Rate of Interfacial Electron Transfer through the 1,2,3-Triazole Linkage

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The rate of electron transfer is measured to two ferrocene and one iron tetraphenylporphyrin redox species coupled through terminal acetylenes to azide-terminated thiol monolayers by the Cu(I)-catalyzed azide– alkyne cycloaddition (a Sharpless "click" reaction) to form the 1,2,3-triazole linkage. The high yield, chemoselectivity, convenience, and broad applicability of this triazole formation reaction make such a modular assembly strategy very attractive. Electron-transfer rate constants from greater than 60,000 to 1 s⁻¹ are obtained by varying the length and conjugation of the electron-transfer bridge and by varying the surrounding diluent thiols in the monolayer. Triazole and the triazole carbonyl linkages provide similar electronic coupling for electron transfer as esters. The ability to vary the rate of electron transfer to many different redox species over many orders of magnitude by using modular coupling chemistry provides a convenient way to study and control the delivery of electrons to multielectron redox catalysts and similar interfacial systems that require controlled delivery of electrons.

Introduction

Self-assembled monolayers (SAMs) of organic thiols on gold¹ are reproducible and controllable interfaces on which to study redox processes dependent on the rate of electron transfer from an electrode surface.^{2–19} One of the major limits to the routine use of this method is the difficulty of forming the desired assemblies of electrode, monolayer, and redox species. Typical assembly strategies rely on appending a spacer or electrontransfer "bridge" terminated with a thiol group to the redox species of interest and then coadsorbing this molecule with a more plentiful unmodified or "diluent" thiol. This coadsorption strategy has proven successful for incorporating appropriate amounts of relatively simple and unreactive redox species onto the surfaces of thiol monolayers. Unfortunately, some of the most interesting species to which one would like to control electron transfer (porphyrins, enzymes, DNA, etc.) are too structurally or functionally complex to be reliably immobilized in this way.

An alternate strategy^{20–26} is to form a mixed monolayer from a diluent thiol and a thiol terminated with a functional group or ligand that can subsequently be coupled covalently to the redox species of interest. While this post-adsorption coupling strategy is intrinsically more flexible, no one coupling reaction has yet been broadly adopted. This can be attributed to one or more of the following limitations of most coupling reactions: (1) incomplete coupling, (2) unwanted side reactions, or (3) disruption of the monolayer by harsh coupling conditions.

Recently we and others have explored a particularly attractive and broadly applicable reaction for coupling species of interest to surfaces which we believe overcomes the limitations of existing coupling reactions and may become widely adopted for post-adsorption modification of monolayers. The procedure relies on the recently discovered Cu(I)-catalyzed variant^{27,28} of the Huisgen 1,3-dipolar cycloaddition²⁹ between an azide group and a terminal acetylene group where one of these groups is incorporated at the surface of the monolayer and the other is appended to the species to be coupled to the monolayer. $^{30-32}$ The resulting linkage is a five-member aromatic heterocycle (specifically a 1,4-disubstituted 1,2,3-triazole), which is thermally and hydrolytically very stable. Sharpless has dubbed this Cu(I)-catalyzed reaction a "click" reaction²⁷ by virtue of its chemoselectivity, high yield, and overall convenience.³³ We have previously used the disappearance of the strong asymmetric IR stretch of the azide on the monolayer after incubation with a Cu(I) catalyst and an acetylene-terminated species in solution to demonstrate that the surface reaction is quantitative:³⁰ omission of the acetylene-terminated species but with otherwise identical incubation conditions results in no loss of the azide stretch, confirming the exquisite chemoselectivity of the coupling. We also showed that, because of the quantitative yield of the coupling, acetylene-terminated redox probes can be used to quantify the number of azide groups initially present in the mixed monolayers.³⁴ Following the work of Sharpless, Fokin, and co-workers,³⁵ we have also shown that the oxygen-tolerant complex of Cu(I) with tris(benzyltriazolylmethyl)amine (TBTA) is an effective catalyst for the click coupling reaction at monolayer surfaces.³⁴ This catalyst has the advantage that it is free of side reactions with O₂ that form partially reduced oxygen species and so can be safely used under aerobic conditions in the presence of oxidatively sensitive compounds, such as the coupling of single-stranded DNA to an azide-terminated mixed monolayer.³⁶ Most recently, we have used this chemistry to selectively modify an array of independently addressable microelectrodes by electrochemically localizing the copper(I) catalyst.37

The work reported here demonstrates that monolayer assemblies coupled to a redox species by Cu(I)-catalyzed triazole formation are well suited for studies where the electron-transfer rate between a given surface redox species and the electrode needs to be reproducibly and predictably controlled but where assembly of the redox-active mixed monolayer in one step is

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Figure 1. Scheme depicting the formation of mixed monolayers on gold electrodes coupled to redox species via Cu(I)-catalyzed azide-acetylene cycloaddition. The modular nature of the approach facilitates studies by allowing the diluent thiol, the nature of the tunneling bridge, X, and the redox species, R, to be independently varied.

prohibited by the reactivity of free thiols and/or the overall complexity of the redox species. In this paper, we report the electron-transfer rates for a number of assemblies of azide-terminated thiol monolayers coupled to different redox species (see Figure 1). By tailoring the length and degree of conjugation of the azide-terminated thiol and the surrounding diluent, we can control the electron-transfer rate to the redox species over many orders of magnitude. In future work we hope to use this methodology to determine how the rate of electron transfer affects the mechanism of oxygen reduction by synthetic models of the active site of cytochrome c oxidase.

Results and Discussion

Our studies were carried out on gold electrodes modified with a mixed monolayer using previously reported procedures.^{30,36} Mixed monolayers were formed from an azide-terminated thiol (11-azidoundecanethiol, 16-azidohexadecanethiol, or azidophenyleneethynylenebenzylthiol (N₃(PEB)SH)) and a diluent thiol that was slightly shorter than the azide-terminated thiol to ensure that the azide group was sterically unhindered for reaction. The coverage of redox species coupled to the surface of the monolayer is controlled by the ratio of azide-terminated to diluent thiol in the monolayer formation step. As documented in detail in our previous work,³⁴ the yield of coupling is 100% up to azide coverages at which steric limitations prevent complete coupling.

Initially, we coupled the acetylene-bearing redox species to the as-formed azide-terminated mixed monolayers. However, we found the rates of electron transfer through the longer alkyl bridging unit to the redox species to be faster than expected and to be irreproducible. Chidsey and co-workers³⁸ have previously reported similar findings for mixed monolayers of longer ferrocene-terminated alkane thiols and methyl-terminated alkane thiols. They found that exposing the as-formed mixed monolayer to an ethanolic solution of the diluent thiol replaced some of the ferrocene thiols with the redox-inactive diluent thiols and that monolayers treated in this fashion showed slower and more reproducible rates of electron transfer. We have used this post-assembly exchange method with the same effect. Immersing our post-coupling monolayers in solutions of diluent thiols slowed the electron-transfer rates and eventually gave reproducibly lower limiting values. We infer that the remaining redox species are in ordered domains of the monolayer where the redox species is held a well-defined distance from the electrode by the densely packed monolayer. Although this post-coupling exchange does yield reproducibly slow rates of electron transfer, it is not an ideal solution; for instance, metal-based redox species with open coordination sites can react with the free diluent thiols during the exchange step. Fortunately, we have found that exchange of the azide-terminated thiols by diluent thiols prior to the coupling reaction also results in reproducibly slow rates of electron transfer. After an overnight incubation in an ethanol solution containing 100 mM diluent thiol, the mixed monolayers are coupled with the redox species and the electron-transfer rates are reproducibly slowed to the slowest values obtained by postcoupling exchange and can be predictably controlled by tailoring the nature of the underlying monolayer. We infer that the exchange process yields monolayers with coupling sites exclusively immobilized in the ordered domains.

Figure 2 shows typical cyclic voltammograms of mixed monolayers of N₃(CH₂)₁₆SH and CH₃(CH₂)₁₅SH after coupling with either ferrocene acetylene or an acetylene-terminated iron tetraphenylporphyrin. The background charging currents are typical of a hexadecanethiol monolayer indicating that neither the presence of the azide nor the coupling chemistry disrupt monolayer packing. For instance, at 0 V vs Ag/AgCl/3 M NaCl, the capacitance determined from the 300 mV/s scan is 1.3 μ F/ cm², the same as that previously reported for a simple hexadecanethiol monolayer.³⁹ As the scan rate for the cyclic voltammogram is increased, the positive and negative current peaks split further apart, indicating that the time to scan through the peak is comparable to or less than the reciprocal of the



Figure 2. Cyclic voltammograms of $N_3(CH_2)_{16}SH + CH_3(CH_2)_{15}SH$ mixed monolayers on gold after click coupling with ferrocene acetylene (left) or the acetylene-terminated iron tetraphenyl porphyrin (right). The arrow indicates the start of the scan. Scan rates: 0.3 (solid), 0.5 (dashed), and 1.0 V/s (dotted). The electrolyte was 1 M HClO4. For the case of the porphyrin, 1 M pyrazine was included to serve as an axial ligand and the electrolyte was degassed thoroughly with nitrogen. The monolayers were formed from an ethanol solution of 0.015 mM N₃(CH₂)₁₆SH and 0.09 mM CH₃(CH₂)₁₅SH followed by exchange with the CH₃(CH₂)₁₅SH as described in the text.⁴¹

electron-transfer rate.⁴⁰ Note that for identical scan rates the splitting for the porphyrin-modified monolayer is not as large as that for the ferrocene-modified monolayer. This is an indication that the electron-transfer rate for the porphyrin is faster than that for the ferrocene. Note also that the area under the voltammetric peaks and thus the redox charge to completely oxidize the two different redox species are very similar. Indeed, integration of the peaks and normalization by the scan rates³⁰ shows that the redox charges are 3.9 \pm 0.01 and 4.0 \pm 0.1 μ C/cm² for the ferrocene and porphyrin modified monolayers, respectively. This constancy of redox charge is as expected if the coverage of the redox species on the surface after the coupling reaction is equal to the coverage of reactive azide on the surface before the coupling reaction. Because nominally identical azide-terminated mixed monolayers were used for both coupling reactions, we expected to obtain identical redox coverages. This constancy of coverage demonstrates another advantage of using a preformed monolayer as a platform for click coupling: coverages can be controlled simply by controlling the amount of azide in the monolayer. Once the azideterminated mixed monolayer has been characterized, changing the nature of the redox species does not require one to once again empirically determine the conditions necessary for a specific coverage. Thus, because of the chemoselective reactivity and quantitative yield of the click reaction, an azide-terminated mixed monolayer can be treated as a platform for obtaining reliable coverages of a wide range of acetylene-terminated species of interest.

One can obtain a value for the standard electron-transfer rate constant, k^0 , between the gold electrode and the surfaceimmobilized redox species from the voltammetric peak splitting using the analysis method of Laviron.⁴⁰ However, a preferable method is measurement of the current transient following a potential step to a final potential, *E*, extraction of the electron-transfer relaxation rate constant, $k_{et}(E)$, and from that determination of the standard rate constant, k^0 . This method reveals any multiphasic character of the electron-transfer rate not only at the standard potential, E^0 , of the couple but also as a function of the standard overpotential, $E - E^{0.2}$ Equation 1 shows the expected exponential decay of the redox current, $i_{redox}(t)$, for a kinetically homogeneous population of one-electron redox sites on the surface of an electrode:²

$$i_{\text{redox}}(t) = eA\Delta\Gamma_{\text{ox}}k_{\text{et}}(E)\exp[-k_{\text{et}}(E)t]$$
(1)

where *e* is the electronic charge, *A* is the area of the electrode, $\Delta\Gamma_{ox}$ is the change in coverage (number per unit area) of the oxidized form of the redox species during the course of the measurement, and the first-order electron-transfer relaxation rate constant, $k_{et}(E)$, is the sum of the first-order reduction rate constant, $k_{red}(E)$, and the first-order oxidation rate constant, $k_{ox}(E)$:

$$k_{\rm et}(E) \equiv k_{\rm red}(E) + k_{\rm ox}(E) \tag{2}$$

Equations 1 and 2 are derived from the first-order rate law for reversible single-electron transfer, $d\Gamma_{ox}(t)/dt = k_{ox}(E)\Gamma_{red}(t) - k_{red}(E)\Gamma_{ox}(t)$, and conservation of the redox species at the monolayer surface, $\Gamma_{red}(t) + \Gamma_{ox}(t) = \text{constant}$.

Figure 3a shows an example of the current transient for a mixed monolayer formed from 0.015 mM $N_3(CH_2)_{16}SH$ and 0.09 mM $CH_3(CH_2)_{15}SH$ in ethanol with overnight exchange in 100 mM $CH_3(CH_2)_{15}SH$ and then click coupled to ferrocene acetylene. The potential was stepped from 10 mV negative of the ferrocene standard potential to the standard potential of the ferrocene redox couple. Thus, according to eq 1, we would expect an exponential decay of the current with a decay rate constant of $k_{et}(E^0)$. A semilog plot (Figure 3b) reveals the decay to be a single exponential over 2 orders of magnitude of the current. The linearity of the semilog plot is an indication that the redox sites are kinetically identical and independent of each other.

The electron-transfer relaxation rate constants at E^0 for all the mixed monolayer redox assemblies examined in this paper were determined in this way and are displayed in Table 1. Both shorter azide-terminated thiols and shorter diluent thiols give larger rates. Use of the conjugated bridge resulted in a rate that was too fast to be accurately measured with conventional chronoamperometry.⁴² The chronoamperometrically determined lower limit to the rate is given in Table 1. These results are expected based on previous work on mixed monolayers formed by coadsorption of diluent thiols with thiols terminated by redox species.^{3,4,6,9,12,15,18} One sees from Table 1 that the rate of electron transfer to the click-coupled redox couples can readily be scaled by over 4 orders of magnitude by modifying the nature of the azide-terminated mixed monolayer.

Near the standard potential of a simple outer-sphere redox couple, one expects the Butler–Volmer parametrization of the potential dependence of the rate constants with a transfer coefficient of 0.5^{43} to be an appropriate approximation, in which case eq 2 becomes:

$$k_{\rm et}(E) \simeq k^0 \{ \exp[-0.5e(E - E^0)/(k_{\rm B}T)] + \exp[+0.5e(E - E^0)/(k_{\rm B}T)] \}$$
(3)

At the standard potential $(E = E^0)$, the electron-transfer relaxation rate constant should thus be twice the standard rate constant:

$$k_{\rm et}(E^0) = 2k^0 \tag{4}$$

Figure 4 displays the measured dependence of $k_{et}(E)$ on potential for a N₃(CH₂)₁₆SH + CH₃(CH₂)₁₅SH mixed monolayer



Figure 3. (A) Current transient for $N_3(CH_2)_{16}SH + CH_3(CH_2)_{15}SH$ mixed monolayers on gold after click coupling with ferrocene acetylene. (B) Semilog plot of the current transient in part A. The potential was stepped from $E^0 - 10$ mV to E^0 . The electrolyte was 1 M HClO₄.

ТАВ	LE	1:	Electron-Transfer	Relaxation	Rate	Constants
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azide	diluent	redox species	$k_{\rm et}(E^0)/{ m s}^{-1}$
N ₃ (PEB)SH	CH ₃ (CH ₂) ₇ SH	ferrocene acetylene	$>6 \times 10^{4}$
N ₃ (CH ₂) ₁₁ SH	CH ₃ (CH ₂) ₆ SH	ferrocene acetylene	$(1.07 \pm 0.05) \times 10^4$
N ₃ (CH ₂) ₁₁ SH	CH ₃ (CH ₂) ₉ SH	ferrocene acetylene	500 ± 2
N ₃ (CH ₂) ₁₆ SH	$CH_3(CH_2)_{11}SH$	ferrocene acetylene	20 ± 6
$N_3(CH_2)_{16}SH$	$CH_3(CH_2)_{13}SH$	ferrocene acetylene	7.2 ± 0.2
$N_3(CH_2)_{16}SH$	$CH_3(CH_2)_{15}SH$	ferrocene acetylene	2.2 ± 0.2
$N_3(CH_2)_{16}SH$	$CH_3(CH_2)_{15}SH$	ferrocene carbonyl acetylene	3.4 ± 1.0
$N_3(CH_2)_{16}SH$	$CH_3(CH_2)_{11}SH$	Fe porphyrin acetylene	$(1.11 \pm 0.05) \times 10^3$
$N_3(CH_2)_{16}SH$	CH ₃ (CH ₂) ₁₅ SH	Fe porphyrin acetylene	34 ± 4

modified by either ferrocene or iron porphyrin. One should in principle be able very accurately determine k^0 by fitting such plots to eq 3 (solid lines). This works well for the faster of the two cases—the iron porphyrin. However, in the case of the ferrocene, the experimental values of $k_{et}(E)$ do not change as much with potential as expected by the Butler–Volmer parametrization. Such "shallow" potential dependences near E^0 are expected if there is a pathway for the redox process that is not limited by electron transfer to and from the electrode. In the



Figure 4. Dependence of $k_{\rm et}(E)$ on potential for a N₃(CH₂)₁₆SH + CH₃(CH₂)₁₅SH mixed monolayer modified by either ferrocene acetylene (circles) or Fe monoaminotetraphenylporphyrin with appended acetylene (squares). Solid lines are best fits of the data to the Butler–Volmer form with a transfer coefficient of one-half ($k^0 = 0.99$ and 18 s⁻¹, and $E^0 = +0.325$ and +0.279V vs Ag/AgCl/3M NaCl(aq), respectively, for the ferrocene ada are better fit with the modified Butler–Volmer form including self-exchange ($k^0 = 0.65$ s⁻¹, $E^0 = +0.330$ V, and $k_{\rm se} = 0.40$ s⁻¹).

case of this particularly slow electron transfer, it may be that there is some residual electron transfer through defects followed by self-exchange among the redox sites. Indeed, if the initial mixed monolayer of azide-terminated and diluent thiol is not incubated in the solution of pure diluent thiol prior to the coupling, then the value of $k_{et}(E)$ is larger near E^0 and the potential dependence is even more shallow. If, for the defect pathway, the self-exchange is rate-limiting rather than the electron transfer between the electrode and redox species at the defective site, then one would obtain a potential independent contribution due to the self-exchange, here labeled k_{se} , in parallel with the electrochemical rate constant:

$$k_{\rm et}(E) \cong k^0 \{ \exp[-0.5e(E - E^0)/(k_{\rm B}T)] + \exp[+0.5e(E - E^0)/(k_{\rm B}T)] \} + k_{\rm se}$$
(5)

The ferrocene data in Figure 4 are indeed well fit by this equation. The fit parameters suggest that about 40% of the electrons are transferred by the defective pathway. We have no evidence for this pathway for the faster porphyrin redox species. We conclude that, for mixed thiol monolayers on gold prepared in this way, rate constants slower than about 1 s^{-1} may be prone to defective electron transfer, but that rates faster than about 1 s^{-1} can be reliably controlled by the structure of the electron-transfer bridge, the intrinsic packing of the monolayer, and the nature of the redox species.

An important question is how the 1,2,3-triazole linkage affects the rate of electron transfer. Forster and co-workers have previously shown that the standard rate constant of electron transfer through a 3,5-bis(pyridin-4-yl)-1,2,4-triazole bridge is of order $1 \times 10^6 \text{ s}^{-1.44}$ If the 1,2,3-triazole linkage is comparable to the 1,2,4-triazole then we would expect in our longer bridges that the 1,2,3-triazole would have a small to negligible effect on the rate of electron transfer. A mixed monolayer of $N_3(CH_2)_{16}SH + CH_3(CH_2)_{15}SH$ modified with ferrocene acetylene should, at least at a structural level, closely resemble the mixed monolayer of $FcCO_2(CH_2)_{16}SH + CH_3(CH_2)_{15}SH$ that was studied by Chidsey.² The reported $k_{et}(E^0)$ for that monolayer was 2.5 s⁻¹. The difference between that assembly and ours is that the ester link has been replaced by a triazole link. Our reported $k_{\text{et}}(E^0)$ of 2.2 s⁻¹ is identical within error, indicating that the triazole seems to behave similarly to an ester with regard to electron tunneling. We modified the same mixed monolayer of $N_3(CH_2)_{16}SH + CH_3(CH_2)_{15}SH$ with ferrocene carbonyl acetylene³⁰ and found a $k_{et}(E^0)$ of 3.4 s⁻¹. This is only slightly faster than the simple triazole case and seems to indicate that the addition of a carbonyl to the linking scheme has a mild accelerating affect on electron transfer. We can hypothesize that this acceleration is due to the carbonyl allowing better π -conjugation of the substituted cyclopentadienyl ring with the triazole by reduction of ortho C-H strain. Previous work with oligophenylene ethynylene and oligophenyl vinylene bridges between ferrocene and gold has shown that π -conjugated linkages have much faster rates of electron transfer over similar distances.^{6,9} Thus it is not too surprising that similar rates are seen for the ester, triazole, and carbonyl triazole linkages, all of which can be π -conjugated to the cyclopentadienyl ring to a greater or lesser degree depending on the exact steric conformation adopted.

The nearly ideal voltammetry of the ferrocenes and porphyrins attached to the mixed alkane thiol monolayers via the polar 1,2,3-triazole linkage (90-100 mV full width at half maximum at slow scan rates) is also reminiscent of the nearly ideal voltammetry observed with the polar ester linkage to ferrocene in the earlier coabsorbed system.³⁸ In that work, a direct, nonpolar CH2 linkage to the ferrocene was also examined and shown to result in much broader, nonideal voltammograms, even at coverages as low as 10%. It was hypothesized that the more polar linkage prevented the formation of aggregates of redox species. It would thus appear that the 1,2,3-triazole linkage has a desirable mixture of conjugation and polarity that could prove useful in many contexts. Among many possible applications, the ease with which functionality can be introduced with the click coupling chemistry should be useful for future studies of how chemical structure in monolayers affects electron tunneling.

One striking aspect of Table 1 is the large difference in electron-transfer rate depending on whether the redox species is a ferrocene or an iron porphyrin. In the two mixed monolayers on which iron porphryins were studied $(N_3(CH_2)_{16}SH +$ $CH_3(CH_2)_{15}SH$ or $N_3(CH_2)_{16}SH + CH_3(CH_2)_{11}SH$ the rates were 10 to 50 times the value for the identical monolayer modified with ferrocene acetylene. A marked difference in reorganization energy between ferrocene and an iron porphyrin with two axial ligands is a likely explanation for this dramatic difference in rates. It is well-known from past work that the reorganization energy of ferrocene on a monolayer is approximately 0.85 eV. In this work, pyrazine was used as an additive to axially ligate the immobilized iron porphyrin.⁴⁵ The relatively small changes expected in the inner-sphere structure and the steric bulk of the aromatic porphyrin and pyrazine ligands should result in small inner- and outer-sphere contributions to the reorganization energy of this redox species. A future study of the temperature dependence of the rate of electron transfer for both the ferrocene and porphyrin-coupled monolayers is planned to verify this hypothesis.

We have demonstrated that electron-transfer rates can be predictably controlled to acetylene bearing redox species that have been coupled by click chemistry to dilute mixed azideterminated thiol monolayers on gold. The electron-transfer rate depends strongly on the length and degree of conjugation of the azide-terminated thiol to which the redox species is coupled as well as the length of the diluent thiol. These assemblies seem nearly ideal for applications where one is interested in predictably controlling and changing the electron-transfer rate to a functionally complex redox species. Although we are currently pursuing studies using these systems to control electron transfer to synthetic bimetallic catalysts one could imagine adapting such systems for electron-transfer studies involving both biomolecules such as redox enzymes or oligonucleotides and also nanoscale electronic materials such as metal or semiconductor nanoparticles or nanowires.

Experimental Section

Substrate Preparation. The gold substrates were prepared by condensation of an adhesion layer of electron-beam evaporated titanium (99.99% purity) followed by gold (99.99% purity) onto 4-in. silicon wafers. Silicon was pre-cleaned for 10 min in hot piranha (1 volume 30% by mass aqueous H_2O_2 :3 volumes H_2SO_4), and rinsed in deionized water. (**Warning**: Piranha solution reacts violently, even explosively, with organic materials. It should not be stored or combined with significant quantities of organic material.)

The titanium and gold depositions were carried out in a cryogenically pumped deposition chamber. Titanium thicknesses (monitored with a quartz oscillator) were on the order of 10-20 nm and gold thicknesses were on the order of 50-100 nm. After deposition, the chamber was backfilled with purified argon.

Formation of Mixed Thiol Monolayers on Gold. Freshly evaporated gold substrates were immersed for 24-36 h in deposition solutions made by dissolving the desired ratio of azide-terminated thiol and diluent thiol in ethanol. The total thiol concentration was always 0.1 mM. After deposition, the monolayer-coated samples were rinsed with ethanol and water and dried with N₂.

Surface Coupling via Cu(I)-Catalyzed Azide–Alkyne Cycloaddtion. Coupling solutions consisted of 3 volumes of dimethyl sulfoxide:1 volume of water containing 400 μ M TBTACuBF₄, 8 mM hydroquinone (to ensure that the catalyst remained in the active Cu(I) oxidation state), and 30 μ M of the desired acetylene. For convenience, the copper complex was formed as a 10 mM stock solution in dimethyl sulfoxide and appropriate aliquots were used. Because this stock solution slowly oxidizes with time, the mild reducing agent, hydroquinone, was added to ensure that the catalyst remained active. Mixed azide- and methyl-terminated monolayers were exposed to coupling solutions for roughly 10–15 min. After reaction, the surfaces were rinsed with ethanol, methylene chloride, ethanol, and water in that order.

Electrochemical Measurements. The electrochemical cell area was defined by pressing a cylindrically bored Teflon cone (4 or 8 mm inner diameter) against the sample. The bore was filled with 1 M aqueous perchloric acid. A platinum counter electrode and a glass frit-isolated Ag/AgCl/3 M NaCl(aq) reference electrode were suspended in the cell.

Synthesized Compounds. Tris(benzyltriazolylmethyl)amine (TBTA) was received as a gift from the Sharpless group.

The synthesis of 1-azidoundecan-11-thiol has been previously described.³⁰ 1-Azidohexadecan-16-thiol was synthesized in an identical manner with the exception that 1-bromohexadecanol was used as the starting material and during the last step

SCHEME 1^{*a*}



 a Reagents and conditions: (a) (1) HCl, NaNO₂, -20 °C, (2) K₂CO₃, Et₂NH. (b) Trimethylsilylacetylene, Pd(PPh₃)₄, CuI, Et₃N. (c) K₂CO₃, MeOH.

SCHEME 2^a



^{*a*} Reagents and conditions: (a) NBS, AIBN, benzene, reflux. (b) Potassium thioacetate, DMA. (c) DEEPT, Pd(PPh₃)₄, CuI, Et₃N.

SCHEME 3^a



 a Reagents and conditions: (a) Azidotrimethylsilane, trifluoroacetic acid. (b) K₂CO₃, MeOH.

(thioacetate deprotection) ethanol was substituted for methanol to maintain solubility.

Synthesis of Azidophenyleneethynylenebenzylthiol (N_3 (PEB)-SH or APEB). Preparation of **1b**. The synthesis was adapted from a previously reported procedure.⁴⁶ A suspension of 4-iodoaniline (3.02 g, 13.8 mmol) in water (30 mL) and concentrated hydrochloric acid (30 mL) was cooled in a ice/ salt bath. To the suspension was slowly added a solution of sodium nitrite (1.5 g, 20.7 mmol) in ice cold water (10 mL) under vigorous stirring. After being stirred for 15 min, the diazonium solution was slowly added to a solution of diethylamine (2.52 g, 35 mmol) in water (30 mL), in an ice bath. Potassium carbonate was added until CO₂ evolution ceased. The mixture was stirred for 1 h at room temperature, extracted with CH₂Cl₂, and washed with brine. The organic phase was dried with anhydrous MgSO₄ and the solvent was evaporated. Column chromatography (silica, hexane/CH₂Cl₂, 1:1 v/v) of the residue yielded a reddish brown oil (3.94 g, 94%). ¹H NMR (CDCl₃, 200 MHz) δ 7.59 (d, 2H), 7.14 (d, 2H), 3.73 (q, 4H), 1.24 (t, 6H).

Preparation of Ic. The synthesis was adapted from a previously reported procedure.⁴⁷ **1b** (3.76 g, 12.4 mmol), Pd(PPh₃)₄ (90 mg), and CuI (130 mg) were placed in a roundbottom flask. The flask was evacuated and backfilled with nitrogen, after which triethylamine (18 mL) was added. After three cycles of evacuation and backfilling with nitrogen, trimethylsilylacetylene (1.83 g, 18.6 mmol) was added, and the mixture was stirred at 40 °C for 2 days. The mixture was filtered, and solvent was evaporated from the filtrate. The resulting residue was chromatographed (silica, hexane/CH₂Cl₂, 1:1 v/v) to yield a tan solid (3.35 g, 99%). ¹H NMR (CDCl₃, 200 MHz) δ 7.41 (d, 2H), 7.32 (d, 2H), 3.74 (q, 4H), 1.24 (t, 6H), 0.23 (s, 9H).

Preparation of DEEPT. To a solution of **1c** (2.5 g, 9.2 mmol) in methanol (40 mL) was added potassium carbonate (1.9 g, 14 mmol). The mixture was stirred for 2 h at room temperature after which it was extracted with CH₂Cl₂. The organic phase was washed with water and then brine, and dried over MgSO₄. Rotary evaporation of the solvent yielded a brown oil (1.8 g, 97%). ¹H NMR (200 MHz, CDCl₃) δ 7.41 (d, 2H), 7.31 (d, 2H), 3.72 (q, 4H), 3.01 (s, 1H), 1.22 (t, 6H).

Preparation of **2b**. A suspension of **3a** (38.8 g, 178 mmol), azobis(isobutyronitrile) (3.2 g), and *N*-bromosuccinimide (36.5 g, 205 mmol) in benzene (70 mL) was placed in a round-bottom flask fitted with a reflux condenser. The reaction chamber was evacuated and backfilled with nitrogen three times. The reaction mixture was refluxed overnight in the dark. The solvent was evaporated and the residue was chromatographed (silica, hexane) to yield a cream-colored solid (28.7 g, 55%). ¹H NMR (CDCl₃, 200 MHz) δ 7.66 (d, 2H), 7.12 (d, 2H), 4.40 (s, 2H).

Preparation of 4-Iodobenzylthioacetate. The synthesis was adapted from a previously reported procedure.⁴⁷ **2b** (1.45 g, 4.9 mmol) and potassium thioacetate (663 mg, 5.8 mmol) were dissolved in dimethylacetamide (10 mL). The solution was stirred for 2 days, then poured into water (200 mL) and extracted with CHCl₃. The organic phase was washed with water and brine, and then dried with anhydrous MgSO₄. The solvent was evaporated, and the residue was chromatographed (silica, hexane:CHCl₃) to yield a pale solid (597 mg, 42%). ¹H NMR (CDCl₃, 200 MHz) δ 7.60 (d, 2H), 7.02 (d, 2H), 4.02 (s, 2H), 2.33 (s, 3H).

Preparation of Pre-APEB. The synthesis was adapted from a previously reported procedure.⁴⁷ 4-Iodobenzylthioacetate (195 mg, 0.67 mmol), Pd(PPh₃)₄ (4.6 mg), and CuI (6.6 mg) were placed in a round-bottom flask. The flask was evacuated and backfilled with nitrogen, after which triethylamine (5 mL) and THF (8 mL) were added. After three cycles of evacuation and backfilling with nitrogen, DEEPT (134 mg, 0.67 mmol) was added, and the mixture was stirred at 40 °C for 2 days. The solvent was evaporated, and the residue was chromatographed (silica, hexane/CH₂Cl₂, 1:1 v/v) to yield Pre-APEB (240 mg, 98%). ¹H NMR (CDCl₃, 200 MHz) δ 7.43 (d, 2H), 7.39 (d, 2H), 7.33 (d, 2H), 7.20 (d, 2H), 4.06 (s, 2H), 3.73 (q, 4H), 2.31 (s, 3H), 1.22 (t, 6H).

Preparation of Pre-APEB* (conversion of triazene to azide). The synthesis was adapted from a previously reported procedure.⁴⁸ To a solution of Pre-APEB (250 mg, 0.67 mmol) in CHCl₃ (4.5 mL) was added trifluoracetic acid (382 mg, 3.35 mmol). After the solution was stirred for 15 min, azidotrimethylsilane (93 mg, 0.8 mmol) was added. After being stirred for 1 h, the mixture was poured into water (100 mL) and





^{*a*} Reagents and conditions: (a) AcOH, reflux, 1 h, 3%. (b) (i) SnCl₂·2H₂O, HCl, room temperature, 16 h; (ii) NH₄OH, 75%. (c) Propiolic acid, DCC, EtOAc, room temperature, 24 h, 70%. (d) (i) FeBr₂, CH₃OH/THF, reflux, 45 min; (ii) O₂, CH₃OH/THF/C₆H₆, room temperature, 1 h; (iii) 8% aq.HCl, room temperature, 85%.

extracted with CHCl₃. The organic phase was washed with brine and then dried with anhydrous MgSO₄. Rotary evaporation yielded Pre-APEB* as an orange solid (201 mg, 98%). ¹H NMR (CDCl₃, 200 MHz) δ 7.48 (d, 2H), 7.42 (d, 2H), 7.24 (d, 2H), 6.98 (d, 2H), 4.10 (s, 2H), 2.34 (s, 3H); mp 61–63 °C.

Preparation of APEB (deacylation of thioacetate). Potassium carbonate (90 mg, 0.65 mmol) was added to a solution of Pre-APEB* (100 mg, 0.33 mmol) in methanol (5 mL). The mixture was stirred for 4 h under nitrogen and then poured into water. The mixture was extracted with CHCl₃ and washed with brine. The organic phase was dried with anhydrous MgSO₄, and the solvent was evaporated. The residue was chromatographed (silica, CHCl₃) to yield a tan solid (70 mg, 81%). ¹H NMR (CDCl₃, 200 MHz) δ 7.49 (d, 2H), 7.45 (d, 2H), 7.29 (d, 2H), 6.99 (d, 2H), 3.73 (d, 2H), 1.75 (t, 1H); mp 65–68 °C; *R*_f (hexane/CH₂Cl₂ 7:3 vol) 0.55.

Synthesis of meso-5-Mono-o-propynamidophenyl-10,15,20triphenylporphyriniron(III) Chloride (3). Porphyrin **3** was prepared in four steps (Scheme 4) starting from the acidcatalyzed ring cyclization of **4** by mixed condensation of benzaldehyde, o-nitrobenzaldehyde, and pyrrole⁴⁹ followed by separation of **4** from the statistical mixture. The reduction of **4** to **5**⁴⁹ with SnCl₂,⁴⁹ followed by dicyclohexylcarbodiimide (DCC) coupling with propynoic acid led to **6**. Iron(II) was inserted into **6** to give **3** with standard procedures.⁵⁰ This occurred without any significant side reactions on the alkyne moiety. The details of the preparation and characterization of new porphyrins **3** and **6** are provided below and follow standard procedures in porphyrin chemistry.^{49,51}

meso-5-Mono-o-propynamidophenyl-10,15,20-triphenylpor-phyrin (6). 5 (100 mg, 0.158 mmol), propynoic acid (500 mg, 7.30 mmol), and DCC (150 mg, 0.73 mmol) were mixed in ethyl acetate (20 mL) and the resulting mixture was stirred at room temperature for 24 h. After most of the starting material had been consumed (monitored by TLC), the volume of the solution was expanded (50 mL EtOAc) and the mixture was washed with NaHCO₃ solution (2 × 50 mL) and water (2 × 100 mL) and dried (Na₂SO₄). After evaporation of the solvent, the residue was subjected to chromatography [SiO₂, 63 μ m (230–400 mesh), 20 × 3 cm, eluent: gradient hexane/dichloromethane]. Evaporation of the solvent led to **6** as a dark residue (70%, 75 mg). ¹H NMR (500 MHz, CDCl₃) $\delta_{\rm H}$ (ppm) 8.90 (m, 6H), 8.75 (d, 2H, *J* = 5.0 Hz), 8.71 (d, 1H, *J* = 8.5 Hz), 8.22 (m, 6H), 8.04 (d, 1H, *J* = 7.0 Hz), 7.84 (t, 1H, *J* =

7.5 Hz), 7.78 (m, 9H), 7.54 (t, 1H, J = 7.5 Hz), 7.14 (s, 1H), 1.97 (s, 1H), -2.73 (s, 2H); ¹³C NMR (75 MHz, CDCl₃) $\delta_{\rm C}$ (ppm) 149.80, 142.13, 141.89, 137.96, 135.15, 134.80, 134.75, 134.62, 131.73, 129.88, 128.12, 127.01, 126.94, 123.84, 121.51, 121.36, 120.88, 112.21, 74.09; MS (ESI⁺) m/z 682.9 [M + H]⁺ (Calcd for C₄₇H₃₁N₅O); UV/vis (CH₂Cl₂) λ (nm) 10⁻³ × ϵ (M⁻¹ cm⁻¹) 374 (12.0), 400 (3.7, sh), 418 (158.2), 482 (2.3, sh), 514 (8.5), 548 (3.6), 588 (2.9), 648 (2.5), 678 (1.1); TLC (SiO₂, hexane/dichloromethane 1:1 v/v) R_f 0.6 (purple spot); mp 185 °C.

meso-5-Mono-o-propynamidophenyl-10,15,20-triphenylporphyriniron(III) Chloride (3). To an O₂-free solution of freebase porphyrin **6** (90 mg, 0.13 mmol) in a CH₃OH–THF mixture (1:4 vol, 25 mL) was added FeBr₂ (71 mg, 0.330 mmol) and the resulting mixture was heated for 45 min. The solution was cooled and air was bubbled through the solution for 1 h. After addition of benzene (50 mL), the μ -oxo complex was hydrolyzed by washing with 8% HCl solution (3 × 50 mL). Solvents were distilled leaving the paramagnetic species **3** as a dark blue residue (85.1 mg, 85%). MS (ESI⁺, *m/z*) 735.3 [M – Cl]⁺ (Calcd for C₄₇H₂₉ClFeN₅O); UV/vis (CH₂Cl₂) λ (nm) 10⁻³ × ϵ (M⁻¹ cm⁻¹) 320 (18.6), 410 (62.6), 508 (4.0), 570 (4.8), 610 (1.9), 674 (0.6); TLC (Al₂O₃, hexane/ethyl acetate 2:1 v/v) R_f 0.5 (green-brownish spot).

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