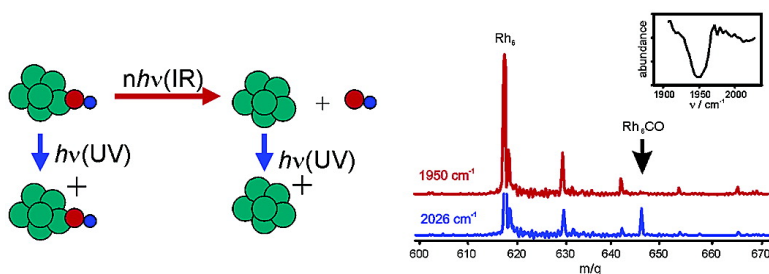


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Vibrational Spectroscopy of CO in Gas-Phase Rhodium Cluster–CO Complexes

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Interest in the chemistry of transition metal atoms and small clusters dispersed on insulating supports goes back many years.¹ Driven by the catalytic activity of metals such as rhodium dispersed on amorphous metal oxides supports, this interest is now strengthened due to the possibility of harnessing size-specific properties in heterogeneous catalysts. New insights into the chemical properties of small deposited metal clusters have been gained from the size-selective preparation of cluster deposits on ordered substrates as well as from characterization techniques that have a high spatial resolution such as the scanning probe microscopies.^{2,3}

One of the techniques that is most widely used to characterize supported metal particles is infrared (IR) spectroscopy of adsorbed carbon monoxide, CO. The stretching frequency of CO, $\nu(\text{CO})$, is highly sensitive to structure and electron density at the binding site. The interpretation of the vibrational spectra of CO chemisorbed on supported metal systems relies on the comparison with $\nu(\text{CO})$ values in stable metal carbonyl compounds, on single crystal surfaces, and with atom–CO complexes in rare gas matrixes. Until now, there is no information for isolated unsaturated metal cluster carbonyls, as conventional IR spectroscopic techniques are difficult to apply for those species.

Here, we report on the vibrational spectroscopy of gas-phase rhodium cluster complexes with CO, Rh_nCO ($n = 6\text{--}20$), one of the most widely studied supported transition metal systems. Spectra in the region of $\nu(\text{CO})$ are obtained using IR multiphoton depletion (IRMPD) spectroscopy. These gas-phase studies provide fundamental insight into metal–ligand interactions and additionally allow one to distinguish between intrinsic properties and support effects in supported clusters. The experiments take advantage of the tunable, IR radiation from the free electron laser for infrared experiments (FELIX)⁴ which is ideal for IRMPD spectroscopy of cluster–ligand complexes.⁵ Briefly, the IR induced fragmentation yields of the clusters in a molecular beam are monitored under FELIX irradiation as a function of IR frequency using mass spectrometry. Details are available as Supporting Information.

In Figure 1 parts of mass spectra are shown around the mass of Rh_6 obtained under FELIX irradiation at two different IR frequencies. The peak due to Rh_6CO , visible with 2026 cm^{-1} radiation is completely depleted with 1950 cm^{-1} radiation. The inset in Figure 1 shows the IRMPD spectrum for Rh_6CO . Clearly, a resonance can be seen that can be straightforwardly attributed to the $\nu(\text{CO})$ stretching vibration of Rh_6CO . Similar depletion spectra have been obtained for Rh_nCO with $n = 6\text{--}20$. Spectra for $n = 6\text{--}15$ are

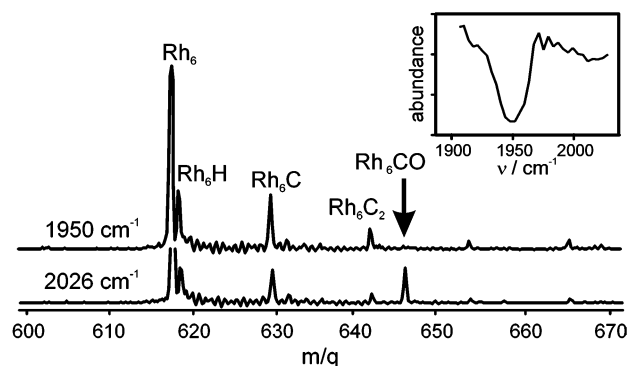


Figure 1. Mass spectra in the region of Rh_6 with FELIX on (1950 cm^{-1}) and off (2026 cm^{-1}) the $\nu(\text{CO})$ resonance in the Rh_6CO complex. Inset shows the frequency dependence of the Rh_6CO signal.

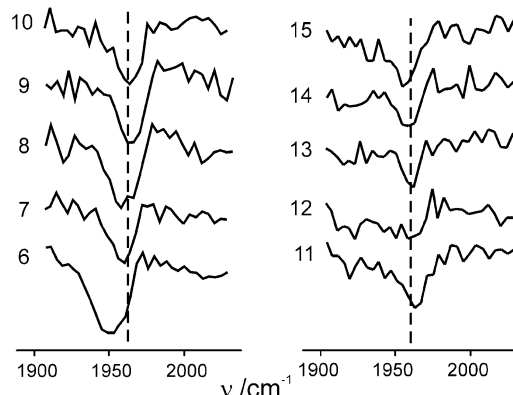


Figure 2. Infrared multiphoton depletion (IRMPD) spectra of Rh_nCO cluster complexes. A dashed line at 1964 cm^{-1} is drawn to guide the eye.

shown in Figure 2, and the peak frequencies are summarized in Table 1. The frequency scale is calibrated on ethylene absorptions measured in a photoacoustic cell, resulting in an absolute frequency accuracy better than $\pm 2\text{ cm}^{-1}$. Rh_6 is the smallest cluster for which we can observe CO complexes, as the smaller Rh_nCO clusters have ionization potentials (IPs) that are above the 6.42 eV photon energy of the ArF ionization laser. Surprisingly, the $\nu(\text{CO})$ resonance position hardly shifts in the studied cluster size range; only a small shift of $+10\text{ cm}^{-1}$ is observed in going from Rh_6CO to Rh_7CO . For bigger clusters $\nu(\text{CO})$ settles around 1964 cm^{-1} . A possible exception to the invariance of $\nu(\text{CO})$ with cluster size is Rh_{12}CO . Comparison of the spectrum of Rh_{12}CO in Figure 2 with that of its near neighbors shows reduced absorption at $\sim 1962\text{ cm}^{-1}$ to the point that it is almost indistinguishable from the noise. There also appears to be an increase of absorption at lower frequencies.

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Table 1. CO Stretching Frequencies ($\nu(\text{CO})$; cm^{-1}) for Isolated Rh_nCO Complexes Together with Experimental Values of $\nu(\text{CO})$ for CO Complexes of Surface Species and of Deposited Clusters Together with Calculated Frequencies

Rh_nCO	n	$\nu(\text{CO})$
isolated, this work	6	1950 ± 2
	7 to 11, 13 to 20	1960–1965 ^a
surface, low coverage ^b on Al_2O_3	Rh(111), (110), (100)	2015, 2008, 1995
(Technical Catalyst) ^c on Al_2O_3 , highly ordered film ^d	unknown	2042–2076 (η_1) 1845–1875 (η_2)
on MgO(100) film, size-selected deposition ^e	5–9 (mean size)	1999
DFT calculation ^f	8	2066
	3	2029
	4	2065

^a Values for individual complexes available as Supporting Information.
^b Reference 6. ^c Reference 7. ^d Reference 2. ^e Reference 3. ^f Reference 8.

The isolated Rh_nCO complexes can be compared to CO adsorbed on clean crystalline Rh surfaces.⁶ There, CO can bind atop and in bridging positions. At low CO coverage ($\theta < 0.1$) the values for $\nu(\text{CO})$ range from 1995 to 2015 cm^{-1} for CO adsorbed in the atop position, and only on Rh(100) η_2 -bridging CO has been found at low coverage with a $\nu(\text{CO})$ frequency of 1875 cm^{-1} . The position of $\nu(\text{CO})$ is influenced by the local electronic structure of the substrate and can be understood using the classical electron donation/back-donation description of the carbonyl bond. From this model, a shift of $\nu(\text{CO})$ to lower frequency is expected for the clusters due to the reduced coordination of the Rh atoms compared to that of the surface. The reduced coordination increases the electron density on the metal atom available for back-donation into the π^* orbital of the CO, which weakens the C–O bond and reduces its stretching frequency.

Our Rh_nCO $\nu(\text{CO})$ values indicate that, with the possible exception of Rh_{12}CO , CO occupies atop binding sites exclusively on small Rh_n clusters. At 30–65 cm^{-1} lower than observed for CO on single-crystal surfaces the $\nu(\text{CO})$ values are low, but within the range accepted for atop-binding on bulk metal. The shift of +10 cm^{-1} in going from Rh_6CO to Rh_7CO indicates that in very small clusters ($n < 7$) reduced metal coordination may make even more electron density available for back-donation. Although the average Rh atom coordination rises with increasing cluster size, CO is expected to find the lowest-energy binding site under equilibrium control. This is associated with the least coordinated Rh atom and with the lowest value for $\nu(\text{CO})$. Surface values for $\nu(\text{CO})$ will only be reached for much larger clusters, where the bulk ccp structure is established. Even then a single CO may preferentially bind to an edge and exhibit a low value for $\nu(\text{CO})$, just as CO on defect sites on surfaces.

The CO stretch frequencies of Rh_nCO are compared to work on supported Rh_n clusters in Table 1. For CO adsorbates on a technical catalyst (Rh/ Al_2O_3), two different adsorption sites have been identified, atop (η_1) and bridging (η_2).⁷ The blue-shift of the η_1 frequency on the catalyst compared to surface values is attributable to a combination of charge transfer from the cluster to the support and adsorption of multiple CO molecules on the clusters. The latter effect might also be responsible for the formation of η_2 species on the catalyst. In our isolated Rh_nCO complexes the $\nu(\text{CO})$ values are $\sim 100 \text{ cm}^{-1}$ lower than those assigned to CO atop-bound on the catalyst, and we find no evidence for bridge-bound CO in the gas phase. A special case is Rh_{12}CO where its atypical spectrum could be due to a degree of occupation of η_2 -bridge sites in this complex. The more recent work on Rh clusters on highly ordered Al_2O_3 films resulted in spectra that indicated the presence of cluster

monocarbonyls.² The frequencies given in the table are for conditions where the average cluster size was determined by scanning probe microscopy to be between about five and nine Rh atoms. It is observed that $\nu(\text{CO})$ is relatively independent of cluster size. The size independence is consistent with our gas-phase results. The shift of +40 cm^{-1} suggests significant electron transfer to the support. For CO bound to size-selected deposited Rh_8 on MgO $\nu(\text{CO})$ is $\sim 105 \text{ cm}^{-1}$ higher than for the here presented value for isolated Rh_8CO .³ This is possibly caused by electron transfer to the support and multiple CO adsorption on the supported metal clusters.

As can be seen from Table 1, the observed stretching frequency for Rh_6CO is about $\sim 5\%$ lower than the recently calculated value (B3LYP DFT calculations) for Rh_4CO , the largest calculated cluster.⁸ A scaling factor of ~ 0.95 would be typical for DFT calculations, but, since $\nu(\text{CO})$ is significantly decreasing from Rh_7CO to Rh_6CO , a further decrease might occur when going to the smaller clusters.

Future studies will focus on those smaller clusters ($n < 6$) as well as on complexes with more than one CO. Although these cannot be ionized at 6.42 eV,⁹ we know that the latter are generated at high CO concentrations where we observe growth of the Rh_nCO signal to the high-frequency side of the Rh_nCO $\nu(\text{CO})$ depletion band due to IR driven $\text{Rh}_n(\text{CO})_m \rightarrow \text{Rh}_n\text{CO}$ dissociation.

It will also be possible to adapt the IR desorption experiment to study CO complexes with ionic clusters. This will provide a quantitative measurement of the effect of charge on CO bonding to metal clusters and will calibrate $\nu(\text{CO})$ as a probe of charge transfer in supported clusters. Another interesting problem concerns the CO oxidation reactions on metal clusters. IRMPD spectroscopy could provide an analytical tool to follow the progress of such reactions.

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Supporting Information Available: Experimental details, complete table of $\nu(\text{CO})$ frequencies (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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