Infrared Induced Reactivity on the Surface of Isolated Size-Selected Clusters: Dissociation of N₂O on Rhodium Clusters

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Infrared multiple photon dissociation spectroscopy (IR-MPD) has recently emerged as a powerful technique in determining the structures of small gas-phase transition metal clusters. A form of indirect or action spectroscopy, IR-MPD relies on the loss of some moiety from the cluster to serve as a mass-spectrometric signature that infrared radiation has been absorbed. Monitoring either the depletion of the parent cluster signal or the enhancement of the fragment signal as a function of wavelength provides a highly sensitive method by which to record the vibrational spectrum of naked and/or decorated metal clusters.

Most IR-MPD studies on naked and decorated transition metal clusters to date have concentrated on the mid-IR region, exciting either the vibrations of molecules adsorbed on the cluster surface[1] or metal−oxygen stretches.[2] More recently, the implementation of the inert messenger technique,[3] in combination with the intense radiation from a free-electron laser (FEL), has extended IR-MPD spectroscopy into the far-infrared. This allows the metal−metal modes to be probed directly thereby yielding more direct structural information on the metal framework itself.[4,5]

Here, we present evidence of infrared driven surface chemistry on Rh$_n$N₂O⁺ clusters. IR-pumping of any vibrational mode of a molecularly adsorbed N₂O molecule results in the dissociation of the adsorbate with the concomitant loss of N₂ and the production of a partially oxidized rhodium cluster.

All experiments were performed at the Free Electron Laser for Infrared eXperiments (FELIX) facility in The Netherlands, and the details of the experiment have been published previously.[4] Briefly, as implemented here, rhodium clusters are generated by laser ablation of a rotating rhodium rod in the presence of a helium carrier gas doped with argon (0.1−0.3%). Nitrous oxide was admitted, post ablation, *via* a late mixing nozzle, and the resulting gas mix was allowed to equilibrate in a cryogenically cooled copper channel (173 K) before expansion into vacuum to form a molecular beam. The cluster beam, containing a range of naked and decorated clusters, both neutral and charged, is intersected by the counter propagating FELIX beam in front of the source region of a reflectron time-of-flight mass spectrometer. Whenever the IR frequency is in resonance with an IR active mode of a species in the molecular beam, that species may absorb photons, heat up, and can eventually fragment. The experiment runs at 10 Hz with the IR radiation present every other cycle. Comparison of the mass spectra of the cationic species present recorded with and without the FELIX beam as a function of the IR wavelength yields depletion/enhancement spectra reflecting infrared absorption and subsequent processes. Spectra are recorded between 100 and 2350 cm⁻¹, covering the

range of ligand vibrations as well as of the internal modes of the metal cluster. The former comprise the subject of the present communication.
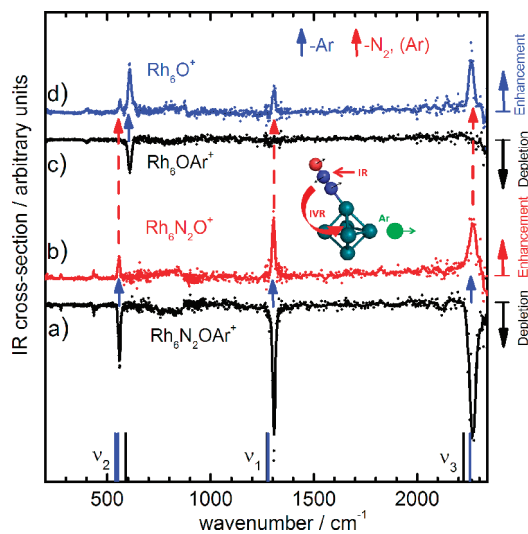
Figure 1. (a) IR-MPD depletion spectra of Rh₆N₂OAr⁺ and (b) the resulting enhancement in the Rh₆N₂O⁺ signal. The close correlation with the N₂O mode wavenumbers (black bars for free N₂O, blue bars calculated for the complex) confirms the molecular nature of the adsorption. (c) IR-MPD spectrum of Rh₆OAr⁺. (d) The spectrum in the Rh₆O⁺ channel shows clear enhancement at wavenumbers corresponding to excitation of Rh₆N₂O⁺ modes indicating infrared driven cluster surface chemistry.

Figure 1a and b show the IR-MPD spectrum of Rh₆N₂OAr⁺ complexes in the region of the free N₂O normal modes. Pumping each N₂O mode results in strong depletion of the Ar-tagged complexes and corresponding enhancement in the Rh₆N₂O⁺ signal, reflecting intramolecular vibrational redistribution (IVR) and the subsequent evaporation of the physisorbed argon atoms,

$$\text{Rh}_6\text{N}_2\text{OAr}_m^+ + xh\nu \rightarrow \text{Rh}_6\text{N}_2\text{O}^+ + m\text{Ar} \qquad (1)$$

The correlation of the depletion/enhancement signals with the known normal modes of free N₂O,[6] as well as with the calculated vibrational wavenumbers for the Rh₆N₂O⁺ complex (see Supporting Information), represents clear evidence of the molecular nature of the N₂O adsorption. This, itself, is somewhat surprising as N₂O binds molecularly to extended crystalline rhodium surfaces only at low temperature with temperature controlled desorption experiments showing it to decompose as low as 95 K on Rh(110).[7] The temperature of the clusters in this study can be assumed to be close to that of the cluster channel, *i.e.*, *ca.* 173 K. Under single collision conditions, however, cationic rhodium

clusters react with nitrous oxide solely to yield sequential oxide clusters with accompanying N_2 release.[8]

In all of our spectra, ν_1 and ν_3, the two stretches, at 1305 cm^{-1} and 2270 cm^{-1}, are observed slightly blue-shifted compared with free N_2O (by *ca.* 34 and 46 cm^{-1}, respectively) while the bending mode, ν_2, at 560 cm^{-1}, is red-shifted by *ca.* 30 cm^{-1}. These shifts agree well with those calculated for the N-bound, $[ONN-Rh_6]^+$ complex using density functional theory (blue bars in Figure 1; see the Supporting Information for details). We are unaware of any IR spectroscopy of N_2O on extended rhodium surfaces, but these spectral shifts are consistent with those for nitrogen-bound N_2O on Pd(110) by reflection−absorption infrared spectroscopy[9] and on Pt(111) and Ru(001) by electron energy loss spectroscopy.[10] In a recent matrix isolation infrared study, the N−O stretching mode of the N-bound Rh-NNO molecule was observed at 1200.6 cm^{-1}.[11]

In addition to the IVR-Ar-loss channel identified above, we have also observed a cluster surface reaction channel for a range of sizes $n = 4-8$. Figure 1d shows the spectrum observed in the Rh_6O^+ channel in the same spectral region. The major features in the production spectrum of Rh_6O^+ can be identified as originating from absorption by a larger cluster complex. The 610 cm^{-1} peak is the expected enhancement arising from the IR-MPD of $Rh_6OAr_m^+$ in the region of the metal−oxygen stretch (Figure 1c),

$$Rh_6OAr_m^+ + xh\nu \rightarrow Rh_6O^+ + mAr \qquad (2)$$

More intriguingly, however, clear increases in the Rh_6O^+ cluster signal is observed upon pumping of each of the N_2O normal modes in $Rh_6N_2OAr_m^+$ ($m = 0, 1, 2$). On the basis of a detailed analysis matching absolute depletions with corresponding enhancements, we can eliminate the possibility that these signals arise from the loss of N_2O and Ar from $Rh_6O(N_2O)Ar_m^+$ clusters (see Supporting Information). Instead, they arise from a reactive channel involving dissociation of the surface bound N_2O with the subsequent loss of molecular nitrogen;

$$Rh_6N_2OAr_m^+ + xh\nu \rightarrow [Rh_6N_2OAr_m^+]^* \rightarrow Rh_6O^+ + N_2, mAr \qquad (3)$$
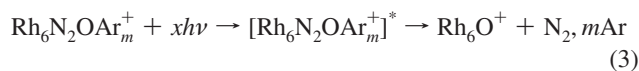
In other words, vibrational pumping of the molecularly adsorbed N_2O results in sufficient heating of the cluster to promote the system over the barrier to dissociative adsorption. If the original N_2O is, as the spectroscopy suggests, bound to the cluster *via* the extreme N atom, this channel represents a significant structural rearrangement as the O atom swings around ending up bound to the metal cluster as the N_2 departs. We calculate the binding energy of N_2O on Rh_6^+ to be 0.78 eV which represents an upper limit for the barrier to dissociation as otherwise only molecular desorption would occur. Calculations performed at the density functional level of theory, using a hybrid functional, have identified several plausible reaction pathways (see Supporting Information).

A detailed study of the various absolute signal depletions and enhancements for $Rh_6N_2OAr_m^+$ provides a lower limit for the branching ratio of the reactive channel (N_2 loss), as a fraction of the total loss, of approximately 0.1, 0.15, and 0.4 for ν_1, ν_2, and ν_3, respectively (see details in the Supporting Information). That ν_3 is more effective in promoting the N_2 loss surface chemistry probably reflects the increased energy per photon absorbed.

It is important to note the distinction between this radiation driven chemistry and photoinitiated chemistry observed in smaller metal-containing clusters such as the mode selective chemistry in $[VCO_2]^+$ in which the reactive vs dissociative branching ratio can be tuned by selectively pumping individual CO_2 vibrational modes.[12] The reaction observed here appears to be essentially thermally driven

with the surface bound N_2O molecule acting as an appropriate chromophore *via* which to raise the internal energy of the cluster. In this sense the reaction reported here represents a cluster analogue of the temperature programmed desorption technique applied to extended surfaces. Precedent for N_2O acting in this manner may be found in studies demonstrating infrared resonant desorption of physisorbed N_2O from the NaCl(100) surface.[13]

This surface chemistry is not limited to the $n = 6$ cluster highlighted here but is observed unambiguously for $n = 4, 6-8$, almost every cluster size with appreciable signal intensity in our study.

A full analysis of the branching ratios for the various product channels, as a function of both metal cluster size as well as the N_2O vibrational mode being excited, is underway and will be published in due course. Likewise, a comprehensive computational study of this surface chemistry is also being performed.

Supporting Information Available: Computational details and results, comparison with experimental data, data analysis. This material is available free of charge via the Internet at http://pubs.acs.org.

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