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Infrared Spectroelectrochemical Study of Cyanide Adsorption on Palladium Surfaces

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In situ FTIR spectroscopy is employed to study the adsorption of cyanide ion (CN^-_{ads}) within the double-layer region on a polycrystalline palladium surface in aqueous perchlorate (0.10 M NaClO_4) electrolyte. Four surface infrared bands in the 1800–2200- cm^{-1} range are observed. Surface bands with peak maxima seen at about 2060 and 1980 cm^{-1} are assigned to linear and bridge-bound CN^-_{ads} , respectively. Two additional bands near 2150 and 2200 cm^{-1} are attributed to Pd/CN surface films. The relative intensities of the bands due to linear and bridged CN^-_{ads} suggest the predominance of the bridge-bound adsorbate on palladium. The experimentally observed frequency potential dependence ($d\nu_{\text{C-N}}/dE$) for the bridged cyanide adsorbate (20 $\text{cm}^{-1} \text{V}^{-1}$) is greater than that for the linearly adsorbed species (12 $\text{cm}^{-1} \text{V}^{-1}$). Potential dependencies of the infrared frequencies due to linear and bridged CN^-_{ads} show little variation with changes in cyanide concentration. Possible explanations for the predominance of bridged bonding are given, along with a discussion of the formation and depletion of surface Pd/CN films. A classical theoretical model, employed previously in the analysis of adsorbed carbon monoxide on platinum, is used to estimate frequencies and potential dependencies of the C–N stretch for linear and bridged CN^-_{ads} on a palladium surface.

Introduction

In recent years infrared spectroelectrochemistry has been shown to be invaluable for investigations involving the interaction of adsorbates with surfaces of electrodes.¹ A wide variety of physical and chemical phenomena can be studied in great detail by the use of in situ infrared (IR) spectroscopic surface probes of electrodes in electrochemical cells. Examples of such phenomena include electrocatalytic oxidation of organic acids,² potential-dependent adsorption and desorption of molecules and ions,² the electrochemically induced polymerization of conducting polymers,³ and studies of dynamics in the electrode–electrolyte interfacial region.^{2,4} A vast literature exists concerning the infrared spectroscopy of adsorbed carbon monoxide (CO) on solid electrodes,² and studies of this species have led to a very good understanding of adsorbate–electrode surface bonding, reactions, and dynamics. There have also been a number of in situ IR spectroelectrochemical studies on adsorbed pseudohalide species such as cyanide (CN^-),^{2,5} azide (N_3^-),² and thiocyanate (SCN^-),^{2,4,6} with goals toward understanding interfacial dynamical properties as well as comparisons with molecular adsorbate systems such as specifically adsorbed CO. Through the utilization of surface-sensitive in situ IR spectroscopy in electrochemical systems, it has become possible to obtain information concerning identification of species (i.e., reactants, intermediates, or products of electrode reactions) at or near smooth electrode surfaces. These observations were previously impossible by conventional electrochemical or other available spectroelectrochemical techniques (e.g., surface-enhanced Raman scattering⁷).

A significant advantage of spectroelectrochemical studies involving adsorbed pseudohalide species (such as CN^- or SCN^-) over similar studies involving adsorbed carbon monoxide is the wide double-layer region available in certain pseudohalide systems. The double-layer region is the potential region in which no faradaic reactions occur, and the electrode surface is said to be “ideally polarized”.⁸ For studies of interfacial dynamics it is beneficial to conduct spectroelectrochemical experiments in the absence of redox reactions that can complicate spectral interpretations. In aqueous solutions containing CO the available double-layer region is relatively narrow, for adsorbed carbon monoxide (CO_{ads}) is more easily oxidized and reduced than, say, its isoelectronic pseudohalide counterpart, adsorbed cyanide (CN^-_{ads}). Therefore studies of interfacial dynamical properties (which can be addressed by following the potential dependence of IR absorption frequencies

of adsorbate vibrational bands¹) are limited in scope if CO is the adsorbate species, since the available applicable potential range is limited. If the double-layer region is not adhered to, spectra may be difficult to interpret due to the presence of other species and/or surface films produced by a surface-mediated electrochemical reaction. Hence for investigations of the potential dependencies of adsorbate IR bands it is of interest to examine pseudohalide systems such as CN^-_{ads} due to the wide double-layer potential regions offered in these systems.

In a preliminary report⁵ we noted striking differences in the potential-dependent IR spectroscopy (PDIRS⁹) of CN^-_{ads} on platinum vs palladium surfaces within double-layer potentials of both metals. Differences of this kind have been observed previously for the analogous case of CO_{ads} on Pt and Pd^{10,11} and have been attributed to differences in adsorbate–surface bonding interactions. In this work we report the results of a detailed study concerned with the adsorption of cyanide on smooth palladium electrodes, using surface infrared spectroscopy as an in situ probe of the interface. The surface infrared spectral frequencies for cyanide

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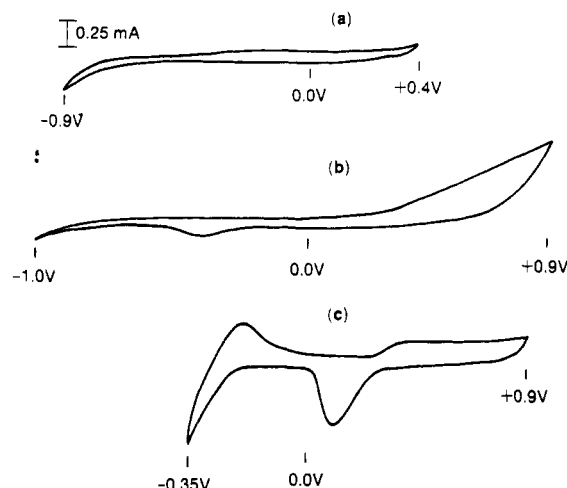


Figure 1. Cyclic voltammograms for (a) 1 mM NaCN in 0.10 M NaClO₄, (b) 25 mM NaCN in 0.10 M NaClO₄, and (c) 0.10 M NaClO₄ obtained at a palladium electrode. Sweep rate = 50 mV s⁻¹; potentials are vs the Ag/AgCl (3 M KCl) reference.

species adsorbed on palladium, as well as the potential dependencies of those frequencies, are then compared with theoretically evaluated frequencies using the model of Korzeniewski et al.¹²

Experimental Section

The in situ IR spectroelectrochemical data were obtained by combining the polarization modulation technique (Fourier transform infrared reflection absorption spectroscopy, or FT-IRRAS¹³) with a potential difference method (subtractively normalized interfacial Fourier transform infrared spectroscopy, or SNIFTIRS¹⁴). FT-IRRAS spectra were taken at the reference and sample potentials by using a photoelastic modulator (Hinds International, ZnSe), operated by 78 kHz, and a two-phase lock-in amplifier (Princeton Applied Research Model 5206). Difference spectra were then obtained by ratioing the two absolute spectra obtained by polarization modulation. This combination of polarization modulation and potential modulation techniques served to optimize the surface specificity of the IR spectroscopic probe. The spectrometer employed was an IBM IR/98 instrument, with a global IR source and liquid nitrogen cooled indium antimonide detector (Infrared Associates). The IR spectroelectrochemical cell was a Kel-F external reflection cell, as described previously,¹⁵ with a bevelled calcium fluoride window (Frank Cooke, Inc.). The bulk polycrystalline palladium mirror working electrode (Johnson-Matthey, 99.99% Pd) was polished mechanically with successively smaller grades (1.0, 0.3, and 0.05 μm, respectively) of polishing alumina (Buehler). This electrode was then polished electrochemically by repeated potential cycling. Surface-sensitive IR difference spectra were obtained by recording reference spectra (within the double-layer potential region) at one potential and sample spectra at another potential; the incidence angle at the electrode surface was approximately 65° with respect to the surface normal. Typically 1000 spectra (approximately 1 s/scan, 4-cm⁻¹ resolution) were recorded at each potential, with the voltage being switched every 32 scans to avoid surface contamination.

Electrode potential was controlled with a Princeton Applied Research 173/175/179 potentiostat-waveform generator system, and voltages were recorded against an Ag/AgCl (3 M KCl) reference (Microelectrodes, Inc.). NaCN and NaClO₄ (reagent grade) were obtained from Aldrich and promptly used as received. Deionized (Nanopure, 18 MΩ), organic-free (Organopure) water

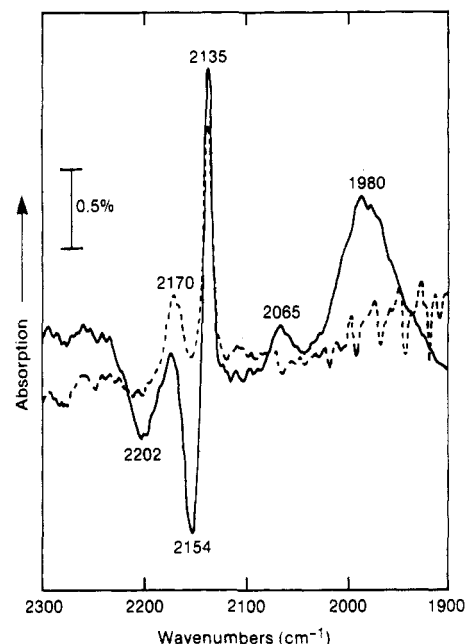


Figure 2. In situ PDIR spectra (4-cm⁻¹ resolution, 1000 scans at both sample and reference potentials) of NaCN (25 mM) in 0.10 M NaClO₄ on polished palladium surface. Solid line, combined SNIFTIRS/IRRAS spectrum (see text for experimental details); dashed line, SNIFTIRS spectrum, s-polarized radiation. The reference potential was -0.90 V vs Ag/AgCl, and the sample potential was +0.70 V vs this reference. See text for details concerning the collection of the FTIR difference spectra.

was used to prepare all solutions, and electrolytes were degassed with pure nitrogen or argon before each experiment. Voltammetric data were recorded on either an IBM Model 7424 MT or Houston Instruments Model 2000 x-y plotter.

Results and Discussion

Electrochemistry. Figure 1 shows representative cyclic voltammograms, obtained at a palladium electrode, for sodium perchlorate electrolytes (0.10 M NaClO₄) with cyanide both present (Figure 1a,b) and absent (Figure 1c) from solution. If cyanide is present in the system, the voltammogram is essentially featureless, even for cyanide concentrations as low as 1 mM (Figure 1a). This indicates that the electrode is "ideally polarized" over a wide potential range, i.e., a wide "double-layer" region is said to exist if cyanide is present. It should be noted that very similar cyclic voltammograms were obtained between about -0.9 and +0.4 V regardless of the cyanide concentration (for solutions containing 1, 5, and 25 mM NaCN). This suggests very strongly that cyanide is specifically adsorbed on the palladium surface over this potential range, even if the cyanide concentration in solution is quite low (e.g., less than 1 mM). Capacitance data obtained on silver surfaces for CN⁻ in 1 M Na₂SO₄ indicate that cyanide is strongly adsorbed even at extremely negative potentials;^{16,17} our voltammetric data on Pd in perchlorate electrolyte suggest cyanide adsorption to rather negative electrode potentials as well. Evidence for Pd/CN film formation is apparent in the increased anodic current observed at potentials more positive than +0.5 V. CN⁻ depletion is also possible at these rather positive potentials, although this can be confirmed only by IR spectroelectrochemistry.

If cyanide is not present in the system (Figure 1c) the effective double-layer voltage range is diminished considerably. Here an oxide layer is formed at relatively low positive potentials, and hydrogen adsorption and subsequent evolution occur at rather low negative potentials on this metal. These data show that cyanide is an effective poison of the palladium surface, preventing electroreduction and electrooxidation of solvent species (water) by the metal. These results are similar to voltammetric results obtained previously for thiocyanate adsorbed on a platinum elec-

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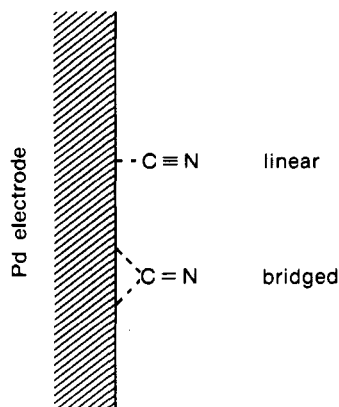


Figure 3. Schematic showing possible structures for linear and bridged CN^-_{ads} on a Pd electrode.

trode.⁴ It is within this wide double layer region between -1.0 and $+0.5$ V or so that we desire to study the potential-dependent behavior of the infrared bands due to surface cyanide species. As previously mentioned, this will enable in situ surface IR spectra to be interpreted more easily since complications from electrode-mediated electron-transfer processes are minimized.

Infrared Spectroelectrochemistry. Figure 2 shows typical in situ IR difference spectra obtained in a 5 mM sodium cyanide-/0.10 M sodium perchlorate system (on palladium) as a function of the light polarization.⁵ The reference and sample potentials were the same for solutions in which cyanide was either present or absent: the reference potential was -0.90 V and the sample potential was $+0.70$ V (vs Ag/AgCl). The potential-dependent infrared (PDIR) spectrum obtained with s-polarized radiation (Figure 2, dashed line) shows positive bands at 2170 and 2135 cm^{-1} , as well as a series of bands due to rotational modes of background water vapor between 1900 and 2000 cm^{-1} . The surface PDIR spectrum for 5 mM NaCN in aqueous perchlorate electrolyte, obtained via polarization modulation (in order to maximize surface sensitivity), yields a series of bands in the 1900 – 2300 - cm^{-1} frequency range. Positive bands are observed at 2135 , 2065 , and 1980 cm^{-1} , and two negative bands appear at 2202 and 2154 cm^{-1} . The results from s-polarized radiation indicate that the bands at 2170 and 2135 cm^{-1} are due to species dissolved in solution; these bands are assigned to $\text{Pd}(\text{CN})_6^{2-}$ and $\text{Pd}(\text{CN})_4^{2-}$, respectively.¹⁸ Thus a solution band at 2135 cm^{-1} still appears in the surface-sensitive PDIR spectrum, despite pains taken to omit solution features. The remaining bands are assigned to surface species. The surface bands at 2202 and 2154 cm^{-1} are attributed to surface films of Pd/CN. These films appear to be precursors to the dissolved Pd/CN complexes that give rise to the two solution bands seen in the s-polarized spectrum. The band near 2200 cm^{-1} is tentatively assigned to a surface film of PdCN or $\text{Pd}(\text{CN})_2$, while the surface feature near 2150 cm^{-1} is attributed to a precursor of the $\text{Pd}(\text{CN})_4^{2-}$ solution complex, surface $\text{Pd}(\text{CN})_4^-$.¹⁹ The bands appearing at 2065 and 1980 cm^{-1} are attributed to linear and bridge-bound CN^-_{ads} , respectively;⁵ these types of adsorbates are schematized in Figure 3. The bonding of cyanide on a palladium surface is thus similar to the case of carbon monoxide adsorption on this metal;^{10,11} both linear and bridged species for CO and CN^- (which are isoelectronic) are detected by surface infrared spectroelectrochemistry, and the band intensity of the bridged moiety greatly exceeds that of the linear bound species.

It is also of interest to note that the infrared band frequency of linearly adsorbed cyanide (CN^-_{ads}) is less than that of the solution species. The IR frequency of cyanide ion dissolved in aqueous solution appears at about 2080 cm^{-1} ,²⁰ so an apparent

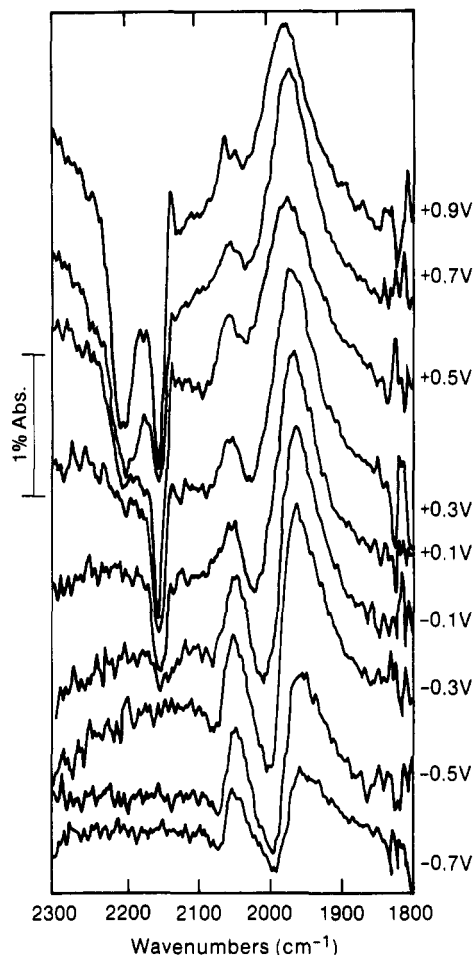


Figure 4. Surface-sensitive in situ PDIR spectra (combined SNIFTIRS/IRRAS, 4-cm^{-1} resolution, 2000 scans, 1000 at each potential) of 1 mM NaCN in 0.10 M NaClO_4 obtained at a palladium electrode as a function of applied voltage (vs. Ag/AgCl). The reference potential was -0.90 V vs Ag/AgCl.

decrease in bond order of the $\text{C}\equiv\text{N}$ bond is observed for linear CN^-_{ads} . This contrasts with the case of cyanide adsorption on other noble metals such as platinum,⁵ gold,^{21,22} or silver,^{22,23} in which the IR band frequency due to the normal C–N stretching mode ($\nu_{\text{C-N}}$) from linear CN^-_{ads} is greater than that of solution cyanide. In a single-electron molecular orbital picture this observation can be explained²⁴ by taking into account the differences in ionization potentials of the metals involved. For example, let us consider the case of cyanide adsorption on platinum vs palladium. In Pd the work function and 4d band lie approximately 1 eV above the work function and 5d band of Pt.²⁴ Thus Pt(5d) back-donation to the π^* orbital of CN^-_{ads} is not as important as the 5σ donation from CN^-_{ads} to Pt. Hence, $\nu_{\text{C-N}}$ is greater for adsorbed cyanide than for free CN^- in solution since the 5σ level is slightly antibonding. For Pd, the σ interaction is not as important as the π interaction; i.e., $d \rightarrow p \pi$ back-bonding is favored over σ donation. Therefore $\nu_{\text{C-N}}$ for linear CN^-_{ads} is less than that of free solution CN^- ; also, formation of the bridged CN^-_{ads} species is favorable, in keeping with our experimental observations. Similar arguments have been employed to rationalize the predominance of bridge-bonding of CO_{ads} on highly ordered rhodium surfaces.²⁵

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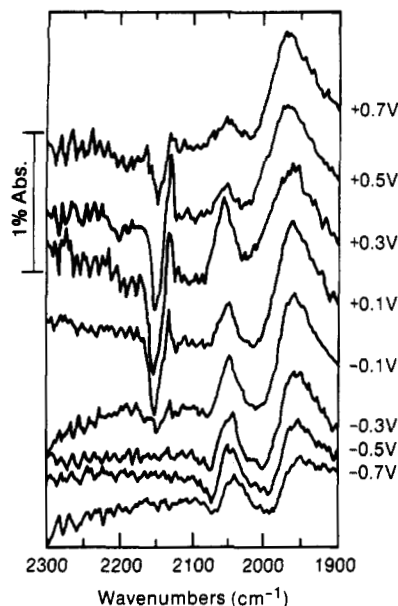


Figure 5. Same as Figure 4, except $[\text{NaCN}] = 5 \text{ mM}$.

Another possible explanation for the decrease in band frequency of linear CN^-_{ads} (with respect to free solution CN^-) can be offered by considering the degree of covalency of the metal–cyanide bond. If the adsorbate–metal bond is largely ionic, we would expect the band frequency of the adsorbed species to be shifted to higher energies when compared to the solution species;²⁶ this seems to be the case for linear CN^-_{ads} on a platinum surface.⁵ Further evidence for ionic bonding of cyanide on platinum is suggested by the possibility for binding through either carbon or nitrogen end down, as suggested by sum-frequency generation experiments²⁷ and FTIR spectroelectrochemistry.²⁸ A lack of evidence for N-bound species, as well as a decrease in band frequency for linear CN^-_{ads} on Pd (when compared to that for solution species), may be due to a metal–adsorbate bonding interaction that is more covalent than for linear CN^-_{ads} on Pt.

Surface in situ FTIR spectra are shown in Figures 4–6 for systems in which the cyanide concentrations are varied from 1 to 25 mM. There are few apparent differences in the potential-dependent behaviors of the linear and bridged CN^-_{ads} species for differences in cyanide concentration (Figure 7). It is of interest to note that the frequency change with potential for the bridged surface cyanide exceeds that of the linearly adsorbed species. We find from linear regression, using the data summarized in Figure 7, that $d\nu_{\text{C-N}}/dE$ for linear CN^-_{ads} is approximately $12 \text{ cm}^{-1} \text{ V}^{-1}$ (correlation coefficient 0.973), while this quantity is on the order of $20 \text{ cm}^{-1} \text{ V}^{-1}$ for bridged CN^-_{ads} (correlation coefficient 0.981). This observation contrasts with what has been seen for linear and bridged CO_{ads} on palladium surfaces, wherein the Stark tuning rates for the two types of adsorbates are more similar.¹⁰ The implication is that in the case of the Pd–CO system, it is an electrochemically induced Stark effect that gives rise to a potential-dependent frequency change for the two types of adsorbed species. However, in the Pd–CN system, it is likely that changes in degree of back-donation from the metal to the adsorbate moiety (as the potential is changed) yield the observed potential-dependent frequency shifts that are observed.

An electrochemically induced Stark effect may also explain the above observations of differences in frequency potential dependencies for cyanide in a linear vs bridged site. It is possible that

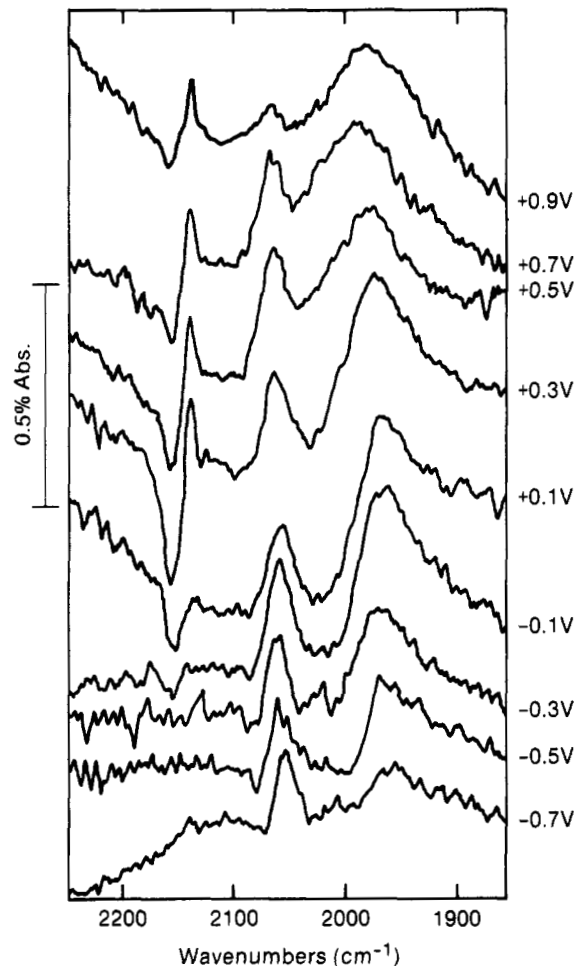


Figure 6. Same as Figure 4, except $[\text{NaCN}] = 25 \text{ mM}$.

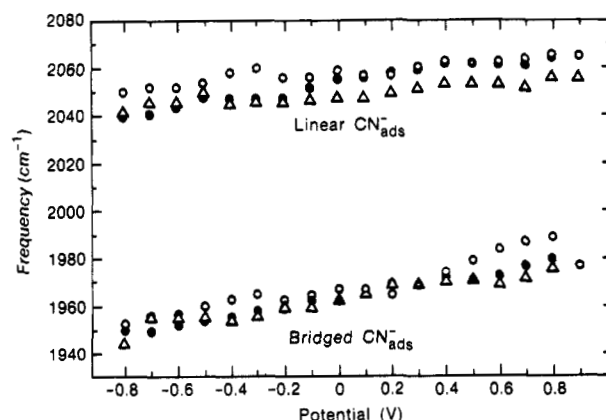


Figure 7. Plot of peak position (in cm^{-1}) vs applied potential (V) for the normal C–N stretching frequency of linearly and bridge-bound CN^-_{ads} on Pd for 1, 5, and 25 mM NaCN in 0.10 M NaClO_4 . The error in the determination of peak position is $\pm 0.5 \text{ cm}^{-1}$. Open circles, 1 mM NaCN; closed circles, 5 mM NaCN; triangles, 25 mM NaCN. Potentials vs Ag/AgCl.

contribution from a surface “wall” effect leads to an increase in frequency that overcompensates the frequency decrease due to π back-donation.²⁹ Consider the case of CN^- adsorbed at a

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bridged site. The C≡N bond is weakened, which suggests back-donation into the π^* orbital of bridged CN^-_{ads} . Formation of a metal-carbon bond results in a smaller distance between the adsorbate and the surface plane. At an equilibrium distance from the surface the forces in balance are stronger for bridged CN^-_{ads} than for linear CN^-_{ads} , resulting in higher Pauli repulsion between closed shells (of surface metal and adsorbate species) against more strongly attractive electrostatic forces. The repulsive force varies exponentially with distance, so the wall effect is larger when the bridge-bound ion moves in an applied electric field; consequently the potential dependence of the frequency is larger. Conversely, for CN^- adsorbed at an on-top site the equilibrium bond length between the adsorbed ion and the metal surface is greater, so the repulsive force is less and the spatial gradient describing the attractive force is weaker. For CO_{ads} , electrostatic forces are less important since this species is not ionic, so the potential dependence of the frequency for linearly adsorbed species is greater than that of bridge-bound adsorbate.

We also observe that the relative and absolute intensities of the linear and bridged surface cyanide species show little or no concentration dependence. The only observable trend that was seen as the cyanide concentration was altered was a small increase in band frequency as the cyanide concentration decreased (Figures 4–6); this was observed for both linear and bridged species. Similar effects have been observed in Pd/CO systems in which coadsorbates served to decrease the band frequencies of adsorbed CO species.¹¹ The origin of such an effect is not well understood and may be due to a combination of changes in dipole-dipole coupling between adsorbates and to shifts in the potential of zero charge of the metal in systems of varying adsorbate concentration.

The behavior of bands due to the surface film near 2150 cm^{-1} is similar in all three cases (Figures 4–6), whereas the 2200- cm^{-1} band appears only in systems with relatively high cyanide concentration (Figure 6). The band near 2150 cm^{-1} , ascribed previously to a surface $\text{Pd}(\text{CN})_4^-$ species, appears at potentials near 0.0 V (this onset potential is independent of cyanide concentration) and grows in intensity as the sample potential is made more positive. Concurrent with the appearance and growth of the surface feature near 2150 cm^{-1} is the appearance of the solution feature at 2135 cm^{-1} , which we have ascribed to dissolved $\text{Pd}(\text{CN})_4^{2-}$. This suggests that the surface feature at about 2150 cm^{-1} is a precursor to the solution band at 2135 cm^{-1} . It is interesting to point out that there is little electrochemical evidence for the formation and dissolution of the surface films seen in the PDIR spectra (Figure 1a,b); the cyclic voltammograms are essentially flat within the voltage range studied, and a faradaic film formation may be so slow kinetically that it does not appear prominently in the voltammetry. It is possible therefore that an initial reaction of cyanide with the palladium surface takes place to form a surface Pd/CN complex prior to the imposition of an electrode potential. Then in the course of obtaining surface in situ IR spectra, the film becomes partially removed as the electrode potential is made more positive, and solution coordination compound is formed. However, we do not think that this compound formation occurs, since the electrode potential is cycled repeatedly before surface FTIR difference spectra are taken; such potential cycling ought to remove any surface film that would form spontaneously in the absence of an applied voltage.

The dependence of the intensity of various bands (due to surface films) with electrode potential is contrary to the expectations based on chemical intuition. The bands at about 2150 and 2200 cm^{-1} are a result of the formation of Pd/CN complexes, as previously mentioned. These complexes should be more abundant at the more positive electrode potentials. Yet the absorption bands observed from these species seem to indicate that these complexes are present in higher concentration at more negative electrode potentials (see Figure 6, for example). This suggests that the PDIR

TABLE I: Morse and Lennard-Jones Parameters Used in the Interaction Potential for Linear and Bridged CN^-_{ads} on a Pd Surface

	Morse Parameters		
	D_e , eV	a , \AA^{-1}	r_0 , \AA
linear CN^-_{ads}			
C–N	10.31 ³⁰	2.354 ^{30,31}	1.166 ³²
N–Pd	0.131 ³³	0.850 ³³	4.60 ¹²
bridged CN^-_{ads}			
C–N	7.991 ³²	2.13 ³¹	1.166 ³²
N–Pd	0.102 ³³	0.65 ³³	4.60 ¹²
	Lennard-Jones Parameters		σ , \AA
	ϵ , eV		
linear CN^-_{ads}			
C–Pd	2.25 ³⁴		1.81 ³⁵
bridged CN^-_{ads}			
C–Pd	2.05 ³³		1.70 ¹²

spectra are not indicative of pure adsorption and desorption on the electrode surface. More likely we have some kinetic effect convoluted with the adsorption-desorption process.

We can postulate a type of kinetic effect that can lead to these spectra (e.g., Figures 5 and 6). When the spectra are collected, the potential is cycled between the sample and reference potentials. At the sample potential that is the more oxidative potential (i.e., more highly positive) we continue to form the Pd/CN complexes. These complexes appear to precipitate on the electrode surface in the form of a patchy, irregular film. A second process that occurs simultaneously is dissolution of the Pd/CN complex in solution. In the very early stages of the dissolution process only the solution in close proximity to the electrode surface has any significant amount of these complexes, leading to a bell-shaped concentration profile in the diffusion layer. As dissolution proceeds the region that shows this concentration gradient moves away from the surface. When we cycle to the reference potential that corresponds to the more negative potential the electrode now begins to reduce these complexes. The reduction begins at the electrode surface of the Pd/CN complex film and the analogous complexes dissolved in solution. The product of the reduction process is CN^- ions, so near the electrode surface the concentration of CN^- ions will be significantly higher than in bulk solution. We might expect the reduction process to proceed more slowly than the oxidation step. Furthermore, solvation of complexes and their diffusion away from the surface may continue during the initial stages of the reduction process. As a result, the depletion of the solvated complexes that will follow reduction of the film will proceed at the diffusion-controlled limit. It is quite likely that on average the IR beam will see more Pd/CN complexes at the reference potential than at the sample potential. This observation could qualitatively explain why the bands corresponding to Pd/CN complexes show the observed intensity variation. This work appears to be the first case where such a unique variation of PDIRS band intensities has been observed.

The classical model of Korezeniewski et al.¹² was used to calculate vibrational frequencies $\nu_{\text{C-N}}$ and $\nu_{\text{Pd-C}}$ for both linear and bridged cyanide species adsorbed on a palladium surface. The total energy of the system, which is the sum of the kinetic and potential energies, is expressed by the Hamiltonian

$$H = \sum_i p_i^2 / 2m_i + \sum_j V_j \quad (1)$$

The first summation includes only carbon and nitrogen atoms; although it is possible to include palladium vibrations as well, the effects of contributions from Pd–Pd vibrational interactions are negligible at this level of approximation. The potential energy consists of the sum of discrete interactions between atoms:

$$V_{\text{tot}} = V_{\text{C-N}} + V_{\text{C-surf}} + V_{\text{N-surf}} \quad (2)$$

Here $V_{\text{C-N}}$ and $V_{\text{N-surf}}$ are expressed by Morse potentials, and $V_{\text{C-surf}}$ is approximated by a Lennard-Jones potential, analogous to the case of CO adsorbed on a platinum surface.¹²

The parameters that were used in the CN^-_{ads} potential interactions are summarized in Table I. The parameter r_0 for the

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TABLE II: Vibrational Frequencies $\nu_{\text{C-N}}$ and $\nu_{\text{Pd-C}}$ for Linear and Bridge-Bound CN^-_{ads} on Pd

	calcd freq, cm^{-1}	exptl freq, cm^{-1}
linear CN^-_{ads}		
$\nu_{\text{C-N}}$	2055	2060
$\nu_{\text{Pd-C}}$	416	
bridged CN^-_{ads}		
$\nu_{\text{C-N}}$	1981	1972
$\nu_{\text{Pd-C}}$	234	

potential $V_{\text{N-surf}}$ (N-Pd interaction) was chosen to make this term repulsive,¹² and the remaining surface-atom interaction parameters (in $V_{\text{C-surf}}$ and $V_{\text{N-surf}}$) were chosen to yield the closest fit to experimentally determined vibrational frequencies (to within $\pm 1 \text{ cm}^{-1}$). Frequencies computed in this manner are compared with experimentally determined vibrational frequencies ($\nu_{\text{C-N}}$) for linear and bridged CN^-_{ads} on Pd in Table II. Experimental values of $\nu_{\text{Pd-C}}$ are not listed since there are no experimental PDIRS data available for the palladium-cyanide system in the far-infrared frequency range, and SERS data in this spectral region are available only for cyanide on gold³⁶ and silver³⁷ surfaces. Binding energies for linear and bridged CN^-_{ads} were calculated as the difference between total energy (from eq 2) and the dissociation energy of an isolated cyanide ion.³⁸ These values were estimated to be 1.4 and 2.0 eV for linear and bridged species, respectively. The computed binding energies for CN^-_{ads} species are smaller than those estimated for adsorbed CO on Pt¹² and reflect the greater degree of ionic bonding in the case of cyanide on palladium vs predominately covalent bonding for the case of carbon monoxide on platinum.²⁶

The potential dependency of the C-N stretching frequency on applied potential for linear and bridge-bound CN^-_{ads} on Pd was estimated by applying a perturbation that represents the effects of an applied electric field.^{12,39,40} This field is added to the interaction potential, and has the form

$$V_{\text{field}} = E_z d\mu/dz (z^0 - z) \quad (3)$$

where E_z is the electric field strength perpendicular to the electrode surface, $d\mu/dz$ is the dipole moment derivative normal to the surface, and $z^0 - z$ represents the relative normal displacement of an atom from its equilibrium position. The experimental value

of $d\nu/dz$ ($2.4 \text{ d}/\text{\AA}$) is available in the literature⁴¹ and differs appreciably from theoretically predicted values, which are higher.⁴² From these quantities the potential dependencies of the band frequencies ($d\nu_{\text{C-N}}/dE$) were estimated to be 8 and $15 \text{ cm}^{-1} \text{ V}^{-1}$ for linear and bridged CN^-_{ads} , respectively. While these estimated values are somewhat less than those observed experimentally, they give qualitative agreement with the fact that $d\nu_{\text{C-N}}/dE$ is greater for the bridged adsorbate than for the linearly adsorbed species. It is also of interest to note that the frequency shift with potential of the C-N stretch from linear CN^-_{ads} on Pd is less than that for linear CO_{ads} on Pt.⁴³ Since the value of $d\mu/dz$ is appreciably smaller for cyanide than for carbon monoxide (this quantity is approximately $3.1 \text{ D}/\text{\AA}$ for gas-phase CO),⁴⁴ a smaller frequency potential dependence is to be expected for the adsorbed cyanide species.

Conclusion

Surface-sensitive in situ FTIR difference spectra of cyanide adsorbed on polycrystalline palladium in perchlorate electrolyte give strong evidence for the predominance of bonding to a 2-fold bridged site on the electrode surface throughout most of the double-layer region. At far negative potentials the relative abundances of linear and bridged CN^-_{ads} species are comparable, but as the potential is made more positive the intensity of the IR band due to bridged CN^-_{ads} becomes much greater than that due to linear CN^-_{ads} . The implication is that back donation from the metal is a more important criterion here than is the electrochemical Stark effect. Surface Pd/CN bands that are precursors to solution palladium cyanide complexes were detected by the PDIR technique, while little evidence for the existence of these species was obtainable by conventional electrochemical methods. The band frequency $\nu_{\text{C-N}}$ due to linear CN^-_{ads} on Pd is lower than that observed previously on other electrode surfaces (e.g., Pt, Ag, Au, Cu), suggesting a higher degree of covalent bonding on Pd compared to the other metals.

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