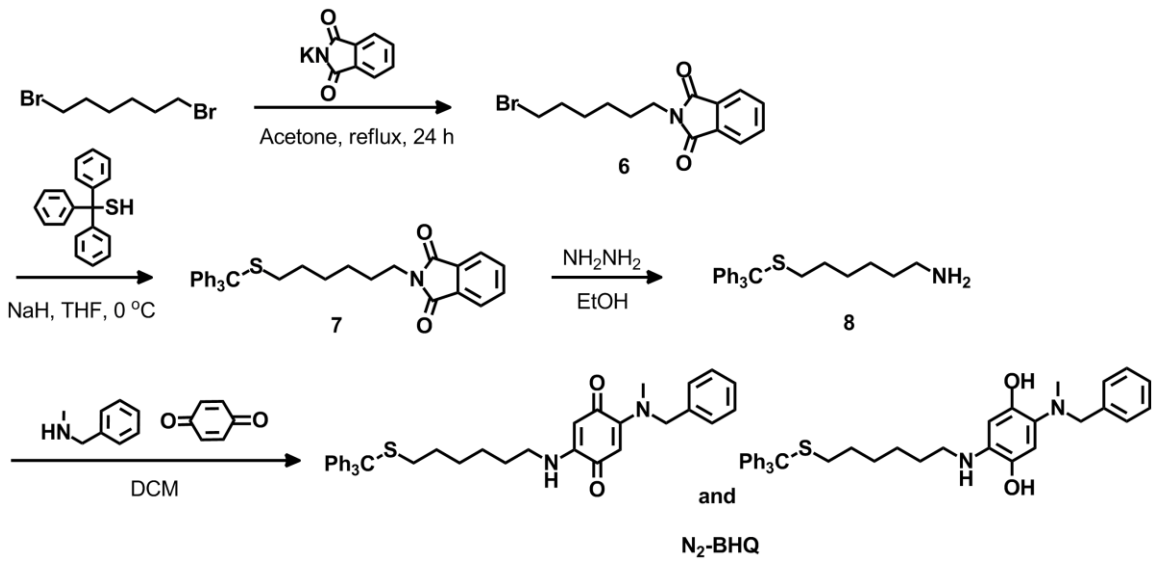
bromocaproyl chloride (1.12 mL, 7.3 mmol) was added dropwise and the suspension was stirred at 0 °C for 2 h. The reaction was quenched by adding 10 mL of aqueous HCl solution (0.1 M) and washed with 20 mL of saturated aqueous $NaHCO_3$ solution. The organic layer was dried with anhydrous Na_2SO_4 and concentrated using a rotary evaporator. The crude product was purified by gradient column chromatography (EtOAc/Hx: 1/10 to 1/4) to give an off-white solid (3.72 g, 82%) as the product. ^{1}H NMR δ 7.28 (m, 2H), 7.26 (s, 1H), 7.20 (m, 3H), 6.68 (s, 1H), 3.99 (s, 2H), 3.81 (s, 3H), 3.78 (s, 3H), 3.42 (t, *J* = 7, 2H), 2.98 (t, *J* = 7, 2H), 1.90 (m, 2H), 1.70 (m, 2H), 1.50 (m, 2H). LRMS (*m/z*): $[M]^+$ calcd. for $C_{21}H_{25}BrO_3$, 404.1; found, 405.2 $[M+H]^+$.

Compound 4 was prepared according to a reported procedure for a similar compound.[3] To 6 mL of THF at 0 °C, $AlCl_3$ (4.3 g, 32 mmol) and $NaBH_4$ (1.3 g, 34 mmol) were added portion-wise. To this suspension, a solution of **3** (1.19 g, 2.9 mmol) in 3 mL of THF at 0 °C was added dropwise. The mixture was warmed to room temperature and heated to reflux for 3 h. The reaction was carefully quenched by 1 ml of acetone and 10 mL of ice water. The aqueous layer was extracted three times with 15 mL of ethyl acetate. The organic layers were combined, dried with anhydrous Na_2SO_4, and concentrated using a rotary evaporator. The crude product was used without further purification. ^{1}H NMR δ 7.27-7.12 (m, 5H), 6.68 (s, 1H), 6.59 (s, 1H), 3.95 (s, 2H), 3.77 (s, 3H), 3.70 (s, 3H), 3.41 (t, *J* = 7, 2H), 2.57 (t, *J* = 7, 2H), 1.87 (m, 2H), 1.58 (m, 2H), 1.48 (m, 2H), 1.38 (m, 2H).

Compound 5. To a solution of triphenylmethanethiol (1.17 g, 4.2 mmol) in 10 mL of 95% EtOH, 2 mL of NaOH (7.5 M) aqueous solution was added. The suspension was stirred at room temperature for 15 min and a solution of **4** (1.1g, 2.8 mmol) in 10 mL of

ethanol was added. The mixture was vigorously stirred at 40 °C for 4 h and filtered. The solvent of the filtrate was evaporated using a rotary evaporator and the oily residue was combined with the filtered residue and dissolved in 20 mL DCM. The organic layer was washed with 20 mL of water, 20 mL of saturated brine solution, dried over anhydrous Na_2SO_4, and concentrated using a rotary evaporator. The crude product was purified by gradient column chromatography (EtOAc/Hx: 1/10 to 1/4) to give a white solid (1.2 g, 73%) as the product. ^{1}H NMR δ 7.45 (m, 6H), 7.31 (m, 8H), 7.25 (m, 4H), 7.21 (m, 2H), 6.70 (s, 1H), 6.62 (s, 1H), 3.99 (s, 2H), 3.79 (s, 3H), 3.72 (s, 3H), 2.56 (t, *J* = 8, 2H), 2.19 (t, *J* = 8, 2H), 1.53 (m, 2H), 1.45 (m, 2H), 1.34 (m, 2H), 1.27 (m, 2H). ^{13}C NMR δ 151.6, 151.4, 145.4, 141.5, 130.4, 130.1, 129.9, 129.1, 128.5, 128.1, 127.6, 126.8, 126.0, 113.8, 113.5, 66.6, 56.5, 36.1, 32.3, 30.4, 30.2, 29.4, 29.2, 28.9. HRMS (*m/z*): $[M+Na]^+$ calcd. for $C_{40}H_{42}O_2SNa$, 609.2803; found, 609.2794.

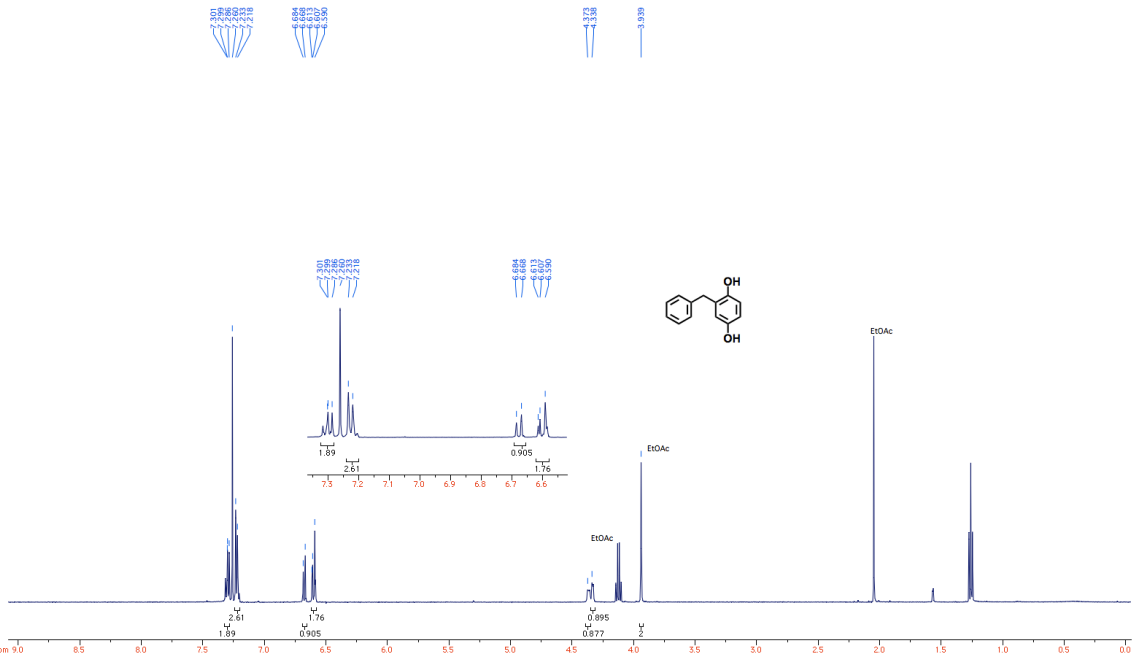
Compound BHQ. To a solution of **5** (20 mg, 0.034 mmol) in 2 mL of DCM at -78 °C, BBr_3 (0.2 mL, 1 M solution in DCM) was added dropwise. The mixture was slowly warmed to room temperature and stirred for 2 h. The reaction was cooled to 0 °C and quenched with 0.2 mL of water. The organic layer was washed with 2 mL of saturated brine solution, dried over anhydrous Na_2SO_4, and concentrated using a rotary evaporator. The crude product was purified by gradient column chromatography (MeOH/DCM: 1/99 to 5/95) to give a white oil (10 mg, 93%) as the product. ^{1}H NMR δ 7.29 (m, 3H), 7.22 (m, 2H), 6.57 (s, 1H), 6.49 (s, 1H), 4.30 (bs, 1H), 3.91 (s, 2H), 3.40 (t, *J* = 7, 2H), 2.53 (t, *J* = 7.5, 2H), 1.86 (m, 2H), 1.60 (m, 2H), 1.47 (m, 2H), 1.40 (m, 2H).



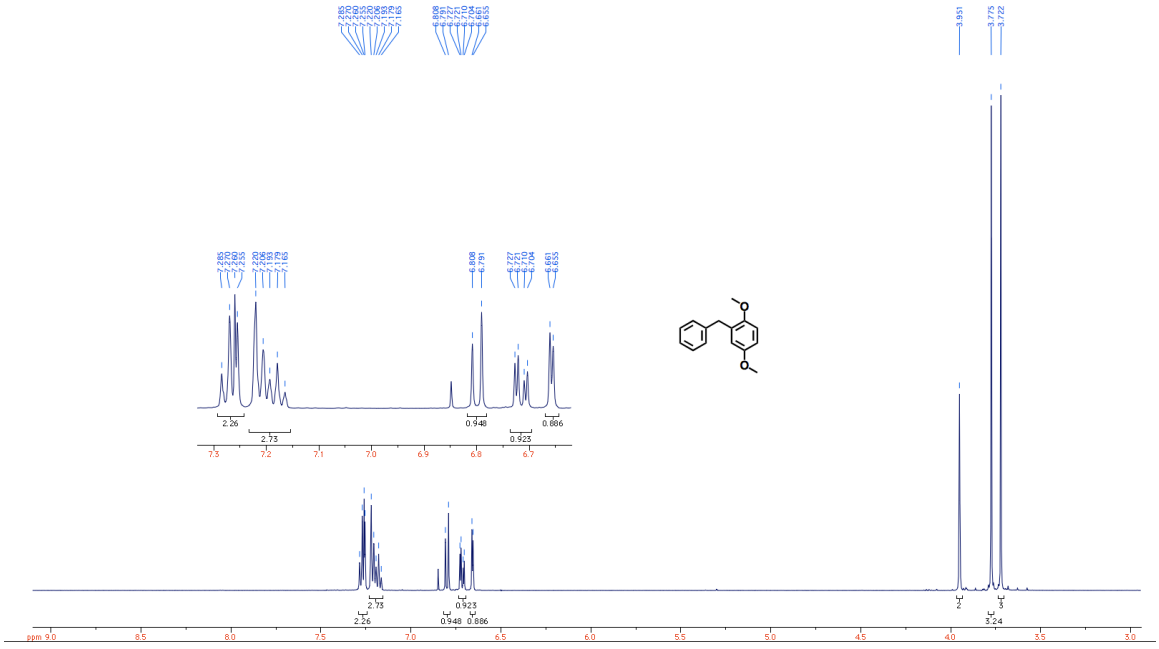
Compound 6, **7**, and **8** were obtained according to reported procedures.[4,5]

Compound N_2-BHQ: To a solution of benzoquinone (10.8 mg, 0.1 mmol) in 2 mL of DCM, *N*-methylbenzylamine (12.1 mg, 0.1 mmol) was added. The mixture was stirred at room temperature for 1 h and **8** (37.5 mg, 0.1 mmol) was added. The reaction was stirred at room temperature for 12 h. The organic layer was diluted with 10 mL of DCM, washed with 15 mL of saturated brine solution, dried over anhydrous Na_2SO_4, and concentrated using a rotary evaporator. The crude product was purified by gradient column chromatography (silica, MeOH/DCM: 0/100 to 5/95) to give a red wax-like solid (yield: 26 mg, 43%, containing both the hydroquinone and benzoquinone forms. The product mixture was not separated because it did not affect the electrochemical analysis given that the molecules tethered to the surface interconvert by redox cycling). HRMS (*m/z*): $[M_{ox}+H]^+$ calcd. for $C_{39}H_{41}N_2O_2S$, 601.2889, found, 601.2891; $[M_{red}+H]^+$ calcd. for $C_{39}H_{43}N_2O_2S$, 603.3045, found, 601.3041.

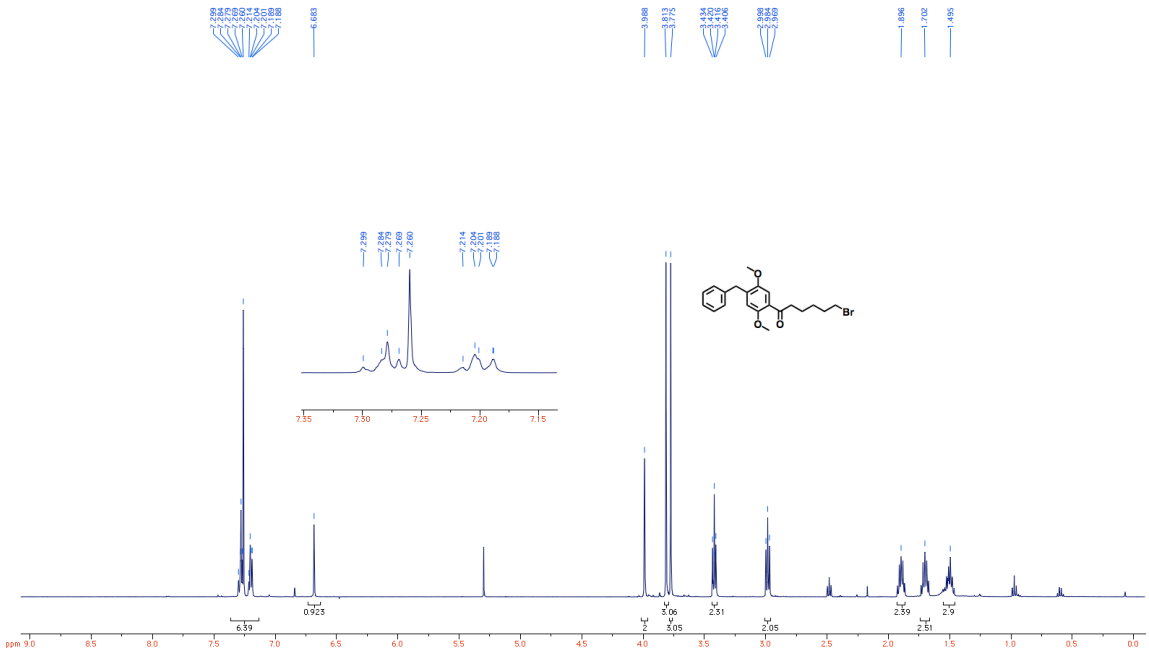
3. NMR spectra



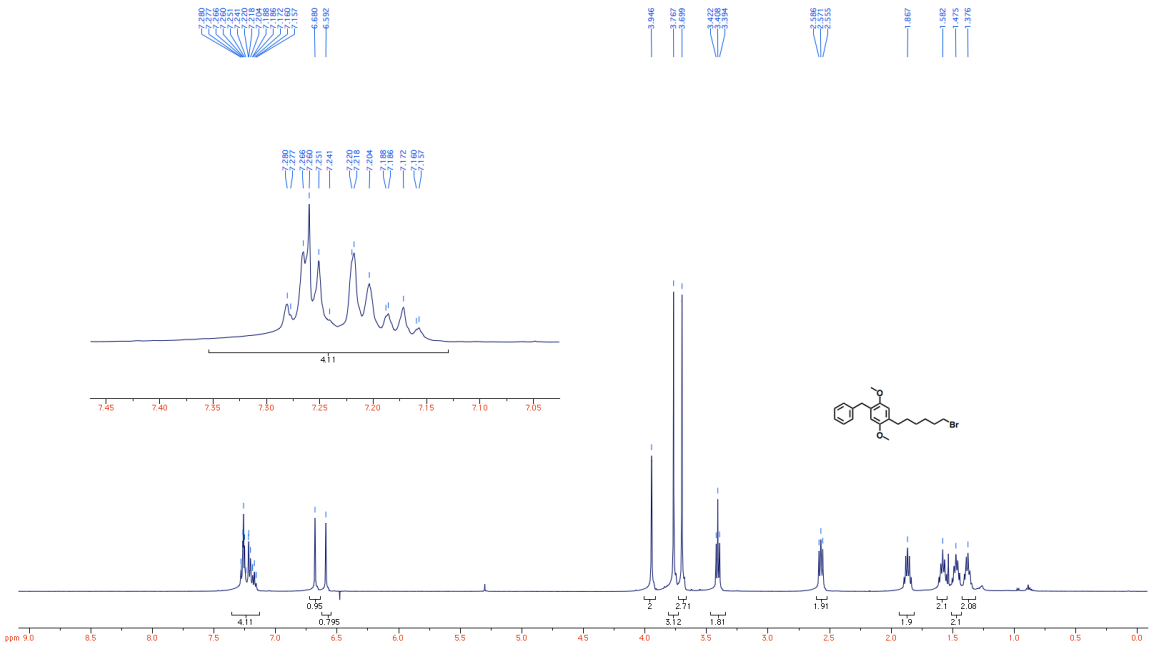
^{1}H NMR spectrum of **1**.



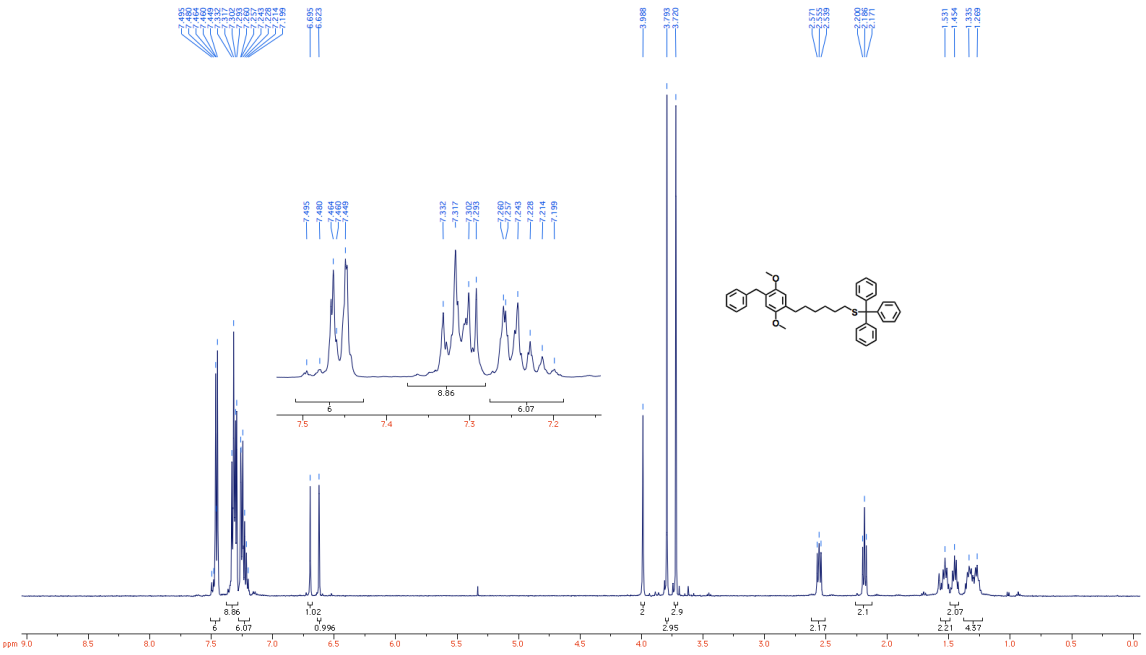
^{1}H NMR spectrum of **2**.



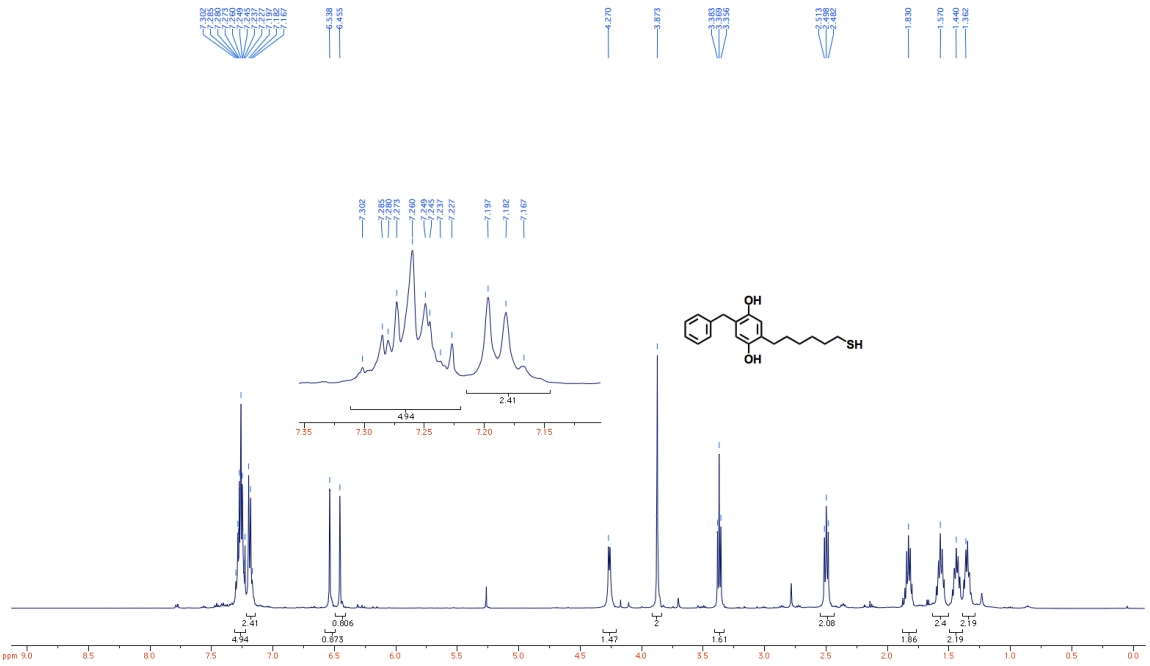
^{1}H NMR spectrum of **3**.



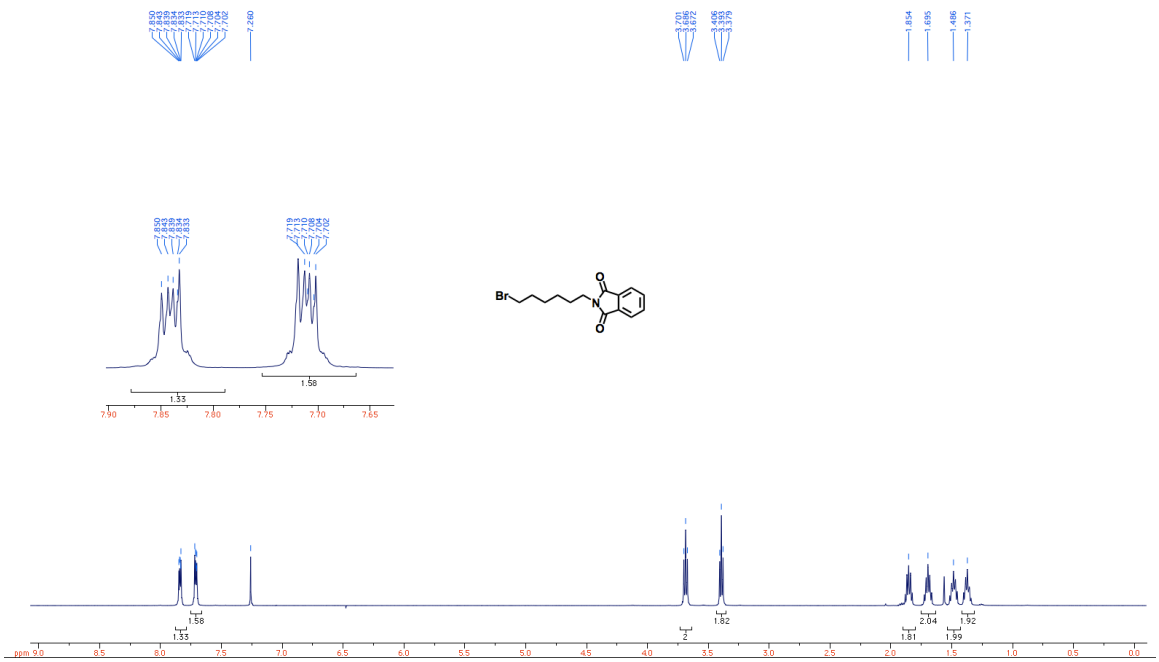
^{1}H NMR spectrum of **4**.



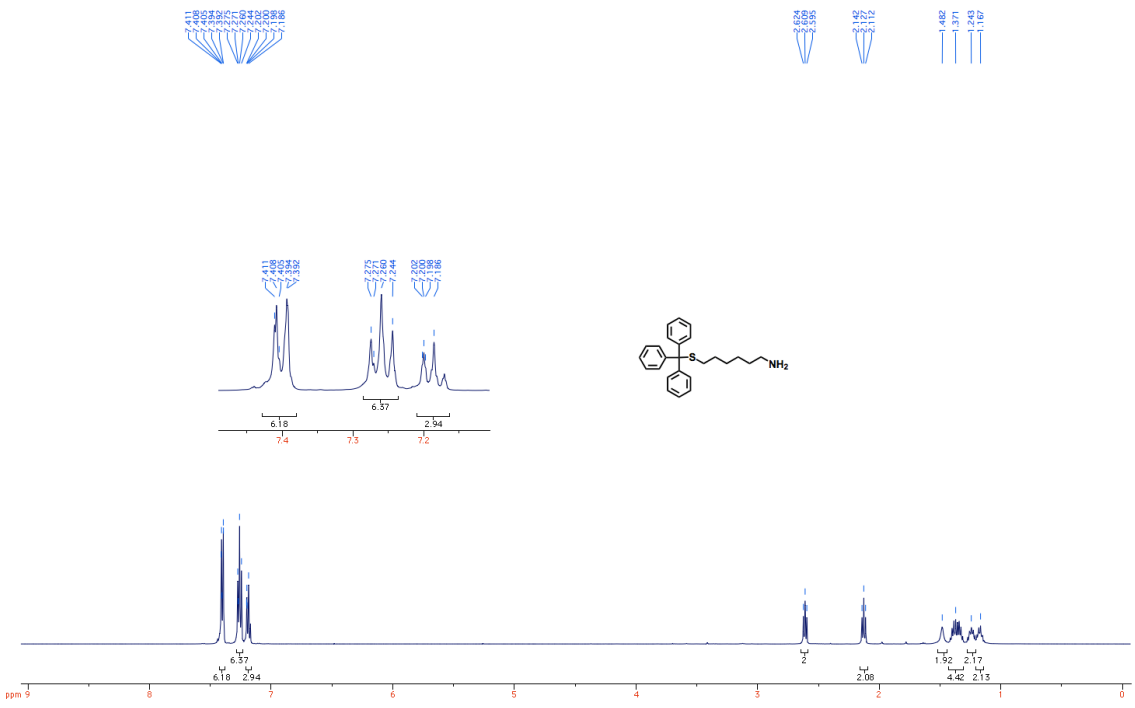
^{1}H NMR spectrum of **5**.



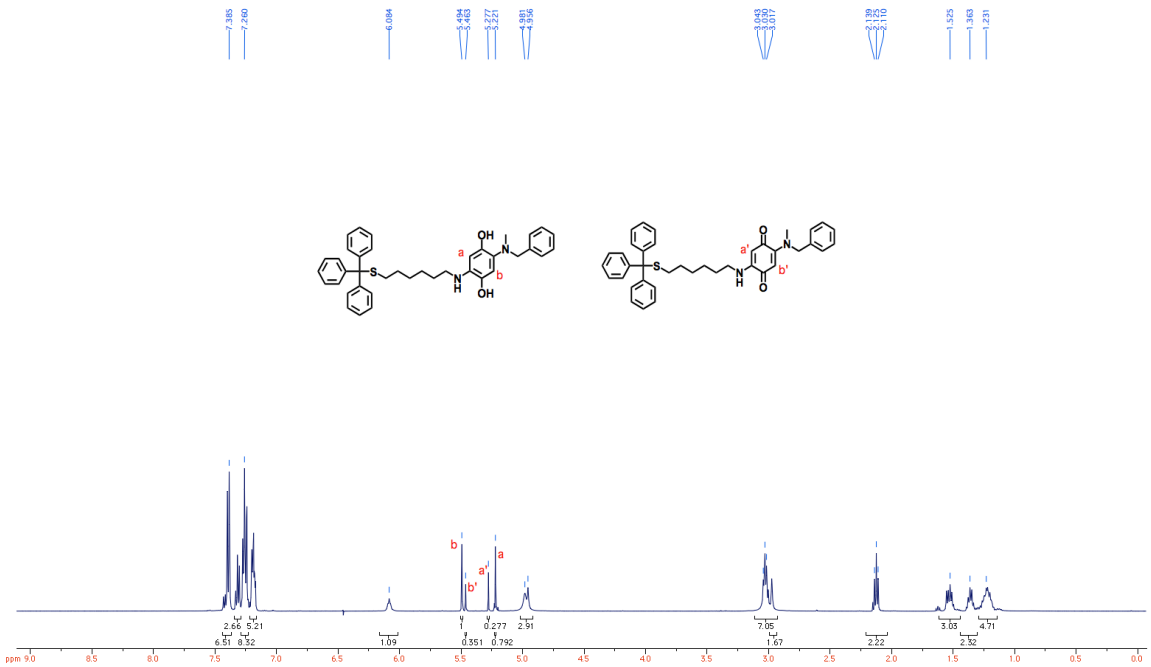
^{1}H NMR spectrum of **BHQ**.



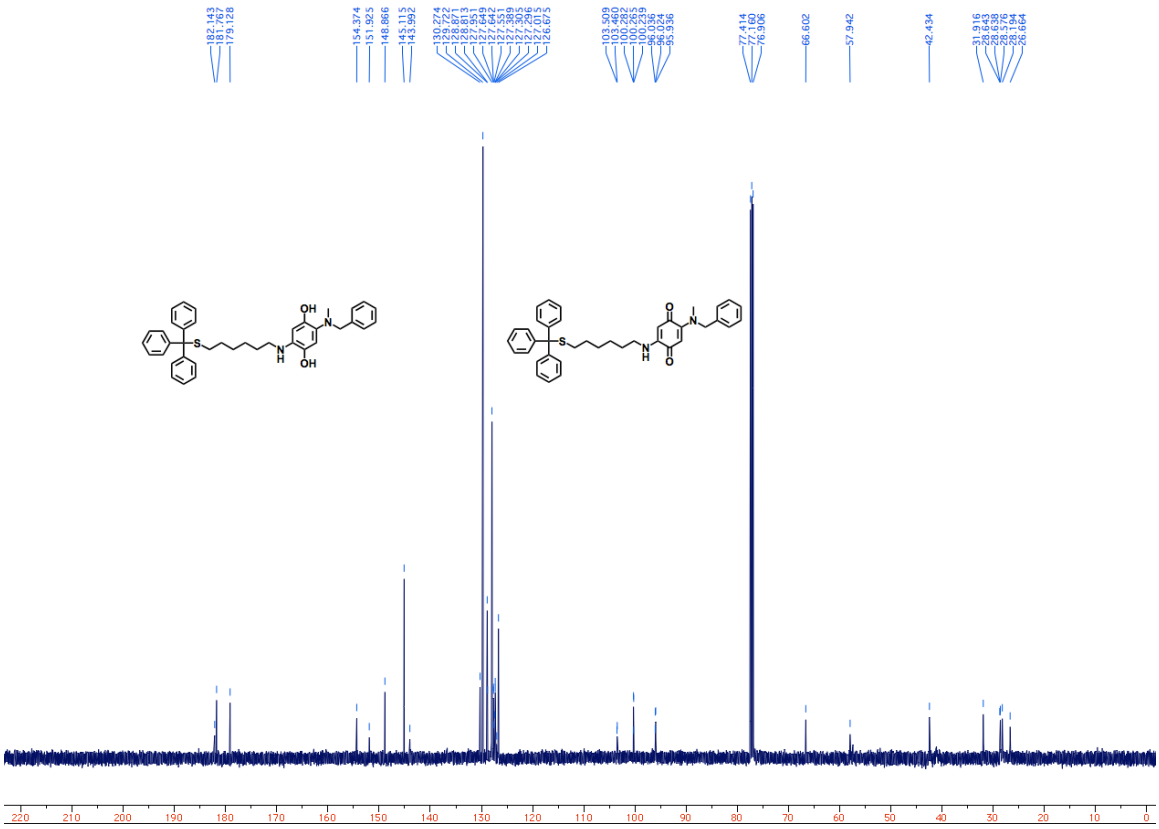
^{1}H NMR spectrum of **6**.



^{1}H NMR spectrum of **8**.



^{1}H NMR spectrum of **N_2-BHQ**.



^{13}C NMR spectrum of **N_2-BHQ**.

4. Electrochemistry studies

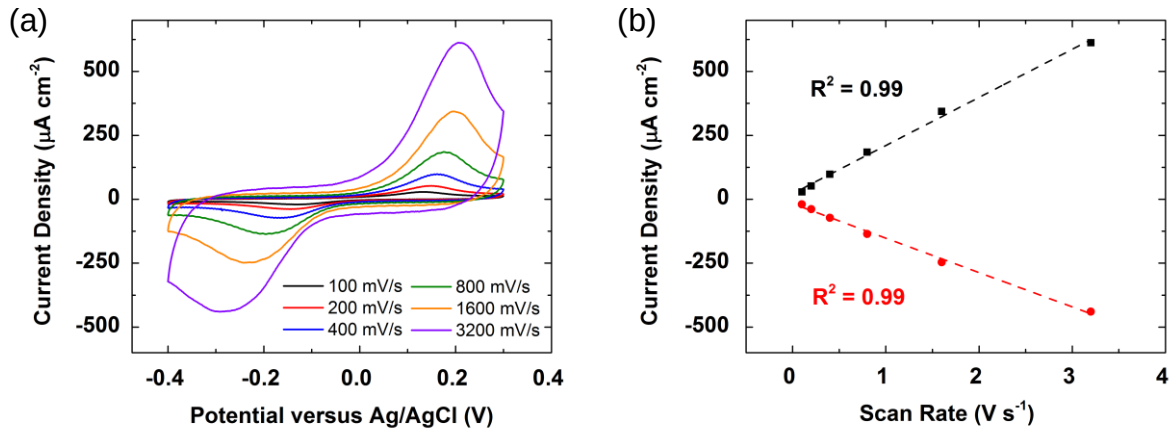


Figure S1. (a) CVs of a SAM of BHQ on Au in pH 3 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red) current densities of a SAM of BHQ versus scan rate.

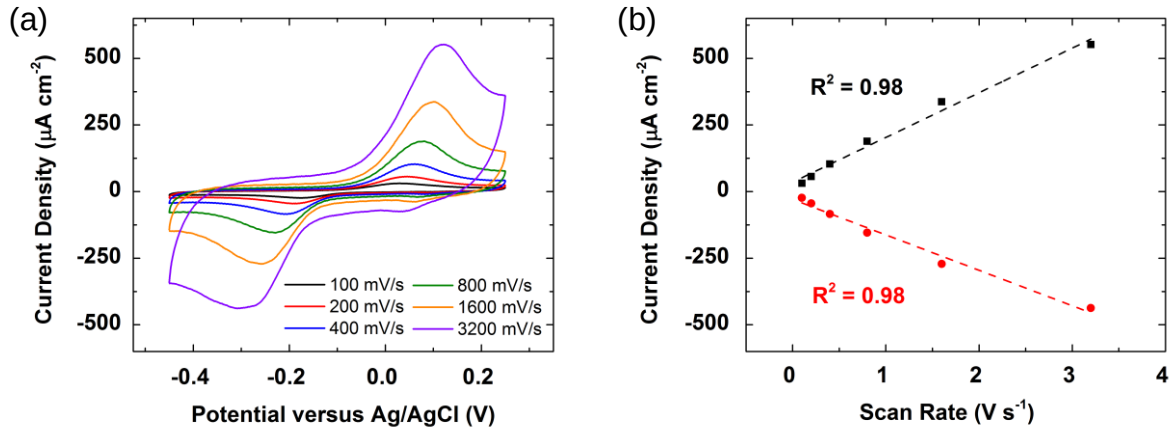


Figure S2. (a) CVs of a SAM of BHQ on Au in pH 5 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red) current densities of a SAM of BHQ versus scan rate.

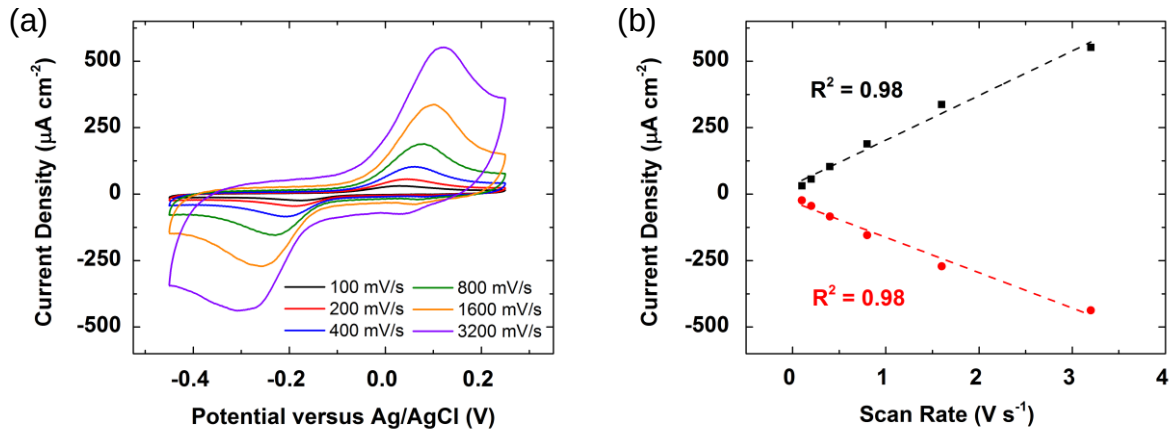


Figure S3. (a) CVs of a SAM of BHQ on Au in pH 9 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red) current densities of a SAM of BHQ versus scan rate.

Table S1. Apparent rate constants of a SAM of BHQ or N_2-BHQ and BHQ- or N_2-BHQ-containing HBMs with and without 1 equivalent of MDP.

System	Cathodic Rate (s^{-1})	Anodic Rate (s^{-1})
BHQ SAM	3.0 ± 1.0	3.9 ± 1.8
BHQ covered by DMPC	3.0 ± 1.4	3.9 ± 1.0
BHQ covered by DMPC with MDP	3.7 ± 0.5	4.4 ± 1.6
N_2-BHQ SAM	2.2 ± 1.1	2.5 ± 0.5
N_2-BHQ covered by DMPC	2.0 ± 0.2	2.3 ± 0.9
N_2-BHQ covered by DMPC with MDP	1.2 ± 1.0	3.6 ± 1.9

Table S2. The integrated charges for the cathodic and anodic waves of a SAM of BHQ, the HBM containing BHQ, and the BHQ-HBM with 1 equivalent of MDP added to the lipid layer.

	pH	Integrated Charges ($\mu C\ cm^{-2}$)	
		Anodic	Cathodic
SAM	3	33 ± 3	33 ± 1
	5	36 ± 3	36 ± 2
	7	33 ± 3	31 ± 2
	9	28 ± 1	32 ± 1
HBM	5	18 ± 1	17 ± 1
	7	17 ± 1	17 ± 2
HBM with MDP	5	34 ± 8	35 ± 5
	7	34 ± 2	(i) 17 ± 2, (ii) 14 ± 3

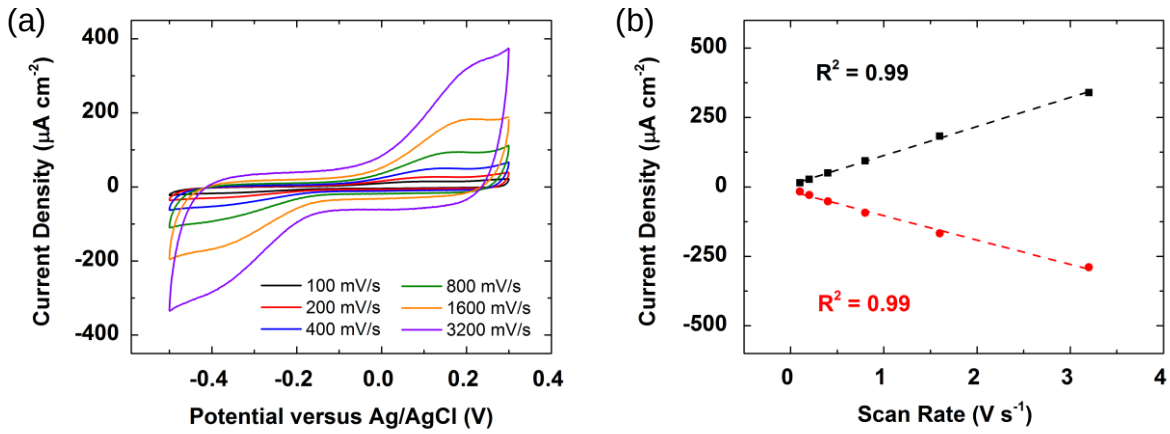


Figure S4. (a) CVs of a SAM of BHQ covered by a DMPC monolayer in pH 7 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red) current densities of a SAM of BHQ covered by a DMPC monolayer versus scan rate.

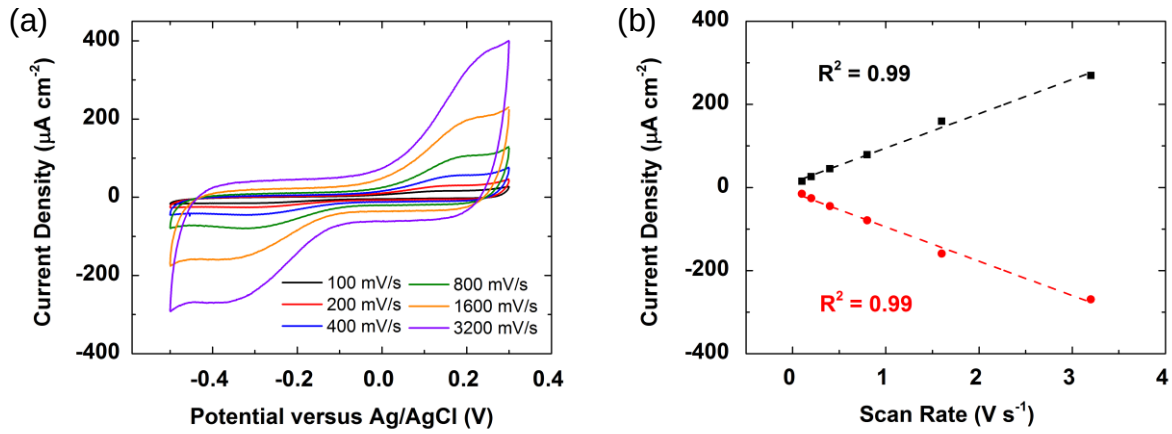


Figure S5. (a) CVs of a SAM of BHQ covered by a DMPC monolayer in pH 5 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red) current densities of a SAM of BHQ covered by a DMPC monolayer versus scan rate.

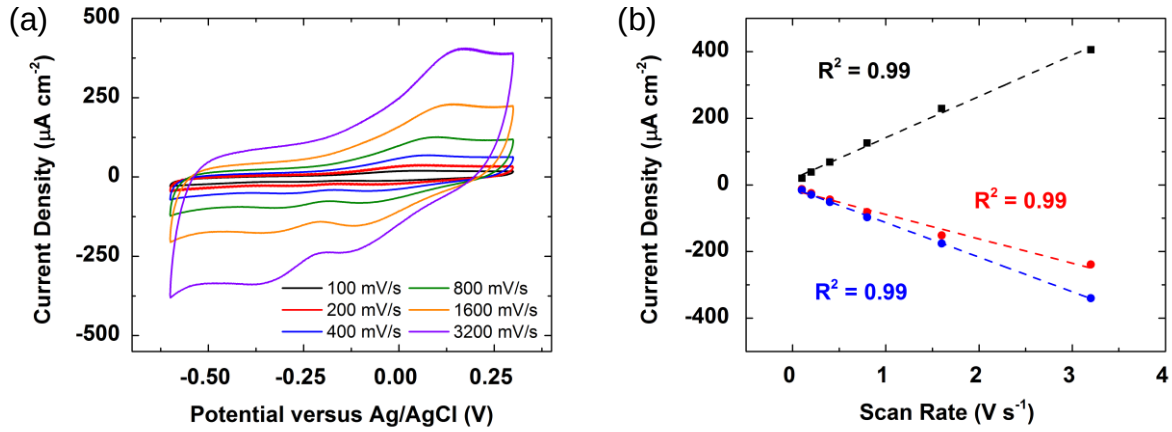


Figure S6. (a) CVs of a SAM of BHQ covered by a DMPC monolayer with 1 equivalent of MDP incorporated in the lipid layer in pH 7 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red, blue) current densities of a SAM of BHQ covered by a DMPC monolayer with MDP incorporated in the lipid layer versus scan rate.

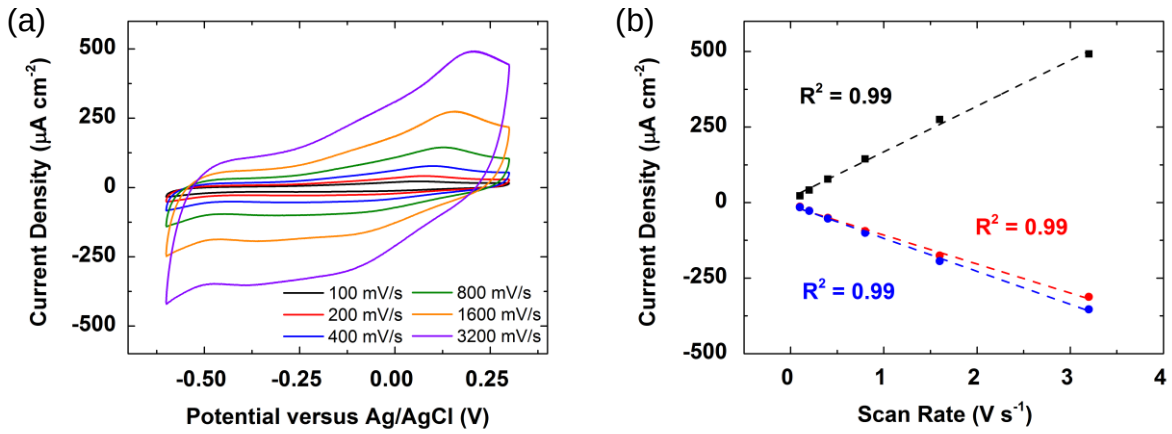


Figure S7. (a) CVs of a SAM of BHQ covered by a DMPC monolayer with 1 equivalent of MDP incorporated in the lipid layer in pH 5 Ar-saturated solution at various scan rates. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red, blue) current densities of a SAM of BHQ covered by a DMPC monolayer with MDP incorporated in the lipid layer versus scan rate.

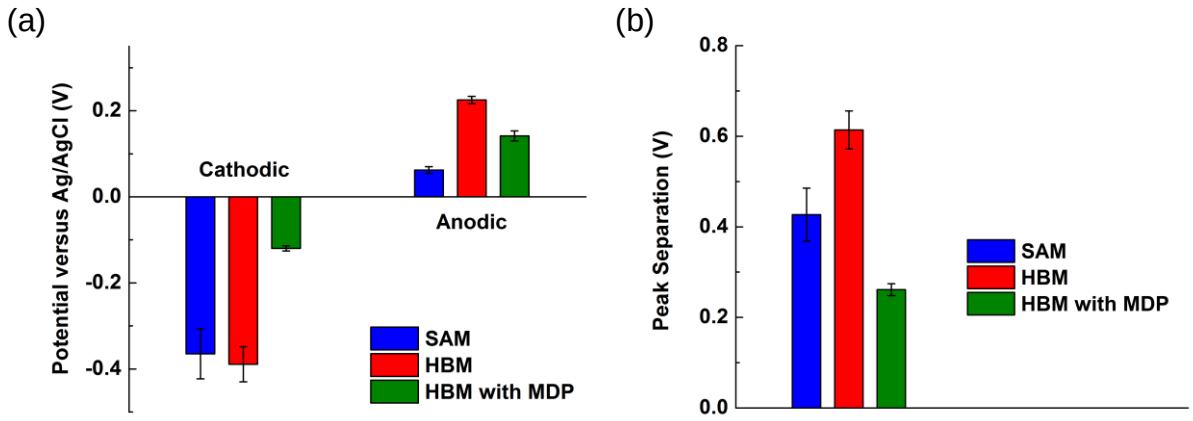


Figure S8. Bar graphs showing BHQ (a) cathodic and anodic peak positions and (b) peak separations at pH 7. Each graph has three sets of bars: open SAM, HBM, and HBM with 1 equivalent of MDP. For HBM with MDP, the cathodic peak position of the more negative cathodic wave is -0.374 ± 0.022 V versus Ag/AgCl.

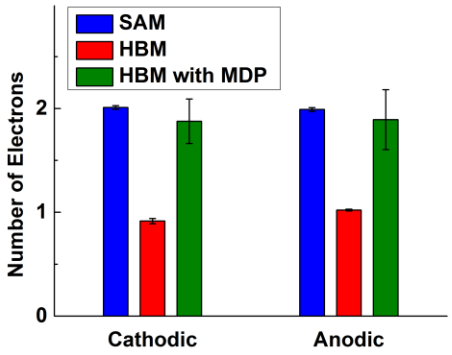


Figure S9. Bar graphs showing the number of electrons transferred for the cathodic and anodic processes of a SAM of BHQ (blue) covered by a monolayer of DMPC (red) with 1 equivalent of MDP incorporated in the lipid layer (green) in pH 5 Ar-saturated solution.

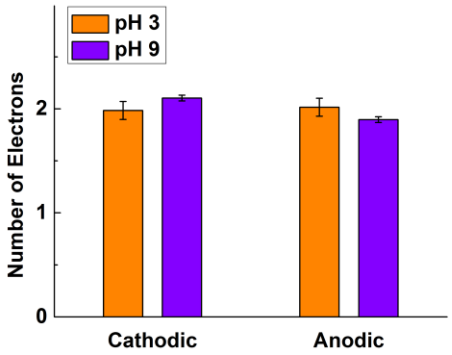


Figure S10. Bar graphs showing the number of electrons transferred for the cathodic and anodic processes of a SAM of BHQ in pH 3 (orange) and 9 (purple) Ar-saturated solutions.

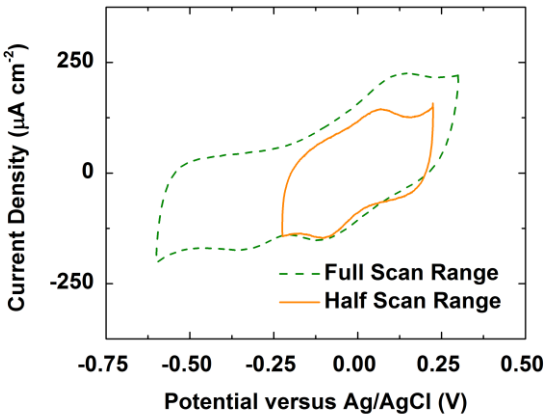


Figure S11a. CVs of a SAM of BHQ covered by a monolayer of DMPC with 1 equivalent of MDP added scanning the full range (dashed green) and half range (solid orange) in an Ar-saturated pH 7 solution at a scan rate of 1600 mV/s.

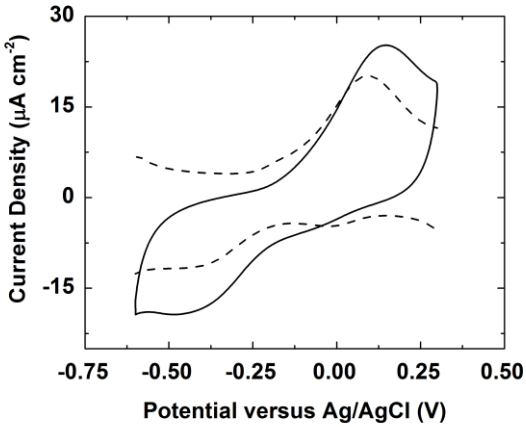


Figure S11b. CV of a SAM of BHQ covered by a monolayer of DMPC with 0.2 equivalents of MDP added in an Ar-saturated pH 7 solution at a scan rate of 100 mV/s (solid line). Square wave voltammetry of the same system performed using an increment voltage of 4 mV, an amplitude of 25 mV, and a frequency of 15 Hz.

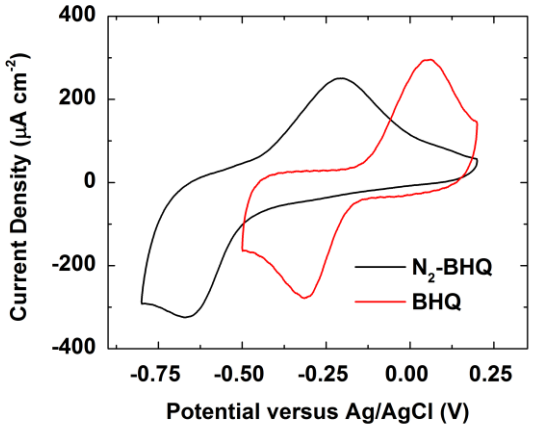


Figure S12. CVs of a SAM of BHQ (red) and a SAM of N_2-BHQ (black) on Au in pH 7 Ar-saturated solution at scan rates of 1600 mV/s.

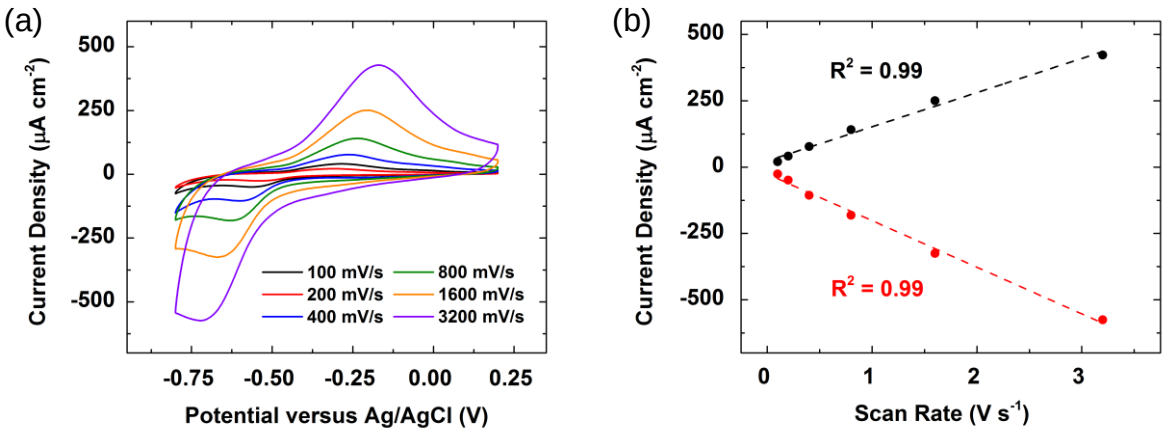


Figure S13. (a) CVs of a SAM of N_2-BHQ on Au in pH 7 Ar-saturated solution at scan rates of 100 (black), 200 (red), 400 (blue), 800 (green), 1600 (orange), and 3200 (purple) mV/s. (b) Randles-Sevcik plot of the peak anodic (black) and cathodic (red) current densities of a SAM of N_2-BHQ versus scan rate.

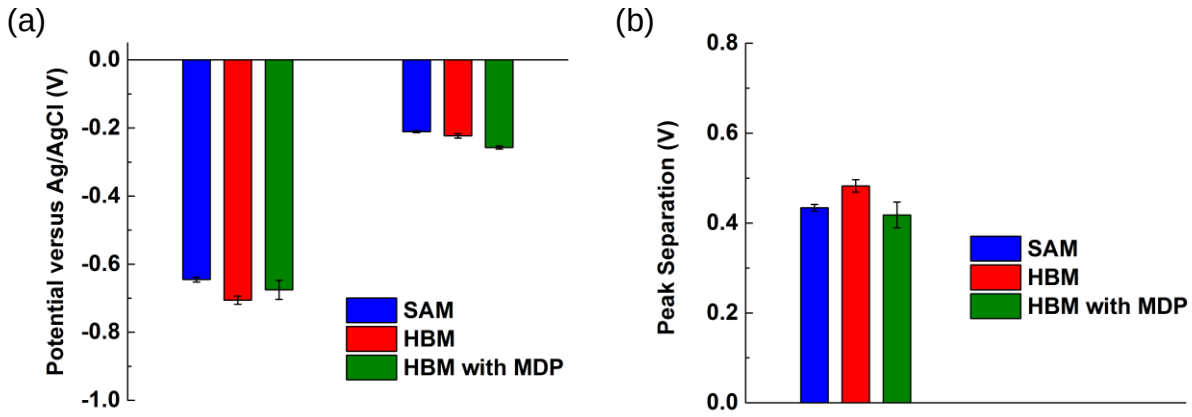


Figure S14. Bar graphs showing N_2-BHQ (a) cathodic and anodic peak positions and (b) peak separations at pH 7. Each graph has three sets of bars: open SAM, HBM, and HBM with 1 equivalent of MDP.

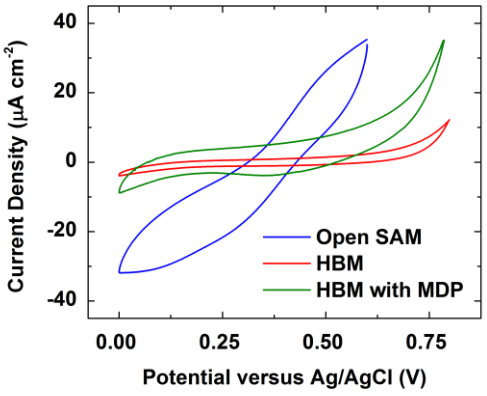
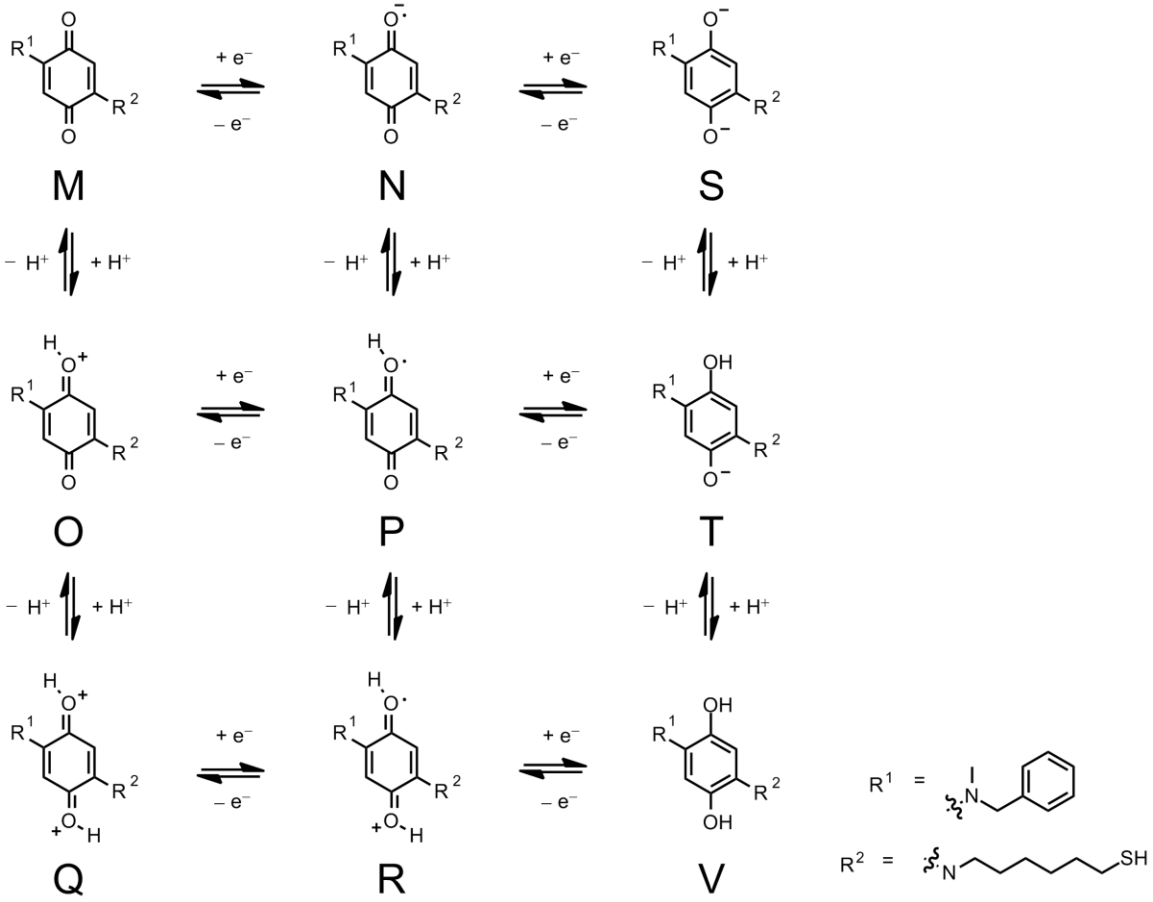


Figure S15. CVs of a SAM of N_2-BHQ (blue), the N_2-BHQ-containing HBM (red), and the N_2-BHQ-HBM with MDP incorporated in the lipid layer (green) in a solution of $K_3Fe(CN)_6$ (1 mM) with KCl (100 mM) at a scan rate of 50 mV/s.



Scheme S1. Nine-member square scheme for the N_2-BHQ system.

5. References

1. Y. Ozaki, A. Hosoya, K. Okamura, S. W. Kim, *Synlett.*, 1997, **4**, 365-366.