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Publication Date
1987-09-01
Submitted to Journal of Chemical Physics

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September 1987
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Infrared Spectroscopy of the Cluster Ions \( \text{H}_3^+(\text{H}_2)_n \)

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ABSTRACT

The vibrational spectra of the clusters \( \text{H}_3^+(\text{H}_2)_n \) were observed near 4000 cm\(^{-1}\) by vibrational predissociation spectroscopy. Spectra of mass-selected clusters were obtained by trapping the ions in a radio frequency ion trap, exciting vibrational transitions of the cluster ions to predissociating levels, and detecting the fragment ions with a mass spectrometer. Low resolution bands of the solvent \( \text{H}_2 \) stretches were observed for the clusters of one to six \( \text{H}_2 \) coordinated to an \( \text{H}_3^+ \) ion. The red-shift of these vibrations relative to the monomer \( \text{H}_2 \) frequency supported the model of \( \text{H}_9^+ \) as an \( \text{H}_3^+ \) with a complete inner solvation shell of three \( \text{H}_2 \), one bound to each corner of the ion. Two additional bands of \( \text{H}_5^+ \) were observed, one assigned as the \( \text{H}_3^+ \) symmetric stretch, and the other as a combination or overtone band. High resolution scans (0.5 and 0.08 cm\(^{-1}\)) of \( \text{H}_n^+ \), \( n = 5, 7, \) and 9 yielded no observable rotational structure, a result of either spectral congestion or rapid cluster dissociation. The band contour of the \( \text{H}_5^+ \) band changed upon cooling the internal degrees of freedom, but the peaks remained featureless. The observed frequencies of \( \text{H}_7^+ \) and \( \text{H}_9^+ \) agreed well with \textit{ab initio} predictions, but those of \( \text{H}_5^+ \) did not. This deviation is discussed in terms of the large expected anharmonicity of the proton bound dimer \( \text{H}_5^+ \).

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I. INTRODUCTION

Ionic clusters such as $\text{H}_3\text{O}^+\cdot(\text{H}_2\text{O})$ are important species in the stratosphere, where molecules readily nucleate about ions as a result of the long range attractive forces that dominate ion-molecule interactions. Such weakly bound molecular cluster ions have thus attracted much attention. Cluster ions have also been studied to shed light on ion-solvent interactions in liquids. The energetics, kinetics, and dynamics of cluster association and dissociation have been investigated by a variety of experimental techniques, but questions about the structure and vibrational motions of these ions remain largely unanswered. Traditionally, these problems have been addressed by gas phase spectroscopy. Although the spectroscopy of molecular ions has developed rapidly in the past decade, the spectroscopy of cluster ions has proven to be very difficult.

While only a handful of spectroscopic investigations of cluster ions have been done, several promising developments have been reported in the past year. In the earliest studies, Schwarz observed low resolution infrared absorption spectra of the $\text{H}_3\text{O}^+\cdot(\text{H}_2\text{O})_m$ and $\text{NH}_3^+\cdot(\text{NH}_3)_m$ clusters created in the pulsed radiolysis of water vapor. More recently, Kennedy and Miller have obtained laser induced fluorescence spectra of the clusters $\text{C}_6\text{F}_7^+\cdot\text{He}$, and from observation of vibronic transitions involving the intermolecular vibrations, have estimated the geometry and force field for this cluster. Smalley and co-workers have reported electronic spectra of $\text{Nb}_2^+$ and $\text{Ni}_2^+$ using a two photon dissociation scheme to probe the bound intermediate state. Several groups are studying cluster anions by photoelectron spectroscopy. An important advance has been made by Bogey et al. who have observed the microwave spectra of $\text{Ar}\cdot\text{H}_3^+$ and $\text{Ar}\cdot\text{D}_3^+$ in a glow discharge, the first high resolution spectra of weakly bound ions. We have recently reported preliminary results on the infrared spectroscopy of cluster ions using vibrational
predissociation spectroscopy. In this paper, we describe our experiments on the hydrogen cluster ions $H_3^+ \cdot (H_2)_n$.

The hydrogen cluster ions are the simplest ionic molecular complexes. The structure of these clusters has generally been described as $H_2$ molecules surrounding the $H_3^+$ ion, $H_3^+ \cdot (H_2)_n$. $H_3^+$ itself is a dominant ion in many hydrogen discharges and plasmas, and is expected to be abundant in the interstellar medium. The proton affinity of $H_2$ is 101 kcal/mol, so the $H_3^+$ ion is strongly bound. The $H_3^+$ ion was first positively identified by Dawson and Tickner in 1962 by mass spectrometry. Larger odd mass clusters were subsequently observed by Buchheit and Henkes in mass spectra and by Clampitt and Gowland using low energy electron bombardment of solid hydrogen. Later workers have observed odd mass hydrogen clusters in various size distributions from ionization and collisional fragmentation studies. Kirchner and Bowers have studied the dynamics of metastable $H_3^+$ fragmentation. High pressure mass spectrometry and drift tube experiments have yielded the enthalpy and entropy of association for the ionic hydrogen clusters, and found that they are bound by less than 10 kcal/mol. Although there is some disagreement concerning the $H_3^+$ dissociation enthalpy, the most recent measurements give $\Delta H^\circ_{300} = 5.8$ and 6.6 kcal/mol for $H_5^+ \rightleftharpoons H_3^+ + H_2$ and $\Delta H^\circ_{110} = 3.1$ kcal/mol for $H_7^+ \rightleftharpoons H_5^+ + H_2$. The only previous reports of hydrogen cluster ion spectra have been charge induced spectra observed in radiation-damaged solid hydrogen isotopes ($D_2$ and $T_2$). Although the observed peaks have been attributed in part to cluster ion formation, no definitive assignment has been made.

Their small size makes these clusters ideal for accurate computational study, and there have been many $ab$ initio calculations. Theorists have also found that these clusters are very weakly bound, and require fairly large basis sets and correlation for converging results. Table I contains a compilation of the experimental results.
and a selection of *ab initio* calculations for the $H_n^+$ dissociation energies. In the best calculation on $H_5^+$ to date, $^{47}$ Yamaguchi *et al.* predict $D_0 = 5.45$ kcal/mol, and inclusion of the thermal contribution (using calculated vibrational frequencies to estimate the vibrational partition function) yields $\Delta H_{300}^0 = 6.5$ to 7 kcal/mol, in good agreement with the most recent experimental values. The *ab initio* studies all conclude that in these clusters, the first three $H_2$ molecules are bound to the three corners of the $H_3^+$. Structures of $H_n^+$, $n = 5$, 7, and 9, are shown in Fig. 1. The theory also confirm the experimental finding of Hiraoka and Kebarle $^{29}$ that the binding energies of additional $H_2$ molecules to $H_3^+$ are smaller than those of the first three $H_2$, as seen in Table I.

The $H_3^+$ ion is the transition complex for the reaction $H_3^+ + H_2$. Experiments on isotope exchange reactions have shown $^{37,48}$ that there is complete isotopic scrambling, with an activation energy of about 2.4 kcal/mol, indicating that all five $H$ atoms can permute in the transition complex. Douglass *et al.* $^{49}$ have investigated the isotopic exchange $D_3^+ + H_2$ in reactive scattering experiments. The *ab initio* theory has found that the potential energy surface for the $H_3^+$ ion is very soft and shallow, $^{37,45,47}$ so that the ion easily isomerizes. Because the potential is flat near the equilibrium geometry, calculations for the dissociation energy and equilibrium geometries have not converged well. For example, Ahlrichs found the $D_{2d}$ geometry to be the minimum, because he did not fully optimize the geometry. $^{37}$ Yamaguchi, Gaw, Remington, and Schaefer have performed impressive full CI calculations $^{47}$ with large basis sets for ten stationary points below the dissociation energy. The equilibrium geometry, shown in Fig. 1, has $C_{2v}$ symmetry, but there are three saddlepoints lying less than 0.6 kcal/mol above it. Perhaps the most important is the $D_{2d}$ structure, with the central $H$ atom symmetrically between the two $H_2$. This structure is the transition state for the intramolecular proton transfer $H_3^+ \cdot H_2 \rightarrow H_2 \cdot H_3^+$ has
a barrier height of only 0.08 kcal/mol. Three of the other saddlepoints lie only 4.8 kcal/mol above the equilibrium geometry. The \( \text{H}_5^+ \) ion is therefore predicted to be a very nonrigid molecule.

While most calculations have focused on the structure and energetics of these ions, in 1983 Yamaguchi, Gaw, and Schaefer\(^45\) published calculations of the harmonic vibrational frequencies of \( \text{H}_2^+ \), \( \text{H}_3^+ \), and \( \text{H}_5^+ \). They used both \((\text{DZ}+\text{P})\) Hartree Fock SCF calculations for \( n = 5, 7, \) and \( 9 \), as well as CISD (configuration interaction, with single and double excitations) for \( n = 5 \) and \( 7 \). Their calculations (harmonic frequencies with an empirical scale factor) predict that the \( \text{H}_2 \) ligands in these clusters have vibrational modes with frequencies red-shifted by 100 to 400 cm\(^{-1}\) from the 4161 cm\(^{-1}\) frequency of the free \( \text{H}_2 \) monomer.\(^5\) Furthermore, they have predicted that, in \( \text{H}_5^+ \) for example, the \( \text{H}_3^+ \) moiety would absorb at approximately 3400 cm\(^{-1}\), about 200 cm\(^{-1}\) above the predicted \( A_1 \) symmetric stretching fundamental of \( \text{H}_3^+ \). These vibrations are dipole forbidden in the respective monomers, but are predicted to become allowed in the clusters. Yamaguchi \textit{et al.} also predict that the \( \nu_2 \) \((E)\) mode of \( \text{H}_3^+ \) at 2521 cm\(^{-1}\), first observed by Oka\(^5\) and subsequently the focus of much attention, is split in \( \text{H}_5^+ \) and red-shifted to 1746 and 1449 cm\(^{-1}\).

The predictions of vibrational frequencies stimulated our efforts to study the infrared spectroscopy of these cluster ions. The highest frequency modes, the \( \text{H}_3^+ \) symmetric stretch and \( \text{H}_2 \) stretching modes, are predicted to lie well above the dissociation limit for all \( \text{H}_n^+ \) clusters. Therefore, exciting the solvent \( \text{H}_2 \) will lead to cluster predissociation. In our apparatus, parent cluster ions extracted from one of a variety of sources are mass-selected and trapped. Once we have collected ions in the trap, we can excite them with a tunable infrared laser. The ion density in the trap is far too low to detect the absorption directly. Instead, we measure the absorption spectrum of the parent ion by detecting its dissociation. For weakly bound clusters,
absorption of a single infrared photon by a high frequency stretching mode can lead to predissociation of the cluster. By detecting the fragment ions produced upon dissociation as a function of laser frequency, we take advantage of the nearly unit efficiency of ion counting detection. Vibrational predissociation spectroscopy is a well known technique in the study of neutral van der Waals complexes, but has had limited success with larger clusters due to both the difficulty in identifying the absorbing cluster and the uncertainties in detection stemming from cracking of the products upon electron impact ionization.

Guided by the theoretical predictions of Yamaguchi, Gaw, and Schaefer, we have searched for the $H_2$ stretching bands of $H_n^+$, $n = 5, 7, 9, 11, 13, \text{ and } 15$. In addition to low resolution observations of vibrational bands, we have sought rotationally resolved spectra, primarily of $H_8^+$. The light $H_8^+$ molecule, a near prolate symmetric top, has a rotational spacing in the P and R branches of $2B \approx 6 \text{ cm}^{-1}$; therefore, one expects to observe well-resolved rotational structure, even at laser linewidths of $0.5 \text{ cm}^{-1}$.

II. EXPERIMENTAL

The hydrogen cluster ions were produced either by electron impact ionization of neutral $H_2$ clusters, or within a high pressure (~200 torr, 0°C) corona discharge. In the former, the ions were created with substantial amounts of excess internal energy; in the latter, the vibrational temperature of ions was expected to be near room temperature. The sources are described in more detail below. After extraction from the source, the beam of ions was mass-selected with a 20 cm radius sector magnet. The ion beam deflected 90° in an electrostatic quadrupole bending field, decelerated to approximately 0.5 eV, then focused into a radio-frequency (RF) octopole ion trap through an entrance aperture lens. Ions were collected in the trap for 0.1 to 1.0 ms;
the potential of the entrance lens was then raised, and the ions confined inside the octopole.

The trap was an octopole ion guide, eight molybdenum rods 0.5 m long equally spaced on a 1.25 cm diameter circle. Details can be found elsewhere.\textsuperscript{53} Trapped ions bounced back and forth between two lens elements, on either side of the octopole, held at a d.c. potential about 20 V above the trap bias. The RF on the octopole created an effective potential well perpendicular to the trap axis, confining the ions to the center of the octopole region. The pressure in this region was typically 1 to $3 \times 10^{-9}$ torr. Collisions in the trap were found to be negligible on the timescale of the experiment.

After 1 to 2 ms, an infrared laser was fired through the trap to dissociate the ions. After excitation with the laser, the ions were then released by lowering the voltage of the aperture lens at the trap exit. The ions were mass selected with a quadrupole mass spectrometer, and detected with a Daly ion detector. Standard ion counting techniques were used. In a typical experiment, counts at a given fragment ion mass were recorded as a function of laser frequency. When measuring the parent ion signal, the ion count rate was often greater than $10^6$ s\textsuperscript{-1}. In that case, the photomultiplier gain was reduced, and the (amplified) ion current measured.

The laser was fired or chopped in alternate data cycles; the signal was the difference in fragment ion counts between cycles with the laser on and cycles with the laser off. This eliminated background fragment counts resulting from decay of metastable ions, and collision-induced dissociation in the trap. The laser power was measured after passing through the trap, for normalization of the spectra.
A. Infrared Lasers

Three tunable infrared lasers were used in this experiment, covering the range from 2200 cm\(^{-1}\) to 6500 cm\(^{-1}\), providing a choice of average power and frequency resolution.

The optical parametric oscillator (OPO)\(^{54}\) was a LiNbO\(_3\) crystal pumped by the far-field output (1 W) of a Quanta Ray DCR-1A Nd:YAG laser. No line narrowing elements were in the OPO cavity; thus, the linewidth was as broad as 20 cm\(^{-1}\) (at 4200 cm\(^{-1}\)), but was more typically 5–10 cm\(^{-1}\) at the wavelengths used (3500–4000 cm\(^{-1}\)). This laser gave the highest powers, and was used for preliminary searches. The wavelength was calibrated using an 0.3 m monochromator. The laser produced 8-10 mJ per pulse at 10 Hz.

A commercial difference frequency laser was used for some moderate resolution spectra. The Quanta Ray Infrared Wavelength Extender mixes the 1.06 \(\mu\) output of a Nd:YAG laser with the output of a near infrared dye laser. The laser linewidth was measured to be 1.2 cm\(^{-1}\). The pulse energy was 0.8-1 mJ at 4000 cm\(^{-1}\) and 0.5 mJ at 3500 cm\(^{-1}\). The laser was operated at 10 Hz.

Both of the above lasers utilize nonlinear mixing in LiNbO\(_3\) crystals. This material has an unfortunate infrared absorption between 3460 and 3490 cm\(^{-1}\) caused by OH absorption. In the case of the difference frequency system, the output dropped over an order of magnitude, to 0.05 mJ per pulse or less in this range.

For high resolution experiments, spectra were taken with an F-center laser (Burleigh Instruments Inc.). Without an intra-cavity etalon, the laser produced 5 to 40 mW, cw, with a nominal linewidth of 0.5 cm\(^{-1}\). With the etalon in place, the linewidth was specified as 1 MHz (3 \(\times\) 10\(^{-5}\) cm\(^{-1}\)), far below the expected Doppler limit for trapped ions of approximately 0.08 cm\(^{-1}\). Because this laser was continuous, the timing of the experiment was modified. When the ions were trapped, the
laser beam was flagged on with a shutter (A. W. Vincent Associates) for 20 ms. As before, the laser was flagged on during alternate cycles. The low duty cycle resulted in a significant decrease in average power and signal, relative to spectra taken with the pulsed lasers. The laser wavelength was calibrated using a Burleigh λ meter.

The Doppler width of the ions was broader than a room temperature width, because the laser beam was collinear with the axis of the trap. The ions moved back and forth along this axis; for H^+_t at a mean energy of 0.5 eV, the expected Doppler width was approximately 0.08 cm⁻¹.

B. Sources

1. Electron Impact Ionization of Neutral (H₂)ₙ Clusters

Most of the spectra reported here were of ions produced by electron impact of neutral hydrogen clusters (H₂)ₙ. The neutral clusters were formed by supersonic expansion of pure hydrogen (99.999% pure, from Matheson or Scientific Gas Products) through a 10 μ nozzle. The stagnation conditions were 20–30 atm, at a temperature of 110 K. The expansion was skimmed with a Beam Dynamics electro-formed skimmer 7 mm from the nozzle. The first region was pumped with a liquid nitrogen trapped ten inch diffusion pump backed by a 150 l/s roots pump. The chamber following the skimmer was pumped by a trapped, six inch diffusion pump, giving a background pressure of 0.5 to 1 x 10⁻⁵ torr. This region contained both the ionizer and electron optics. The molecular beam was ionized in a conventional hot filament electron beam ionizer. The electron energy was 80–100 eV, and the ionizer emission current was ≈ 4 mA. H₂⁺ and H₃⁺ were the dominant ions; the H₅⁺ current was approximately 100 pA. The beam intensity decreased monotonically with cluster size, but always showed a large drop after H₆⁺.
Upon ionization of the \((H_2)_n\) clusters, the reaction

\[
H^+_2 + H_2 \rightarrow H^+_3 + H
\]  

(1)

proceeds within the cluster. The excess energy in the reaction of 40 kcal/mol is deposited as internal energy in the cluster. Since, for larger clusters, the average binding energy of an \(H_2\) is 3 kcal/mol or less,\(^{29}\) the cluster probably fragments extensively. Several \(H_2\) molecules evaporate from the cluster to carry off the excess energy.

The ionization and subsequent rearrangement and fragmentation leaves the cluster internally excited. We observed that approximately 0.1% of the ions fragment in the trap within the first 2 ms, predominantly by loss of a single \(H_2\). The fragmentation in the trap arises from metastable ions which have survived the 50 \(\mu s\) flight from source to trap. Any fragments from in-flight dissociation would not have enough energy to enter the trap. Such fragmentation was not observed for ions created internally cold. Previous experiments under similar trapping conditions have shown that collisional dissociation in the trap is negligible. Thus we have direct evidence for metastable cluster ions with predissociation lifetimes on the order of milliseconds.

The background counts arising from the metastable fragmentation of \(H^+_{2n+1}\)

\[
H^+_{2n+1} \rightarrow H^+_{2n-1} + H_2
\]  

(2)

were comparable to the laser-induced dissociation signal. For spectra recorded with the \(H^+_{2n-1}\) dissociation channel, this background was subtracted, but it consequently reduced the signal-to-noise ratio. For \(H^+_5\), this was the only channel. The background counts were equal to the signal counts at the peak of the absorption bands, causing a significant decrease in the signal-to-noise ratio. For the larger clusters, loss of one \(H_2\) was not a dominant dissociation channel; thus, the signal-to-noise ratio
was very poor, but better spectra could be recorded using other channels involving loss of more than one H₂.

2. Corona Discharge Source

To eliminate spectral congestion and to reduce the background of fragment ions, a source of internally cold ions was needed. Several such sources have been described in the literature, all involving ionization at relatively high pressures (p > 1 torr). There must be enough collisions for the rotational and vibrational degrees of freedom to be at least partially equilibrated with the source temperature. These sources tend to create thermodynamically stable ions, often terminal ions "at the end of the food chain." Since the density of charged species is low, the presence of trace impurities can have a pronounced effect on the mass spectrum. For example, in a high pressure hydrogen discharge, the dominant ion may be H₃O⁺, not H₃⁺. The proton affinity of water is 165 kcal/mol, 64 kcal/mol higher than that of H₂. As a result, unless the source and gas is thoroughly dried, all H₃⁺ will react with trace water by very exothermic proton transfer.

Corona discharges have been used as sources of ionic clusters in a number of previous experiments. Searcy and Fenn developed a corona discharge source to study water cluster nucleation about an ion during a supersonic expansion, while Beuhler, Ehrenson and Friedman used one for measurements of hydrogen cluster ion equilibria prior to expansion. In the apparatus of Searcy and Fenn, a discharge was struck from a tungsten needle to a tungsten grid; the volume between the grid and a nozzle was a field-free drift region, in which the ions could equilibrate. Beuhler et al. did not use such a drift region. Beuhler et al. reported ion currents of only 10⁴ ions per second; however, they used very small apertures (12 µ) to minimize cooling effects after the nozzle.
The corona discharge source used in this experiment is shown in Fig. 2. The body of the source was copper and was in thermal contact with a reservoir. It was designed for cooling with liquid nitrogen, although Freon-12 and Freon-22 were the primary coolants in this experiment. The electrode was a nickel-plated steel sewing needle which could be translated to vary the distance from body to point. We expected that the discharge would be located in a conical-shaped region. This tapered down at 30° to a cylindrical volume 1.0 mm in diameter, 1.7 mm in length before the nozzle in which the ions could react and equilibrate. The drift time in this region was estimated to be approximately 0.5 ms. The nozzle was a 70 μ aperture in a platinum disk (Ted Pella, Inc.). The source was floated at +350V above ground.

The needle was fixed at a minimum distance of 3.3 mm from the tapered wall of the source, 5.7 mm from the beginning of the drift region. It was in series with a 1 MΩ ballast resistor. Typical discharge conditions were 2.5 kV and 30 μA. Ultra-high purity hydrogen (99.999 % pure, as in the previous source) at 100 to 200 torr was used. The gas was always passed through a liquid nitrogen cooled trap containing Linde 13X molecular sieve. The inlet line and the source were baked out daily and pumped to a base pressure of 10⁻⁵ torr or less. Without these precautions, no hydrogen cluster ions appeared. Instead, in a "dirty" source at temperatures above approximately −10°C, protonated water clusters were the dominant species. If the source was cooled further, the water clusters were replaced by protonated nitrogen clusters. Hydrogen cluster ions could only be produced in useful currents by keeping the source and inlet system clean.

The skimmer aperture was 1.4 mm, and was approximately 7 mm from the nozzle. The skimmer was kept to within 1 V or less of the nozzle voltage, to prevent acceleration and subsequent collisional heating of the ions. A grid surrounding this
region and held at the same potential as the source was necessary to prevent stray fields from penetrating into the nozzle-skimmer region. The skimmer was followed by a conical extractor, 2 cm behind, at a potential of 10 to 20 volts below the skimmer. Variations of this voltage could alter the ion size distribution. This result was probably due to extraction and focusing effects, because there was never any indication of collisional heating, either in the spectra or as background counts from metastable ion dissociation. The ions were then accelerated and focused. During normal operation, the pressure of the source differential chamber was 1 to $2 \times 10^{-4}$ torr, while the ion optics region after the skimmer was $6 \times 10^{-6}$ torr.

The $H_5^+$ current through the machine was about $3 \times 10^5$ counts/s at a source temperature of 260 K. At lower temperatures (80 K), the total ion current was comparable, but was dispersed over a large range of cluster sizes; the intensity of a given cluster was significantly lower.

III. RESULTS

A. Clusters Formed by Electron Impact Ionization

Low resolution OPO spectra were recorded from 3800 cm$^{-1}$ to 4200 cm$^{-1}$ for the ions $H_n^+$ ($n = 5, 7, 9, 11, 13$, and $15$) created by electron impact ionization. With the exception of $H_5^+$, all ions had a single, slightly asymmetric peak in this region. For each parent ion, we searched for spectra with the OPO at all possible fragment masses; in general, only one or two channels were important. Fig. 3 shows the branching ratios of the different dissociation channels with the laser set at the peak of each absorption. In general, the major channel for each cluster was consistent with loss of the maximum number of solvent $H_2$ energetically allowed.

The spectrum of $H_5^+$, shown in the upper panel of Fig. 4 was taken with the OPO,
detecting the $H_3^+$ fragment. The peak, at 3910 cm$^{-1}$, was red-shifted 250 cm$^{-1}$ from the vibrational origin of unbound $H_2$ monomer at 4161 cm$^{-1}$. In addition to an asymmetric peak, there was a long shoulder going to higher frequencies, extending over 300 cm$^{-1}$.

The OPO spectrum of $H_3^+$ is shown in the middle panel of Fig. 4. Two spectra are shown, one for dissociation to $H_3^+$ and one for dissociation to $H_5^+$. The two spectra were similar, with absorption maxima at the same frequency. The peak was more symmetric than in $H_3^+$, with a much smaller high frequency shoulder. The spectrum arising from dissociation to $H_3^+$ was slightly broader, and had a larger relative contribution from the high frequency shoulder. The peak occurred at 3980 cm$^{-1}$, with a red shift 70 cm$^{-1}$ less than that of the $H_5^+$ peak.

The peak of the $H_5^+$ absorption at 4020 cm$^{-1}$ shown in Fig. 4, was at an even higher frequency than those of the smaller clusters. The shift was only 40 cm$^{-1}$ from the $H_7^+$ maximum. Again, spectra recorded detecting different fragments were similar, with the $H_3^+$ channel yielding the broadest peak, and the $H_7^+$ channel the narrowest. The signal-to-noise ratio in the $H_7^+$ channel was low, in part because the background was higher, and in part because it was a weak channel. The dominant products were $H_5^+$ and, to a lesser extent, $H_3^+$, as seen in Fig. 3.

When detecting the $H_7^+$ fragment, an additional feature appeared in the spectrum. There was a background of $H_7^+$ present in the trap, created from (laser independent) dissociation in the trap of metastable $H_9^+$. During the laser on cycle, the laser would dissociate some of the $H_7^+$, giving rise to a small depletion in the background $H_7^+$ counts, at frequencies centered on the $H_7^+$ absorption at 3980 cm$^{-1}$. This resulted in a negative signal on the low frequency side of the $H_9^+$ peak. The absolute number of background ions was small, relative to the number of parent $H_9^+$, and did not make a significant contribution to the signal at mass 5 or mass 3.
In the larger clusters H_{11}, H_{13}, and H_{15}, the peak positions at 4028, 4035, and 4048 cm\(^{-1}\) were close to that of the H_{9}^+ peak at 4020 cm\(^{-1}\). Dissociation with loss of only one H\(_2\) molecule was not observed. As seen in Fig. 3, the dominant channels were loss of three or four H\(_2\). Only a depletion peak (as described above) was observed when detecting the channel H_{n-2}^+, peaked at the H_{n-2}^+ absorption maximum.

Spectra were recorded for all parent ions, at selected daughter ion masses, using the color center laser. The spectra shown in Fig. 5 were all taken at a resolution of 0.5 cm\(^{-1}\), with the intracavity etalon removed. Additional scans were taken with the intracavity etalon in place, giving a laser line width of \(\approx 3 \times 10^{-5}\) cm\(^{-1}\) and Doppler limited resolution of approximately 0.08 cm\(^{-1}\). The high resolution scans did not fully cover the peaks observed at lower resolution, but we did scan selected 5–10 cm\(^{-1}\) wide segments. We searched the H_{5}^+ spectrum the most intensively. In no case was any additional spectral structure resolved with the higher resolution. The signal-to-noise was worst in the high resolution scans, usually no better than 10:1 after signal averaging. An individual scan with the intra-cavity etalon in place had a typical range of 0.5 cm\(^{-1}\).

The larger clusters H_{n}^+, n= 11, 13, and 15, all exhibited a weak shoulder near 4080 cm\(^{-1}\), which increased in relative intensity with increasing cluster size. This is seen in the OPO spectra in Fig. 6.

Based on the calculations of Yamaguchi et al.\(^{41,41}\) we expected the mode in H_{5}^+ correlating to the H_{3}^+ symmetric stretch to occur near 3400 cm\(^{-1}\). Fig. 7 shows the peak we observed using the color center laser with 0.5 cm\(^{-1}\) resolution. It had a maximum at 3532 cm\(^{-1}\), with an intensity approximately equal to that of the 3910 cm\(^{-1}\) peak, as predicted by Yamaguchi, Gaw and Schaefer at the DZ+P SCF level. No rotational structure was observable at this resolution. We also scanned
from 3000 cm$^{-1}$ to 3600 cm$^{-1}$, searching for the corresponding band in H$_5^+$ and H$_5^+$, but found no absorption. Any peak was therefore at least an order of magnitude less intense to go unobserved.

**B. Results with the Corona Discharge Source**

The large fraction of metastable dissociation in the trap (up to 0.1% of the beam) indicated that clusters created by electron impact ionization had high internal temperatures. Ions extracted from the corona discharge source were expected to have vibrational temperatures at or below the source temperature (approximately $-20^\circ$C in these experiments), and rotational temperatures cooled by the supersonic expansion to well below room temperature. We expected that such cooling would considerably narrow and simplify the spectra, if they were inhomogeneously broadened. As stated above, the hydrogen cluster beam intensity of the corona discharge source was two to three orders of magnitude less intense than that of the electron impact source, and was predominantly H$_5^+$ at these temperatures. Thus, it was difficult to take spectra of the larger clusters. We therefore limited scans for the most part to the H$_5^+$ cluster.

Fig. 8b compares the $\nu_1$ spectrum taken with the OPO of H$_5^+$ formed in the corona discharge source with the spectrum of H$_5^+$ formed by electron impact ionization. A significant difference in the band contour was seen. The main peak at 3910 cm$^{-1}$ did not shift, but became somewhat narrower. The high frequency shoulder decreased in intensity, except near 4230 cm$^{-1}$. Thus, the spectrum of cold H$_5^+$ appears to have an additional weak band 340 cm$^{-1}$ above the main band. The spectrum of H$_5^+$ formed by electron impact ionization could be reproduced if either the grid voltage was set to ground, or if there were a voltage drop of 10 to 30 V across the nozzle and skimmer. The difference between the two spectra is there-
fore caused in part by the different internal temperatures of the ions created in the
two sources. Fig. 9 shows the H$_3^+$ $\nu_1$ spectrum taken with the difference frequency
laser at a resolution of 1.2 cm$^{-1}$. The band has a more sharply defined peak, with
a relatively flat shoulder at lower frequencies, but otherwise contains no further
structure. A similar band contour was seen in the F-center spectrum of H$_3^+$ formed
by electron impact. The detail in the lower panel (Fig. 9b) was taken with the
WEX at 0.75 cm$^{-1}$ resolution, and reveals the lack of structure in the spectrum.

Again, we took extensive scans of the peak with the F-center laser, at both
0.5 cm$^{-1}$ and 3$\times$10$^{-5}$ cm$^{-1}$ resolution, but still found no evidence of resolvable
structure within the experimental uncertainty. We also scanned sections of the H$_2^+$
and H$_3^+$ spectra using both the F-center laser and the difference frequency laser, but
again saw no evidence of resolvable lines.

The observation of a weak band at 4230 cm$^{-1}$ for H$_3^+$ prompted a search for other
weak combination bands or overtones at higher frequencies. We scanned 3900 cm$^{-1}$
to 5300 cm$^{-1}$ using the difference frequency laser (1.2 cm$^{-1}$ resolution) in the H$_3^+$
spectrum, but found no new features, despite the higher laser power obtainable at
these wavelengths from the difference frequency laser.

IV. DISCUSSION

A. Vibrational Frequencies

The observed peak frequencies of the H$_2$ stretch are plotted as a function of
cluster size for all observed clusters in Fig. 10. As noted above, the peaks are red-
shifted from the vibrational frequency of the H$_2$ monomer. The observed red-shifts
from the monomer H$_2$ frequency are 100 to 250 cm$^{-1}$, far larger than those seen
in neutral H$_2$ complexes. In Kr-H$_2$, for example,$^{61}$ the observed shift is only 1 to
2 cm\(^{-1}\). Even in solid H\(_2\),\(^{62}\) the para \(Q_1(0)\) line \((v = 1, J = 0)\) is shifted by only 11 cm\(^{-1}\). Bernholdt \textit{et al.}\(^{63}\) predict that the vibrational frequency of H\(_2\) hydrogen bonded to HF will be shifted by 20 cm\(^{-1}\). The shifts seen in H\(_4^+\) clearly reflect the strength of the charge induced dipole interactions present in these clusters.

For H\(_5^+\), the red shift is 250 cm\(^{-1}\). As the cluster size increases, the frequency shift relative to the monomer frequency decreases; however, after H\(_5^+\), the frequency shift changes very little, from 140 cm\(^{-1}\) to 115 cm\(^{-1}\). This result can be understood from the structures and nature of the binding predicted by the \textit{ab initio} calculations,\(^{37,39,45}\) which indicate that the H\(_2\) molecules bind first to the three corners of the H\(_3^+\) ion. After the first three H\(_2\), additional H\(_2\) molecules attach far more weakly, as depicted in Fig. 11. The reason for the lack of change in the spectrum is two-fold. First, the three H\(_2\) molecules at the corners are strongly perturbed by the ion, and thus possess the most oscillator strength at \(\approx 4000\) cm\(^{-1}\). The outer H\(_2\) molecules, darkened in Fig. 11, are far less perturbed, and thus do not absorb strongly. The weak shoulders observed near 4080-4100 cm\(^{-1}\) in clusters larger than H\(_5^+\) may be due to absorption by these outer H\(_2\) moieties. Second, these outer H\(_2\) do not strongly perturb the H\(_3^+\) core; thus, the H\(_2\) at the corners absorb at a similar frequency, despite the added H\(_2\) molecules.

Such a description of the larger clusters is supported by the trends observed in the experimental \(\Delta H^\circ\). Hiraoka and Kebarle have measured the enthalpies of clusters larger than H\(_3^+\); they have found enthalpies\(^{29}\) for H\(_3^+\)-(H\(_2\))\(_n\) \(\leftrightarrow\) H\(_3^+\)-(H\(_2\))\(_{n-1}\) + H\(_2\) in H\(_7^+\), H\(_9^+\), and H\(_{11}^+\) to be 4.1, 3.8 and 2.4 kcal/mol, respectively. The fourth H\(_2\) is bound by 40% less energy than the third H\(_2\). Their measurements for the smaller clusters disagree with the most recent experiments, implying possible systematic error, but the observed trend is probably qualitatively correct.

The location of the last two H\(_2\) (above and below the H\(_3^+\) plane) shown in Fig. 11
are based on SCF calculations without full geometry optimization. Such a structure does not account for the apparent stability of $\text{H}_1^5$ as seen in cluster size distributions, and collisional dissociation experiments. It might be possible to shed further light on the structure of the "second solvation" shell, if the sensitivity of the experiment were increased and details of the weaker $\text{H}_2$ stretches observed.

Some groups have observed the infrared absorption spectra of solid hydrogen and its isotopes after irradiation with high energy protons or $\beta$ particle emission from tritium.\textsuperscript{33,34,35,64} No spectra were assigned to $\text{H}_n^+$ entities in solid $\text{H}_2$ but some of the features to the red of the vibrational fundamental in the $\text{D}_2$ and $\text{T}_2$ spectra were assigned as charge-induced spectra from molecules perturbed by a positive charge. With a simple reduced mass correction, one obtains a corresponding frequency for $\text{H}_2$ of 4055 cm$^{-1}$, close to our value of 4048 cm$^{-1}$ for $\text{H}_1^5$. The fairly large bond energies for $\text{H}_n^+$ formation (relative to neutral $\text{H}_2$ interactions), and the significant anisotropy of the potential about an $\text{H}_n^+$ ion suggest that $\text{H}_n^+$ clusters (or its isotopes) form in the solid, followed by subsequent solvation of the $\text{H}_n^+$. The lines observed in the solid would then be assigned to the three $\text{H}_2$ in the $\text{H}_n^+$.

Hunt and Poll\textsuperscript{65} have calculated the Stark shift of the vibrational frequency of an $\text{H}_2$ molecule perturbed by a charge, as a function of the charge to $\text{H}_2$ separation. If one uses the \textit{ab initio} results of Yamaguchi for an estimate of the distance between the $\text{H}_2$ and the $\text{H}_n^+$ center of charge, one obtains predicted vibrational frequencies that are 58 cm$^{-1}$ and 42 cm$^{-1}$ too low for $\text{H}_1^+$ and $\text{H}_3^+$ respectively. The separation in $\text{H}_5^+$ is 1.855 Å, smaller than the shortest distance considered by Hunt and Poll, but extrapolation leads to an expected error of at least 60 cm$^{-1}$. This simple model thus appears to provide a semi-quantitative estimate of the perturbed $\text{H}_2$ frequency, but overestimates the red-shift by $\sim$30%.

Our results allow us to test the accuracy of the \textit{ab initio} calculations of vi-
brational frequencies for cluster ions. Yamaguchi, Gaw, and Schaefer 45 calculated harmonic vibrational frequencies for $H_n^+$ using both (DZ+P basis set) Hartree Fock SCF calculations for $n = 5, 7, \text{ and } 9$, and (DZ+P basis set) single and double configuration interaction calculations (CISD) for $n = 5$ and 7. Their results, including predicted intensities, were valuable in our initial search for the spectra. Since then, Yamaguchi, Gaw, Remington, and Schaefer 47 have performed higher level theory for Ht+, including (DZ+P) full CI as well as CI calculations with larger basis sets for several geometries. Table II lists the frequencies of the observed peak maxima for $H_n^+$ with $n = 5, 7, \text{ and } 9$ along with the frequencies predicted by various levels of ab initio theory.

One must use care in comparing the experimental and theoretical vibrational frequencies. The experimental frequencies are maxima of unresolved bands, not true vibrational band origins. Band heads and other pileups of lines could lead to band maxima displaced from the origin. This uncertainty is particularly important for $H_5^+$, which has an asymmetric band shape.

One of the largest uncertainties in the theoretical values lies in the scaling of frequencies to correct for both the systematic error and the anharmonicity. The calculated harmonic frequencies tend to systematically overestimate the true harmonic frequencies, as well as neglecting anharmonic effects. The theorists can crudely compensate for these errors by scaling the frequencies. Furthermore, the normal mode analysis is inadequate for weakly bound complexes with large amplitude vibrations. Recent advances 66 in the computation of anharmonic constants using analytic second derivatives should improve the accuracy of the calculations, but in cases with large anharmonic coupling, as in floppy molecules, such an expansion may not be satisfactory.

Despite the uncertainties, the theoretical and experimental values are in good
agreement for $H^+_2$ and $H^+_6$. The scaled frequencies are correct to within 15 cm$^{-1}$ at the SCF level, as seen in Table II. The agreement is more in line with previous results on strongly bound ions such as $H_3O^+$, and probably results from the fact that the $H_2$ is less strongly perturbed by the charge as the cluster size increases. Although two nearly degenerate modes are predicted for both $H^+_2$ and $H^+_6$, in each case only one band is observed.

The agreement is far worse for the $H^+_3$ cluster, despite the larger basis sets and use of full CI. Table II lists both harmonic and scaled vibrational frequencies, for two configurations: the $C_{2v}$ minimum, and the low lying $D_{2d}$ saddlepoint (predicted to be 0.087 kcal/mol or 30 cm$^{-1}$ higher in energy).

For $\nu_1$, the $H_2$ stretching mode observed at 3910 cm$^{-1}$, the DZP basis set full CI frequency is, after scaling, low by 66 cm$^{-1}$. Yamaguchi, Gaw, Remington and Schaefer have calculated an “extended II” (6s3p) basis set CISD frequency which can be scaled to obtain an estimated (6s,3p) basis set full CI frequency of 3884 cm$^{-1}$. This value is low by only 26 cm$^{-1}$. The theoretical predictions for the frequency at the saddle point geometry $D_{2d}$ deviates the most, with an estimate 197 cm$^{-1}$ below the observed frequency.

The $\nu_2$ mode of $H^+_3$ could not be properly scaled by Yamaguchi et al. because the symmetric stretch of $H^+_3$ had not been experimentally observed. They could still estimate the scaling factor, by using a theoretical prediction for the $H^+_3$ symmetric stretch. This calculation involved numerically solving the vibrational hamiltonian on a potential energy surface derived from $ab$ initio points. Recently, Majewski et al. have determined the $\nu_1$ frequency to be 3175.0 cm$^{-1}$ from perturbations in the $\nu_2$ band, in excellent agreement with theoretical results. This gives a scaled DZP full CI frequency of 3433 cm$^{-1}$ for the frequency of the $\nu_2$ mode of $H^+_3$ at the $C_{2v}$ geometry, 99 cm$^{-1}$ below our observed band at 3532 cm$^{-1}$. The scaled frequency
at the $D_2d$ geometry is 3609 cm$^{-1}$, 77 cm$^{-1}$ above the observed frequency. The estimated full CI value with the extended II (6s,3p) basis set, scaled from the (6s,3p) CISD result, is 3402 cm$^{-1}$, 130 cm$^{-1}$ below the observed frequency. This contrasts with the small deviation in the estimated frequency for $\nu_1$, off by only 26 cm$^{-1}$, obtained at the same level of theory. We conclude that scaling $ab\ initio$ harmonic frequencies cannot accurately predict the H$_t^+$ peak frequencies observed in our spectra, despite the high level of theory used.

The weak band at 4230 cm$^{-1}$ in H$_t^+$ could be either a combination band or an overtone. It lies 340 cm$^{-1}$ above the $\nu_1$ band at 3910 cm$^{-1}$. Two lower frequency modes are good candidates.$^{45,47}$ Both $\nu_4$ (H$_t^+$ antisymmetric stretch) and $\nu_8$ (intermolecular stretch) modes involve large motions of the central proton, and consequently large changes in the dipole moment. These two modes are in fact the strongest absorbers of the nine vibrational modes of H$_t^+$, with predicted intensities in the double harmonic approximation over five and ten times larger (for $\nu_8$ and $\nu_4$ respectively) than the $\nu_1$ and $\nu_2$ modes.

The $ab\ initio$ calculation$^{47}$ predicts that the low frequency stretch $\nu_8$ of the complex bond has a harmonic frequency of 478 cm$^{-1}$. This mode is clearly anharmonic, and the true frequency is undoubtedly much lower. Thus, the weak band could be the $\nu_1+\nu_8$ combination band. If the 4230 cm$^{-1}$ band is assigned as the combination band $\nu_1+\nu_8$, then the $\nu_8$ vibrational frequency is approximately 340 cm$^{-1}$, neglecting the anharmonic term $x_{18}$. This assignment raises the question of where the $\nu_2+\nu_8$ combination mode would lie. We predict that it would occur at 3870 cm$^{-1}$, only 40 cm$^{-1}$ below the observed $\nu_1$ band. This might give rise either to spectral congestion, or even the possibility of a Fermi resonance, since both modes will have $a_1$ symmetry.

The 4230 cm$^{-1}$ band could also conceivably be an overtone. Yamaguchi, Gaw,
Remington, and Schaefer predict a mode, the strong $\nu_4$ mode, to have a harmonic frequency of 1746 cm$^{-1}$. Again, this number may seriously overestimate the true vibrational frequency. The scaled value for this mode is 1641 cm$^{-1}$, placing the second overtone at less than 4900 cm$^{-1}$, requiring the anharmonic term $\omega_c x_c$ to be 60 to 70 cm$^{-1}$.

The above discussion suggests an alternate assignment of the 3532 cm$^{-1}$ band, as the first overtone of the 1746 cm$^{-1}$ $\nu_4$ mode. The intensity of the band is what one would expect, given that overtone intensities are approximately one order of magnitude weaker than the corresponding fundamentals. However, the position of the band is somewhat high; twice the calculated harmonic frequency is 3492 cm$^{-1}$ but this is an upper bound and should severely overestimate $2\omega_c - 6\omega_c x_c$. Twice the scaled frequency is 3282 cm$^{-1}$, well below the observed band. Therefore, this is an unlikely candidate for the assignment of the 3532 cm$^{-1}$ band.

B. Linewidths

Despite using high resolution lasers, we were unable to resolve rotational structure in any of the vibrational bands. These clusters are relatively light, and from the predicted rotational constants, the rovibrational spectrum should be resolved for $n = 5, 7, \text{ and } 9$. There are several possible explanations for the absence of rotational structure. The asymmetry of the peaks, particularly those of H$_5^+$, and the observed narrowing of the spectrum with temperature indicate that at least part of the linewidth is inhomogeneous. We can rule out instrumental artifacts, because we have observed rotational structure in the spectra of other ions created by the corona discharge source. Thus, the trapping does not give rise to unexpectedly large Doppler widths, and the instrument is in fact capable of Doppler-limited resolution. Another possibility is that the spectrum consists of both sharp and broadened
transitions. The spectrum might then appear as small lines on top of a continuous baseline, and would require more signal averaging to observe the structure. From the signal-to-noise ratio in our experiment, we would conclude that the discrete spectrum must be at least ten times weaker than the continuous spectrum.

One possibility is that the spectra are very congested. The internal temperature is quite sensitive to the field between the nozzle and the skimmer; it is possible that the field was still large enough to partially heat the ions. The large rotational constants, $3.2 \text{ cm}^{-1}$ for $\text{H}_2^+$ and $1.2 \text{ cm}^{-1}$ for $\text{H}_3^+$, would indicate that the line density should be low; however, there are many low frequency modes which could contribute to the congestion, particularly if the molecules are internally hot. The larger clusters will also have overlapping bands at $\approx 4000 \text{ cm}^{-1}$, since more than one $\text{H}_2$ will absorb. If the $\text{H}_2$ stretches are coupled, they will give rise to splittings which may congest the spectra. Precedence for such congestion at or near dissociation is seen in the highly congested spectrum of $\text{H}_3^+$ observed by Kennedy and Carrington.69

The peaks could also be at least partially homogeneously broadened. This would require that the linewidth be on the order of the rotational spacing of 2 to 6 cm$^{-1}$. If the mechanism were lifetime broadening, the corresponding lifetimes would be approximately 1 ps. Several authors report observing such linewidths in the vibrational predissociation spectra of van der Waals complexes, e.g. the $\nu_7$ mode of the ethylene dimer.70,71 Attempts in other laboratories to observe $\text{H}_2^+$ spectra by velocity modulation absorption spectroscopy in a hydrogen glow discharge have thus far failed.72 This high resolution technique cannot detect significantly broadened transitions. The inability to detect any transitions can be explained if the transitions have large, homogeneously broadened linewidths. However, the high vibrational temperatures and low pressures may limit the concentration of $\text{H}_3^+$ in the discharge, and the negative result is therefore not conclusive.
The clusters $H^+_2$ and larger, as well as their products after loss of one $H_2$, possess several low frequency vibrations and internal rotations. Therefore, these clusters will have very high densities of states at 4000 cm$^{-1}$. Furthermore, there will be many rovibrational dissociation channels available. The interaction between an $H_2$ at the corner of the $H_3^+$ and the $H_3^+$ is very anisotropic, so dissociation leading to loss of an $H_2$ occupying a corner site can proceed with transfer of excess energy into rotation.$^{70,73}$ The small moments of inertia of $H_2$ and $H_3^+$ allow large energy transfer to rotation with very small changes in rotational quantum numbers. For these reasons, one might expect these clusters to undergo efficient vibrational predissociation.

C. The $H_5^+$ Ion

The recent calculations of Yamaguchi et al.$^{47}$ have begun to give us a clearer picture of the $H_5^+$ ion. Their high level \textit{ab initio} calculations have found the $H_5^+$ potential to be very flat. The resulting difficulty in pinpointing the exact location of the equilibrium geometry has prompted theorists$^{37,39,42,45,47}$ to conclude that among the hydrogen cluster ions, the $H_5^+$ ion deviates the most from the simple model of an $H_2$ molecule weakly bound to an $H_i$ ion. In this section, we examine what is known of the $H_5^+$ potential energy surface, and discuss implications for the vibrational frequencies and dynamics.

Considered as $H_2 \cdots H^+ \cdots H_2$, it is the simplest of the proton bound complexes $A \cdots H^+ \cdots B$ such as $H_3O^+ \cdot H_2O$, $NH_3^+ \cdot NH_3$, and $H_3O^+ \cdot NH_3$. Theorists$^{42,74}$ have investigated these complexes extensively. Experimental studies in the gas phase are far more limited. The location of the proton depends to a first approximation on the relative proton affinities of the two bases. At small separations, the potential well for the proton tends to be very flat; as the bases are pulled apart, the potential
bifurcates and becomes a double minima well. At the equilibrium separation, the nature of the well, single or double, depends on the pair of bases A and B. In neutral hydrogen-bonded dimers such as (HF)$_2$ and (NH$_3$)$_2$, there is no question of proton transfer. The vibrational problem of intra-molecular proton transfer is well known, but has not been solved quantitatively for an isolated complex.

In their extensive study of H$_5^+$, Yamaguchi, Gaw, Remington, and Schaefer have computed the properties of ten stationary points at very high levels of theory, and found only one minimum. Their calculations show that there are three saddle points lying less than 0.6 kcal/mol above the energy minimum. These differences are in fact at the limit of the accuracy of these calculations. The minimum energy geometry is the $C_{2v}$ H$_3^+$·H$_2$, but the $D_{2d}$ transition state for intramolecular proton transfer to H$_2$·H$_3^+$ is calculated to be only 0.08 kcal/mol or 30 cm$^{-1}$ higher at the full CI level using an extended (larger than DZ+P) basis set. The calculated harmonic frequency is 478 cm$^{-1}$ at the (DZ+P) full CI level. Thus, the $D_{2d}$ barrier lies below the zero point energy level, and the zero point motion therefore involves the isomerization H$_3^+$·H$_2$ ⇌ H$_2$·H$_3^+$. The height of the barrier depends upon the separation between the two H$_2$. As the intermolecular distance between the two H$_2$ is stretched, the barrier height will increase, and the proton, finding itself in a double well, must follow one of the H$_2$. The proton transfer well thus adiabatically changes as the complex undergoes low frequency stretching.

Another low frequency motion is the torsional mode. This is the propeller-like rotation of the H$_2$ molecule about the $C_2$ axis. The $C_{2v}$ barrier for this internal rotation at the extended basis set full CI level is only 128 cm$^{-1}$. At most, only two rotational levels could lie below this barrier. Thus, the internal rotation is only slightly hindered.

The third low lying stationary point, with $D_{2h}$ symmetry, is the planar barrier
for H\textsubscript{2} rotation from the symmetric \textit{D\textsubscript{2d}} configuration. The energy of this point is 178 cm\textsuperscript{-1}, very nearly the sum of the two previous barrier heights. Thus, the barrier for internal rotation is very low, regardless of the location of the central proton.

The in-plane rotation of the H\textsubscript{3} about its own \textit{C\textsubscript{3}} top axis has a much larger barrier, calculated by Yamaguchi \textit{et al.} to be 4.8 kcal/mol (DZ+P full CI). It is readily seen that combinations of the above isomerizations can lead to exchange of any pair of hydrogen atoms in H\textsubscript{5}\textsuperscript{+}. Thus, compared to a rigid structure, all five H atoms can be permuted, and the floppy H\textsubscript{5}\textsuperscript{+} can access 5! = 120 \textit{C\textsubscript{2v}} potential minima. The large amplitude motions greatly increase the number of states, relative to a naive, rigid molecule assumption. This may result in a more congested spectrum than expected, as well as a significantly larger density of states at the dissociation energy. However, nuclear spin symmetry considerations for such high permutational symmetry greatly reduce the expected degeneracy and splittings.

What are the vibrational modes of such a nonrigid molecule? Can normal mode analysis properly predict the vibrational frequencies? As seen in Table II, both the \nu\textsubscript{1} and \nu\textsubscript{2} vibrational frequencies change by over 200 cm\textsuperscript{-1} from the \textit{C\textsubscript{2v}} geometry to the \textit{D\textsubscript{2d}} geometry, and they become nearly degenerate. The \nu\textsubscript{3} through \nu\textsubscript{5} modes, which involve stretching of the bonds being formed/broken, change by 200 to 400 cm\textsuperscript{-1}, while the other three modes are relatively unchanged. The observed frequencies should not be interpreted as a means of choosing between two alternate equilibrium geometries. The large changes in vibrational frequencies with small changes in the stretching of the weak bond imply coupling of these higher vibrations with this low frequency coordinate (labeled \nu\textsubscript{8} in the \textit{C\textsubscript{2v}} geometry). The empirical scaling of the harmonic frequencies should only account for the anharmonicity inherent in the isolated molecule. The anharmonic mixing of modes may be so strong that the harmonic frequencies predicted from the equilibrium geometry
would be of limited use.

Examination of the *ab initio* calculations suggest that the coordinate associated with the 478 cm\(^{-1}\) mode changes in character from an intermolecular stretch at large separations, to purely motion of the central proton at the saddlepoint. In other words, the intermolecular stretch, i.e. the dissociation coordinate, is strongly coupled to the proton motion, and in turn to the higher frequency modes in H\(_5^+\). This picture is consistent with the large change in vibrational frequencies for those normal modes such as the H\(_3^+\) antisymmetric stretches which include motion of the central H.

It is not clear that a Taylor expansion of the potential at the equilibrium geometry alone will adequately represent the full potential surface. The anharmonic interactions may be too large. At the least, a numerical solution of the dynamics of the two large amplitude degrees, the stretching of the H\(_4^+\)···H\(_2\) bond and the central proton transfer motion, seems necessary to accurately predict the vibrational frequencies and splittings in H\(_5^+\). The \(\nu_3\) and \(\nu_4\) should be particularly sensitive to the accuracy of the dynamical calculation. The \(\nu_4\) mode is predicted to have a large intensity, and a better estimate of its frequency would greatly aid the search for this band in direct absorption experiments.

The large couplings in H\(_5^+\) may also explain the observed linewidths. In general, vibrational predissociation of complex clusters is not yet fully understood.\(^{52}\) As mentioned in the previous section, the large rotational constants of the products, and the relatively high density of states should facilitate predissociation of H\(_5^+\) excited 1500 to 2000 cm\(^{-1}\) above the dissociation limit. The discussion here suggests that rapid dissociation may also be a consequence of the strong coupling between the H\(_2\) stretches, the proton motion, and the dissociation coordinate. With four electrons, calculation of at least part of the H\(_5^+\) potential energy surface should be practical.
Studies of the dynamics on this surface should yield insights into the problems of intra-molecular proton transfer, cluster vibrations, and cluster predissociation.

V. SUMMARY

Using vibrational predissociation spectroscopy, we have observed the H$_2$ stretching vibration in the infra-red spectra of the ionic clusters H$_n^+$, with $n = 5, 7, 9, 11, 13,$ and $15$. We have also observed the H$_3^+$ symmetric stretch mode in H$_5^+$. These spectra are an important first step in our investigation of the infrared spectroscopy of cluster ions. The H$_2$ stretch band positions we have observed for these clusters are consistent with the prediction that H$_5^+$ is a stable species, with a completed coordination shell of three H$_2$ at each corner of the H$_3^+$ ion. Spectra of all ions were scanned at 0.5 cm$^{-1}$ resolution, but in no case were rovibrational lines observed. The spectrum of H$_5^+$ was searched at Doppler limited resolution (<0.08 cm$^{-1}$), but again no resolvable lines were seen, although the expected line spacing was 6 cm$^{-1}$. To eliminate hot bands and congestion, the ions were created in a high pressure corona discharge source to create thermalized ions. Only a change in the band contour was observed, including the emergence of a weak combination or overtone band. These results indicate the possibility of homogeneous broadening. Calculations by ab initio theory suggest that H$_5^+$ has a very shallow potential surface. We have discussed possible implications, based on the theoretical information available. Calculations of the H$_5^+$ potential energy surface and dynamics are eagerly awaited. Most of the effort reported in this paper was expended searching the H$_5^+$ spectrum. Selected high resolution scans of the spectra of the larger clusters H$_7^+$ and H$_9^+$ also revealed no structure, but the scans covered only a limited range. No scans using the F-center laser or the difference frequency laser were performed for the larger clusters created in the discharge source. A more detailed examination of the larger
clusters therefore would be in order. It might also be interesting to search for weak absorption by the outer H₂ molecules in the larger clusters.

A clear extension of this work would be to study the deuterated isotopes of H₅⁺. More exotic hydrogen clusters can also be studied. Even mass clusters H₄⁺, H₆⁺, and H₈⁺ have been observed in a mass spectrometer by Kirchner, Jarrold, and Bowers. Theoretical work suggests that the geometry of the H₄⁺ is H₃⁺⋯H, with a dissociation energy comparable to that of H₅⁺. Such an ion should have a symmetric H₃⁺ stretch mode at approximately 3500 cm⁻¹, similar to that of H₅⁺. The negatively charged hydrogen cluster ions would also be worth studying. Recent calculations indicate that they are bound with energies roughly an order of magnitude less than the positive clusters H₄⁺, and their structures are quite different: The H₂ are solvated around a single H⁻, and thus the octahedral H⁻₁₃ is predicted to be the ion with the completed inner shell.

ACKNOWLEDGMENTS

We would like to thank Y. Yamaguchi, J. F. Gaw, and H. F. Schaefer for many stimulating discussions, and for providing us with the results of their calculations prior to publication. This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Chemical Sciences Division of the US Department of Energy under Contract No. DE-AC-0376SF00098.
REFERENCES


TABLE I. Experimental and theoretical dissociation energies and enthalpies for the hydrogen cluster ions $H_n^+$.  

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$^a$Ref. 31.
$^b$Ref. 32.
$^c$Ref. 28.
$^d$Ref. 30.
$^e$Ref. 29.
$^f$Ref. 27.
$^g$Ref. 26.
$^h$Ref. 45 and 47.
$^i$Ref. 42.
$^j$Ref. 40 and 46.
TABLE II. Experimental and theoretical vibrational frequencies in cm\(^{-1}\) for the clusters \(H_n^+, n = 5, 7, \text{ and } 9\). Theoretical values in parentheses are unscaled harmonic frequencies. DZ+P basis set was used for all levels tabulated here. From Ref. 45 and 47.

<table>
<thead>
<tr>
<th>Expt.(^a)</th>
<th>symmetry</th>
<th>SCF</th>
<th>CISD</th>
<th>full CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>(H_2)</td>
<td></td>
<td>(4657)</td>
<td>(4533)(^c)</td>
<td>(4515)</td>
</tr>
<tr>
<td>(H_3^+)</td>
<td>(D_{3h})</td>
<td>(3604)</td>
<td>(3574)</td>
<td>(3566)</td>
</tr>
<tr>
<td>(2521)(^e)</td>
<td>(E)</td>
<td>(2905)</td>
<td>(2826)</td>
<td>(2819)</td>
</tr>
<tr>
<td>(H_5^+)</td>
<td>(C_{2v})</td>
<td>(3677)(4173)</td>
<td>(3711)(4083)</td>
<td>(3713)(4067)</td>
</tr>
<tr>
<td>(3532)</td>
<td>(D_{2d})</td>
<td>(3234)(3663)</td>
<td>(3402)(3801)</td>
<td>(3433)(3824)</td>
</tr>
<tr>
<td>(H_7^+)</td>
<td>(C_{2v})</td>
<td>(3995)(4491)</td>
<td>(4008)(4380)</td>
<td></td>
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<tr>
<td>(3980)</td>
<td>(B_1)</td>
<td>(3992)(4488)</td>
<td>(4004)(4376)</td>
<td></td>
</tr>
<tr>
<td>(H_9^+)</td>
<td>(C_{3v})</td>
<td>(4020)(4516)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(4020)</td>
<td>(E)</td>
<td>4015(4511)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)This work, except as noted.
\(^b\)Ref. 50.
\(^c\)\(H_2\) and \(H_3^+\) held 1000\(\sigma_0\) apart. Ref. 66
\(^d\)Ref. 67.
\(^e\)Ref. 15.
FIGURE CAPTIONS

FIG. 1 Sketch of $H_n^+$ clusters, $n = 5$, $7$, and $9$, based on ab initio predicted geometries. See, for example Ref. 42.

FIG. 2 Corona discharge source used to create internally cold ions. Typical source conditions were 200 Torr of $H_2$ at 260 K. The discharge was a positive point corona discharge with a current of 30-50 $\mu$A.

FIG. 3 Fragmentation ion branching ratios for photodissociation of $H_n^+$ created by electron impact ionization of neutral clusters. For each parent cluster, the laser was tuned to the absorption maximum of the $H_2$ stretch band.

FIG. 4 Low resolution OPO spectra of $H_5^+$, $H_7^+$, and $H_9^+$ (upper, middle, and lower panels respectively). For each cluster, the spectra obtained detecting the product ions from every dissociation channel are shown. The ions were created by electron impact ionization of neutral $(H_2)_m$ clusters. Typical laser resolution ranged from 5 to 20 cm$^{-1}$.

FIG. 5 Low resolution spectra taken with F-center laser of (from top to bottom) $H_5^+$, $H_{11}^+$, $H_{13}^+$, and $H_{15}^+$ created by electron impact ionization.

FIG. 6 Shoulder in the spectra of $H_5^+$, $H_{11}^+$, $H_{13}^+$, and $H_{15}^+$ created by electron impact ionization. All spectra were taken with the OPO at a resolution of 10 to 20 cm$^{-1}$, and normalized to the same peak height (full scale).

FIG. 7 Spectrum of the $\nu_2$ mode of $H_5^+$, created by electron impact, taken at 0.5 cm$^{-1}$ resolution with an F-center laser.

FIG. 8 Comparison of OPO spectra of $H_5^+$ a) created by electron impact, and b) created in the corona discharge source.
FIG. 9 a) Spectrum of $\text{H}_3^+$ created in the corona discharge source, taken with difference frequency laser and a resolution of 1.3 cm$^{-1}$. Lower plot shows detail of upper spectrum taken at 0.75 cm$^{-1}$, with higher signal-to-noise and smaller laser wavelength step size.

FIG. 10 Observed peak positions of the $\text{H}_2$ stretch as a function of cluster size.

FIG. 11 Artist's conception of larger ($n > 9$) hydrogen cluster ions, with the three $\text{H}_2$ at the corners of the $\text{H}_3^+$ in $\text{H}_9^+$ forming a complete inner solvation shell.
Fig. 2

- 60 μ NOZZLE
- ELECTRODE SUPPORT
- SKIMMER
- CORONA DISCHARGE TIP

XBL 8612-5035
Fig. 4

\[ H_5^+ \rightarrow H_3^+ + H_2 \]

\[ H_7^+ \rightarrow H_5^+ + 2 H_2 \]

\[ H_9^+ \rightarrow H_7^+ + H_2 \]

\[ H_9^+ \rightarrow H_7^+ + 3 H_2 \]

\[ H_9^+ \rightarrow H_7^+ + 2 H_2 \]

\[ H_9^+ \rightarrow H_5^+ + H_2 \]
Fig. 5
Fig. 7
Fig. 8
Fig. 9

(a) \(\text{H}_3^+\) counts vs. frequency (cm\(^{-1}\))

(b) \(\text{H}_3^+\) counts vs. frequency (cm\(^{-1}\))
Fig. 10