# Understanding the Role of Adsorption in the Reaction of Cyclopentadiene with an Immobilized Dienophile

**Eugene W. L. Chan, Muhammad N. Yousaf, and Milan Mrksich\***

*Department of Chemistry, The University of Chicago, Chicago, Illinois 60637*

*Received: February 10, 2000; In Final Form: July 12, 2000*

This paper presents a kinetic characterization for the Diels–Alder reaction of cyclopentadiene with 2-mercaptobenzoquinone chemisorbed to a gold substrate. Cyclic voltammetry was used to investigate the rate of the reaction because the quinone undergoes a reversible two-electron reduction but the product of reaction is not electroactive. Reactions were performed in 1:1 THF:H$_2$O (2 mM phosphate and 70 mM NaCl, pH = 7.4) and monitored by voltammetric scanning between −120 and −20 mV. The rate of loss in peak current correlated with the rate of Diels–Alder reaction and was described well by an exponential decay in agreement with the pseudo-first-order kinetics expected with the high concentration of cyclopentadiene relative to quinone. The first-order rate constants, however, did not increase linearly with the concentration of diene as would be expected for a second-order bimolecular reaction. Instead, the first-order rate constants reached a limiting value with higher concentrations of cyclopentadiene. The kinetic behavior was better explained by a pathway wherein the cyclopentadiene first adsorbs to the monolayer and then reacts with the immobilized quinone. The data were fit well by a rate law based on a Langmuir isotherm for adsorption of diene to the monolayer and a first-order rate constant for the Diels–Alder reaction and gave a first-order rate constant of 0.011 s$^{-1}$ and an equilibrium constant for association of cyclopentadiene with the substrate of 65 M$^{-1}$. The equilibrium constant for adsorption depended on the composition of solvent and was larger in an electrolyte containing 1:2 THF:H$_2$O (163 M$^{-1}$) and smaller in 2:1 THF:H$_2$O (28 M$^{-1}$). But in all cases, the first-order rate constant for cycloaddition was unchanged. The combination of self-assembled monolayers as structurally well-defined substrates and cyclic voltammetry to measure the rates of reactions provides a methodology that is well suited for studying many mechanistic features of interfacial reactions.

An understanding of the reactions of organic molecules immobilized at the solid–liquid interface is of fundamental interest and is important to a number of applications, including sensing,[1] solid-phase combinatorial synthesis,[2] and heterogeneous catalysis.[3] Mechanistic studies of reactions at interfaces are usually more complicated than are studies of the same reactions in solution. Consequently, many factors that affect reactivity at surfaces, but which have no counterpart in solution chemistry, are not well understood. Studies of interfacial reactions would benefit from model substrates that present immobilized groups in a homogeneous and well-defined environment and from convenient techniques that can characterize the kinetics and products of these reactions.[4] This paper uses a combination of self-assembled monolayers and cyclic voltammetry to illustrate two important factors—the role of adsorption of reactant molecules and the role of solvent—that affect the kinetic pathway for the reaction of cyclopentadiene with an immobilized benzoquinone.

Several investigators have reported on the reactions of soluble molecules with immobilized molecules. Myles and co-workers, for example, used grazing angle IR to characterize the formation of an imine by the condensation of an alkylamine with an aldehyde presented on a self-assembled monolayer.[5] Whitesides and co-workers described a convenient method to immobilize amines to self-assembled monolayers presenting carboxylic acids that were first activated with trifluoroacetic acid.[6] Corn and co-workers reported the activation of carboxylic acids to the acid

chlorides, and a subsequent reaction with a soluble amine or alcohol, to give the corresponding amide or ester.[7] These examples, and many others, aimed to develop methods for the attachment of molecules to monolayers that were already formed. Consequently, much of this work has characterized the yields and products of the reactions, but usually has not investigated the mechanistic and kinetic features of the reactions. Furthermore, the analytical techniques used in these studies— grazing angle Fourier transform infrared spectroscopy, X-ray photoelectron spectroscopy, ellipsometry, and goniometry—are not well suited for recording kinetic information in situ and in real time. Additional studies are needed to address mechanistic aspects of interfacial reactions, including the effects of environment surrounding the immobilized reactants, the density of reactants, and the composition of the contacting solution.

Several early reports show that the rates and kinetic pathways for reactions of immobilized molecules can differ substantially from those of the same reactions in solution.[8] Chechik and Stirling, for example, used grazing angle IR spectroscopy to measure the rates for condensation of soluble amines with an activated nitrophenylester that was incorporated into a self-assembled monolayer.[9] The reactions proceeded with second-order kinetics and the magnitude of the rate constant depended on the position of the ester within the monolayer. As expected, the overall rate of reaction was fastest when the ester was exposed at the surface and decreased as it was positioned below the surface of the monolayer. In all cases, however, the rate constants were greater than the second-order rate constant for reaction of the amine with a soluble nitrophenylester. The

* To whom correspondence should be addressed.

authors reasoned that the increased rate was due to a preassociation of the amine with the monolayer, which served to increase the local concentration of amine near the ester. But this model may not be consistent with the experimentally determined second-order rate constants, since the amount of amine that is associated with the monolayer is not expected to increase linearly with the concentration of amine in the bulk solvent. Further studies are required to understand the mechanisms by which association (or adsorption) of reagents can affect the rates and kinetic order for interfacial reactions.

In this paper, we present a kinetic characterization for the reaction of cyclopentadiene (Cp) with 2-mercaptobenzoquinone chemisorbed to a gold substrate. Unlike the reaction of these two molecules in solution, this reaction did not proceed with second-order kinetics. Instead, the kinetic data are consistent with a mechanism wherein Cp adsorbs to the substrate in an equilibrium manner and subsequently reacts with the immobilized quinone. We present a kinetic analysis of the experimental data that provides both a thermodynamic association constant for adsorption of the diene to the monolayer and a first-order rate constant for the cycloaddition reaction.

## Results

Monolayers of 2-mercaptohydroquinone chemisorbed to gold have been prepared and characterized extensively by the groups of Soriaga,[10] Scherson,[11] Uosaki,[12] and Hubbard.[13] This previous work has established that the mercaptohydroquinone attaches to the gold in a vertical orientation and through coordination of the thiol group. The hydroquinones are irreversibly adsorbed (on the time scale of cyclic voltammetry experiments) and undergo a reversible electrochemical oxidation to give the quinone. We prepared substrates used in the present work according to the method of Uosaki.[12] Cyclic voltammetry of this substrate in 1:1 THF:H$_2$O showed that the hydroquinone undergoes a two-electron oxidation at −20 mV (versus Ag/AgCl) and the resulting quinone undergoes reduction at −120 mV.[14] The larger peak to peak separation for this redox couple is known for quinones, and is due in part to the transfer of protons needed to go between quinone and hydroquinone. The large dependence of peak separation on pH supports this view. Integration of the area under the waves for either oxidation or reduction gave a density of adsorbed quinone of $3.9 \times 10^{-10}$ mol·cm$^{-2}$: this value agrees with values found in previous studies.[13]

The monolayers could be cycled between the oxidized and reduced forms greater than 30 times with no change in the voltammograms and showed that the chemisorbed hydroquinone was stable under these conditions. When this same experiment was repeated in the presence of cyclopentadiene (7.6 mM), consecutive voltammograms showed a decrease in peak currents for both oxidation and reduction (Figure 1). The following observations supported our interpretation that the decrease in peak currents during consecutive scans was due to the Diels−Alder reaction of Cp with the immobilized quinone. The addition of other dienes (including cyclohexadiene and 1-cyclopentadienylmethyl acetate) to the electrolyte gave similar losses in current over consecutive cycles (although with different rates), but the structurally related cyclopentane and cyclopentene (which do not participate in the Diels−Alder reaction) had no effect over the same number of scans. Ellipsometry showed that the thickness of the monolayer increased by an amount consistent with the Diels−Alder reaction. The monolayer of 2-mercaptobenzoquinone chemisorbed to gold had an average thickness of 4.4 ± 0.8 Å. Following reaction with 1-hexylcy-
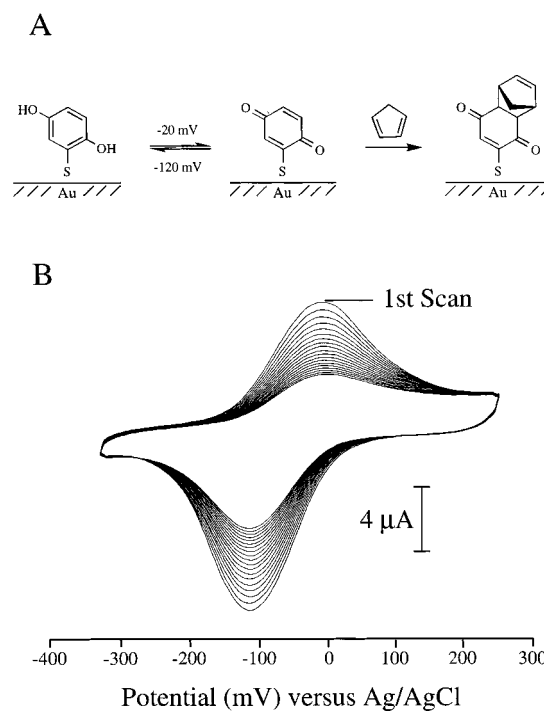
A



B



**Figure 1.** (A) Reversible oxidation of 2-mercaptohydroquinone chemisorbed to a gold electrode giving the corresponding benzoquinone. This quinone serves as a dienophile in the Diels−Alder reaction with cyclopentadiene. (B) Consecutive cyclic voltammograms of a monolayer of 2-mercaptohydroquinone chemisorbed to a gold electrode in 1:1 THF:H$_2$O (2 mM phosphate, 70 mM NaCl, pH = 7.4) containing cyclopentadiene (7.6 mM) with a scan rate of 25 mV/s. Consecutive scans show decreasing peak currents for both the oxidation and reduction waves. The loss in peak current for the reversible oxidation of hydroquinone represents the extent of the Diels−Alder reaction.

clopentadiene (the hexyl side chain served to increase the contrast in the thickness measurements), the monolayer had a thickness of 12.4 ± 0.9 Å. Finally, we have used this Diels−Alder reaction for the immobilization of ligands.[8a] This functional demonstration gives a strong evidence that the two molecules react to give a covalent adduct at the monolayer. Scherson and Uosaki used difference Fourier transform IR reflection adsorption spectroscopy to characterize films of 2-mercaptoquinone on the gold substrate.[10,15] Difference spectra of the monolayers at different potentials, to contrast the oxidized and reduced forms, were necessary to observe the weak intensities of stretches. We were not able to use this technique to characterize the product of the Diels−Alder reaction, since it does not undergo reversible electrochemical reduction.

Figure 2 shows a plot of relative peak current versus time for the data illustrated in Figure 1. We expected that the loss of peak current should follow pseudo-first-order kinetics because the diene was present in large excess relative to the quinone. Indeed, the data were fit well by a first-order decay (eq 1), where $I_t$ is the peak current for oxidation

$$I_t = I_f + (I_0 - I_f) \exp(-k't) \qquad (1)$$

at time $t$, $I_0$ is the peak current in the first voltammogram (at time 0), $I_f$ is the nonfaradaic current when all of the quinone has been consumed, and $k'$ is the first-order rate constant. We repeated the same experiment several times with increasing concentrations of diene in order to obtain the second-order rate constant. Surprisingly, the first-order rate constants ($k'$) did not increase linearly with the concentration of Cp (Figure 3). The
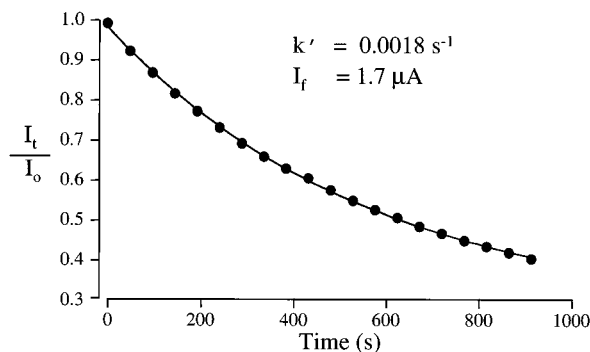
**Figure 2.** A plot of the ratio of peak current ($I_t$) to initial peak current ($I_0$) for the oxidation of hydroquinone versus time for the reaction of cyclopentadiene with immobilized quinone shown in Figure 1. The difference between peak current ($I_t$) and final current ($I_f$) is directly proportional to the density of benzoquinone ($\Gamma_Q$) chemisorbed to the gold surface. The curve is the best fit exponential to the data using eq 1 and provides a first-order rate constant ($k'$) for the reaction.
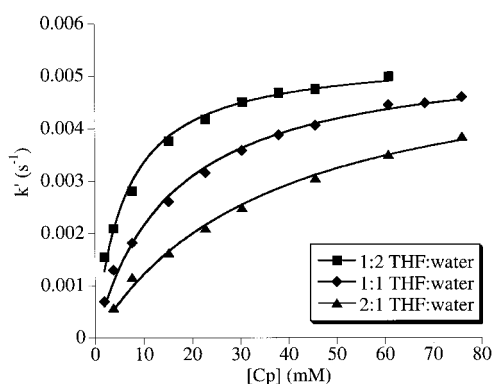


**Figure 3.** Dependence of first-order rate constants (as determined in Figure 2) on the concentration of cyclopentadiene. Each data point represents the exponential decay ($k'$) at a single concentration of cyclopentadiene and in a single solvent composition (see legend in inset). The three sets of data represent experiments performed in electrolytes having different compositions of THF and $H_2O$. The curves are the best nonlinear least-squares fit of the data to eq 4 with $K_{ads}$ and $k_{rxn}$ as adjustable parameters. The best-fit values of these parameters are presented in Table 1.

kinetic data are clearly inconsistent with a reaction that proceeds through a single, bimolecular collision. We reasoned that the nonlinearity in this plot could be better explained by a kinetic scheme wherein the diene first associates with the monolayer in an equilibrium manner and subsequently undergoes Diels–Alder reaction with the quinone.

We next derive a rate law that accommodates this model. The derivation makes the assumption that the density of sites to which diene can adsorb is equivalent to the density of quinone molecules chemisorbed to the gold. In the discussion section that follows, we offer a structural model that is consistent with this assumption. The rate of the reaction is given by the product of a first-order rate constant ($k_{rxn}$, units of s$^{-1}$) and the surface coverage of quinone groups that are associated with adsorbed diene ($\Gamma_{Cp\cdot Q}$, units of mol·cm$^{-2}$).[16] We define $\theta$ as the fraction of quinone groups that are associated with an adsorbed diene, and represent this term as the ratio $\Gamma_{Cp\cdot Q}/\Gamma_Q$, where $\Gamma_Q$ is the surface coverage of total quinone (as revealed by cyclic voltammetry) and both coverages are time dependent quantities. Because the rate of disappearance of quinone (-$d\Gamma_Q/dt$) is equal to the rate of formation of product, the rate of reaction is given by eq 2. Rearrangement of eq 2 followed by integration and exponentiation gives eq 3, which relates the rate of decay of quinone ($\Gamma_{Q_{max}}$ is the surface concentration of quinone

$$\text{rate} = -\frac{d\Gamma_Q}{dt} = k_{rxn}\theta\Gamma_Q \qquad (2)$$

$$\frac{\Gamma_Q}{\Gamma_{Q_{max}}} = \exp^{(-k_{rxn}\theta_t)} \qquad (3)$$

at initial time and is a constant) to the first-order rate constant and the fractional occupancy $\theta$. The experimental values $k'$ shown in Figure 3 are therefore equal to the quantity $k_{rxn}\theta$. We used a Langmuir isotherm to express $\theta$ in terms of the concentration of diene in the bulk solution ([Cp]) and the equilibrium constant for adsorption of Cp to the monolayer ($K_{ads}$). The Langmuir isotherm makes the assumptions that adsorption is reversible, at equilibrium, and that the energy of association of a molecule at a given site is independent of adsorption of a second molecule at a neighboring site.[17] The dependence of $k'$ on the concentration of Cp is given in eq 4. We fit the ($k'$, [Cp]) data to eq 4, with $K_{ads}$ and $k_{rxn}$ as adjustable parameters. The fit was excellent and gave

$$k' = \frac{k_{rxn}K_{ads}[Cp]}{1 + K_{ads}[Cp]} \qquad (4)$$

values of 65 M$^{-1}$ and 0.0055 s$^{-1}$ for $K_{ads}$ and $k_{rxn}$, respectively. This value of $k_{rxn}$ understates the true rate, since it does not take into account the time during which the unreactive hydroquinone was present on the monolayer during the cyclic voltammetry. The value of $k_{rxn}$ was divided by the fraction of time during which quinone was present to give the true rate constant for the Diels–Alder reaction: $k_{DA} = 0.011$ s$^{-1}$.

This treatment of the data provides both an equilibrium constant that describes the free energy of adsorption of Cp to the monolayer and a microscopic rate constant for the reaction of adsorbed Cp with immobilized quinone. We reasoned that $K_{ads}$ would depend on the solvent, because the chemical potential of Cp will vary with solvent composition, but that $k_{rxn}$ for the reaction of Cp with the chemisorbed quinone might be independent of solvent composition. To test this hypothesis, we repeated the determination of $k'$ for a range of concentrations of Cp in electrolyte having solvent composition of either 1:2 or 2:1 THF:$H_2O$. For each experiment, the reaction of Cp with quinone proceeded with first-order kinetics and to completion. For both solvent systems, the experimental data relating $k'$ to the concentration of Cp were again described well by eq 4. The best-fit values of $K_{ads}$ and $k_{rxn}$ are listed in Table 1. A comparison of the values shows that $K_{ads}$ does indeed depend on the solvent composition and is smaller for solvents that contain a higher proportion of THF, and in which Cp has a higher solubility. The experimental values of $k_{rxn}$, by contrast, are nearly constant and show that the first-order reaction of adsorbed Cp with quinone proceeds with a first-order rate constant that is independent of the ratio of THF and $H_2O$ over the range used here. Control experiments showed that the values of $K_{ads}$ and $k_{rxn}$ were influenced only by solvent composition and not by the activity of electrolyte. The best-fit values of $K_{ads}$ and $k_{rxn}$ in 1:1 THF:$H_2O$ remained unchanged when the concentrations of phosphate and NaCl were varied from 0.7 to 3 mM and from 23 to 210 mM, respectively.

## Discussion

This paper provides a clear example of the role of adsorption of a reactant on the rate behavior of an interfacial reaction. Our data for the reaction of Cp with quinone chemisorbed to a gold

**TABLE 1: Best-fit Values of $K_{Ads}$ and $k_{rxn}$ in Cosolvents Having Three Different Ratios of THF and $H_2O$**

| | THF:$H_2O$ | | |
|---|---|---|---|
| | 1:2 | 1:1 | 2:1 |
| $K_{ads}$ ($M^{-1}$) | $160 \pm 18$ | $64 \pm 3$ | $29 \pm 2$ |
| $k_{DA}$ ($s^{-1}$) | $0.0112 \pm 0.0004$ | $0.0112 \pm 0.0003$ | $0.0113 \pm 0.0003$ |

*[a]* Uncertainties represent the standard deviation from three independent experiments.

substrate is most consistent with a pathway that involves association of cyclopentadiene with the surface prior to the reaction of the two molecules. The kinetic data are described remarkably well by a model that assumes a Langmuir isotherm for the adsorption of diene to the substrate. This correlation implies that the association constant and the rate constant are independent of the extent of adsorption or reaction. This behavior contrasts with the usual observation that interfacial reactions give heterogeneous kinetics because as the reaction progresses the structure of the substrate changes and affects the reaction of remaining groups. We next discuss the structure of the monolayer to provide a possible explanation for the well-behaved kinetics.

Scherson and co-workers characterized the structure of a monolayer of 2-mercaptohydroquinone on gold using in situ second harmonic generation measurements.[18] These studies were consistent with a $\sqrt{7} \times \sqrt{7}R19.1°$ superstructure of chemisorbed thiohydroquinone on the gold (111) substrate. The unit cell for this arrangement contains one hydroquinone group and has an area of 50 Å$^2$. The total area occupied by the vertically oriented hydroquinone group is 22 Å$^2$, which leaves an area of approximately 28 Å$^2$ as a void that can be occupied by cyclopentadiene (the projected area of a vertically oriented cyclopentadiene is approximately 27 Å$^2$). Figure 4 shows a space-filling model for the monolayer that is consistent with the structural data and that illustrates one way in which cyclopentadiene can intercalate in the voids between thioquinone molecules. We have made the assumption that the hydroquinone groups are all oriented in parallel and at an angle that reveals the vacant site that can accommodate the diene. We emphasize that this analysis does not prove the mechanism for adsorption of diene, but is intended to give a reasonable structural picture that is consistent with the data. Of course, in the absence of intercalated cyclopentadiene, the quinone groups likely undergo rotational dynamics and the free volume is occupied by solvent molecules. Nevertheless, this model provides a reasonable explanation for the observed Langmuir behavior in adsorption since the intercalation sites are each separated from one another and to a first approximation, adsorption in one site does not dramatically change the structure and energetics for association of a second Cp with a neighboring site. Finally, we note that our data cannot rule out a related model wherein the diene does not adsorb to the monolayer, but rather partitions between the bulk solution and the near-surface region.

The dependence of the thermodynamic adsorption constant ($K_{ads}$) on the composition of solvent is readily explained. The adsorption constant represents the difference in free energy for transferring a molecule of diene from the bulk solvent to the monolayer (presumably in the intercalation site). The chemical potential of the molecule in the bulk solvent will depend on the ratio of THF and water. As the proportion of THF increases, the chemical potential of diene decreases. The chemical potential of the molecule when associated with the monolayer may also depend on the solvent composition, but this dependence should be much less significant. Hence the magnitude of $K_{ads}$ should

increase with cosolvents that have lower proportions of THF. This trend is what we find. The free energies of adsorption of Cp to the monolayer in 2:1, 1:1, and 1:2 THF:water are $-1.6$, $-2.0$, and $-2.5$ kcal·mol$^{-1}$, respectively.

This result is analogous to Breslow's description of the "antihydrophobic effect" wherein the rate for dimerization of cyclopentadiene in water decreases as ethanol is added to the water.[19] In that work, ethanol is termed an antihydrophobic solvent, because it is better at solvating the diene than is water. The stronger solvation increases the barrier to reaction of the two molecules. In our work, THF is better at solvating the diene, and hence higher concentrations of THF lead to better solvation that must be overcome for the diene to adsorb to the monolayer.

It is notable that the first-order rate constants showed no dependence on the composition of solvent. We offer two possible explanations for this result. First, the composition and structure of solvent at the liquid−solid interface are likely different from those in the bulk, and may be independent of the composition of cosolvents. In this case the ratio of cosolvents is by itself not important: it is only the composition of solvent at the interface that is important. We also note that the ratios of solvents were varied over a relatively small range (33%−66% THF). Second, intercalation of diene into the monolayer may give a reaction complex which is largely desolvated and therefore not affected by changes in solvent composition.

Our analysis of the kinetics for the interfacial reaction did not explicitly consider mass transport of diene from the solution to the substrate. In many interfacial reactions, and especially redox reactions at the solution−electrode interface, the kinetics are often dominated by the rates of diffusion of molecules from the bulk to the reaction layer. Here we explain why the Diels−Alder reaction is not rate-limited by diffusion of the diene to the substrate. We first consider the use of high concentrations of Cp that give values of $\theta$ near 1. In these cases, the diene is associated with the monolayer at the start of the reaction and therefore progression of the reaction does not deplete diene from the near-surface region. The use of lower concentrations of Cp, where the diene is associated with only a small fraction of immobilized quinones, does lead to depletion of diene from the near-surface region as the reaction proceeds. A comparison of the flux of Cp into the reaction layer due to diffusion and the flux of Cp out of the reaction layer due to the reaction establishes that the concentration of Cp in the reaction layer does not appreciably decrease over the course of the reaction. The flux of Cp due to reaction is given by eq 2. For a value of $\theta = 0.1$, the initial rate of reaction (where $\Gamma_Q = 3.9 \times 10^{-10}$ mol/cm$^2$) is $4.3 \times 10^{-13}$ mol/(cm$^2$·s). This value represents the maximum flux; of course, the flux decreases as the reaction proceeds and is also smaller for lower values of $\theta$. The flux of Cp from the bulk to the reaction layer is given by the product of the diffusion constant of Cp (for small molecules, approximately $10^{-6}$ cm$^2$/s) and the gradient of [Cp] with distance. If we assume a concentration of 1 mM in the bulk, 0.9 mM in the reaction layer, and a reaction layer thickness of 1 mm, then the initial flux of Cp into the reaction layer is $10^{-9}$ mol/(cm$^2$·s). It is apparent that the rate of reaction is approximately 1000-fold slower than the rate of diffusion of Cp into the reaction layer and that the concentration of Cp in the reaction layer is constant (and equal to the bulk concentration) over the entire course of reaction.

The reactions of organic molecules at interfaces are important in several applied areas, including the preparation of combinatorial libraries by solid-phase routes, the use of immobilized arrays of molecules to identify catalysts, and the modification of surfaces to tailor properties. In many of these examples, the
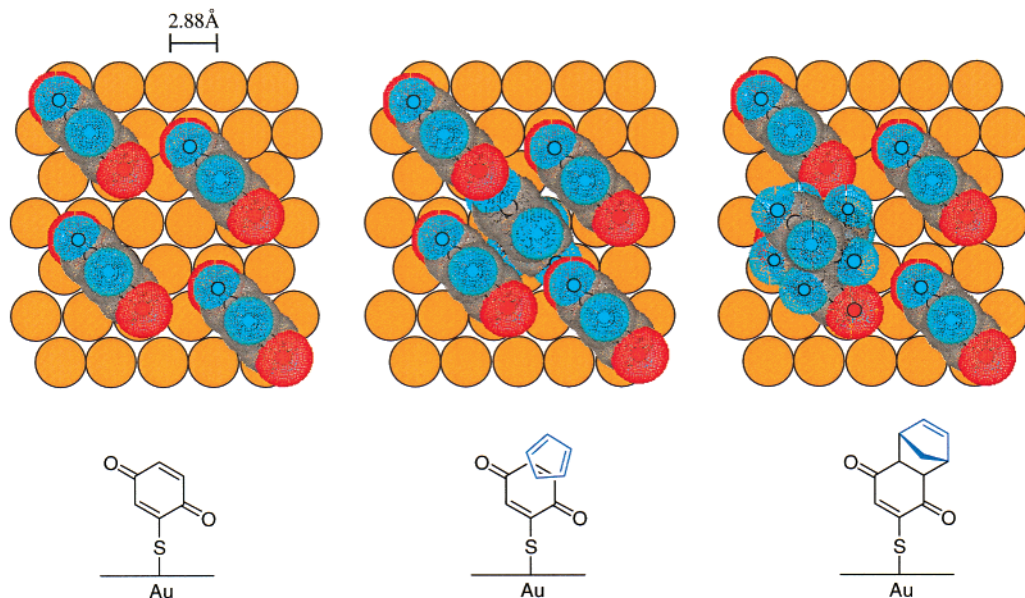
Reaction of Cyclopentadiene with an Immobilized Dienophile

*J. Phys. Chem. A, Vol. 104, No. 41, 2000* **9319**



**Figure 4.** A proposed model for the association of cyclopentadiene to the monolayer of chemisorbed quinone. The 2-mercaptoquinone groups were arranged in a $\sqrt{7} \times \sqrt{7}R19.1°$ superstructure and in a parallel manner to illustrate a void (left) in the monolayer that can accommodate the intercalation of a cyclopentadiene (middle). The structure of the monolayer following cycloaddition with Cp is shown on the right.

interfacial reactions have not been studied in sufficient detail to know whether the mechanistic effects reported in this paper (and others) play a role. Indeed, studies of the type reported here will establish a better fundamental understanding of the factors that affect interfacial reactions and in turn provide a mechanistic framework for controlling the reactions of organic molecules at interfaces.

**Conclusion**

This paper illustrates one way in which an interfacial reaction can differ markedly from the same reaction in solution. The rate of a reaction that proceeds through a pathway involving adsorption of a soluble reactant to a surface to which the co-reactant is confined can differ dramatically from the rate of the analogous reaction in solution. The rate can also respond in unexpected ways to changes in the composition of the solvent. In furthering this work, it will be important to use scanning probe techniques to characterize the structure of the monolayers of chemisorbed quinone in the presence and absence of diene, and to better understand the basis for adsorption of Cp. We believe that the combination of self-assembled monolayers and electrochemistry described here provides a methodology that is well suited for understanding many features characteristic of the physical organic chemistry of interfacial reactions.

**Experimental Section**

**Reagents.** Deionized ultrafiltered water, tetrahydrofuran (HPLC grade), and absolute ethanol were purchased from Fisher Scientific. Phosphate-buffered saline was purchased from Gib-coBRL. Benzoquinone, dicyclopentadiene, thiourea, and sodium hydroxide were purchased from Aldrich. Cyclopentadiene was distilled to remove the dimer resulting from cycloaddition prior to each experiment. 1-Hexylcyclopentadiene was prepared from the reaction of sodium cyclopentadiene with 1-bromohexane in THF. 2-Mercaptohydroquinone was synthesized as described by Burton[20] and purified by filtration through silica gel in hexane:ethyl acetate (3:1) to give a white crystalline solid. The mecaptohydroquinone was stable for periods of 2 weeks when stored under $N_2$ and protected from light.

**Preparation of Monolayers Substrates.** Titanium (100 Å) and then gold (1000 Å) were evaporated onto the silicon wafers (111, Silicon Sense) using a Thermionics e-GUN evaporator. These wafers were cut into pieces approximately 1 cm² in size and immersed in solutions of 2-mercaptohydroquinone in EtOH (10 mM) for 1 h, removed from solution and rinsed with water, ethanol, hexane, and then dried with a stream of nitrogen gas.

**Cyclic Voltammetry.** All electrochemical experiments were performed in a solvent mixture of tetrahydrofuran and water containing 2.0 mM phosphate and 70 mM NaCl that was thoroughly degassed with nitrogen. Cyclic voltammetry was performed with a Bioanalytical Systems CV-50W potentiostat. All experiments were performed in a glass cylindrical cell with stirring of the electrolyte, and fitted with the gold/QSH as the working electrode, a platinum wire as the counter electrode, and a Ag/AgCl reference electrode.

**Ellipsometry.** Thicknesses of monolayers were determined by ellipsometry with a Gaertner model L116S Research Type instrument operating at 632.8 nm (He−Ne laser) and an angle of incidence of 70°. A value of 1.45 was used for the average refractive index of the monolayer. The reported thickness of the monolayer was averaged over 10 measurements to give a standard deviation of 0.8 Å (before) and 0.9 Å (after the Diels−Alder reaction).

**Curve Fitting.** The curve fitting approach used to model the experimental data in Figure 3 was obtained from a least-squares fit using the Levenberg−Marquardt algorithm. All fits gave a correlation coefficient ($R$) of better than 0.99.

**References and Notes**

(1) (a) Lin, V. T.; Motesharei, K.; Dancil, K. P. S.; Sailor, M. J.; Ghadiri, M. R. *Science* **1997**, *278*, 840. (b) Blonder, R.; Levi, S.; Tao, G.; Ben-Dov, I.; Willner, I. *J. Am. Chem. Soc.* **1997**, *119*, 10467.

(2) (a) Chen, C.; Lisa, A.; Randall, R.; Miller, B.; Jones, D.; Kurth, M. *Tetrahedron* **1997**, *53*, 6595. (b) Jacobs, J. W.; Fodor, S. P. A. *Trends Biotechnol.* **1994**, *12*, 19.

(3) (a) Tollner, K.; Popovitz-Biro, R.; Lahav, M.; Milstein, D. *Science* **1997**, *278*, 2100. (b) Bartz, M.; Kuther, J.; Seshadri, R.; Tremel, W. *Angew. Chem.* **1998**, *37*, 2466.

(4) For examples of the kinetic characterization of interfacial reactions, see: (a) Sun, L.; Thomas, R. C.; Crooks. R. M.; Ricco, A. J. *J. Am. Chem. Soc.* **1991**, *113*, 8550. (b) Maskus, M.; Abruna, H. *Langmuir* **1996**, *12*, 4455.

(5) Horton, R. C.; Herne, T. M.; Myles, D. C. *J. Am. Chem. Soc.* **1997**, *119*, 12950.

(6) Yan, L.; Marzolin, C.; Tefort, A.; Whitesides, G. M. *Langmuir* **1997**, *13*, 7604.

(7) Duevel, R. V.; Corn, R. M. *Anal. Chem.* **1992**, *64*, 337.

(8) (a) Yousaf, M. N.; Mrksich, M. *J. Am. Chem. Soc.* **1999**, *121*, 4286. (b) Yousaf, M. N.; Chan, E. W. L.; Mrksich, M. *Angew. Chem.* **2000**, *39*, 1943. (c) Fryxell, G. E.; Rieke, P. C.; Wood, L. L.; Engelhard, M. H.; Williford, R. E.; Graff, G. L.; Campbell, A. A.; Wiacek, R. J.; Lee, L.; Halverson, R. E. *Langmuir* **1996**, *12*, 5064. (d) Zhuang, X.; Lackritz, H.; Shen, Y. R. *Chem. Phys. Lett.* **1995**, *246*, 279 (e) Ahmad, J.; Astin, B. *Langmuir* **1990**, *6*, 1797.

(9) Chechik, V.; Stirling, C. J. M. *Langmuir* **1998**, *14*, 99.

(10) Sasaki, T.; Scherson, D. A.; Bravo, B. G.; Soriaga, M. P. *Langmuir* **1990**, *6*, 1234.

(11) Mo, Y.; Sandifer, M.; Sukenik, C.; Barriga, R. J.; Soriaga, M. P.; Scherson, D. *Langmuir* **1995**, *11*, 4626.

(12) Sato, Y.; Fujita, M.; Mizutani, F.; Uosaki, K. *J. Electroanal. Chem.* **1996**, *409*, 145.

(13) Bravo, B.; Mebrahtu, T.; Soriaga, M. P.; Zapien, D. C.; Hubbard, A. T. *Langmuir* **1987**, *3*, 595.

(14) Sato et al. (*J. Electroanal. Chem.* **1996**, *409*, 145.) reported the $E_{1/2}$ at pH 7 in buffered solutions containing 0.1 M $ClO_4^-$ for the surface-attached $H_2QSH$ on gold was $-60$ mV. This value is consistent with the $E_{1/2}$ ($-70$ mV) we obtained using the THF:water solvent system.

(15) Ye, S.; Yashiro, A.; Sato, Y.; Uosaki, K. *J. Chem. Soc., Faraday Trans.* **1996**, *92*, 3813.

(16) We use the symbol $\Gamma$ to represent surface coverage and not the more formal surface excess. For a discussion of parameters used in describing adsorption, see*: Pure Appl. Chem.* **1972**, *31*, 579.

(17) Adamson, A. U. *Physical Chemistry of surfaces*, 6th ed.; Wiley: New York, 1997.

(18) Kim, S.; Zhao, M.; Scherson, D. A.; Choi, K. J.; Bae, I. T. *J. Phys. Chem.* **1994**, *98*, 9383.

(19) Breslow, R.; Zhu, Z. *J. Am. Chem. Soc.* **1995**, *117*, 9923.

(20) Burton H.; David S. B. *J. Chem. Soc.* **1952**, 2193.