FINAL TECHNICAL REPORT FOR CONTRACT

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"PENNING TRAP AND RESISTIVE COOLING OF PROTONS"

[TEXAS A&M RESEARCH FOUNDATION: RF-8461]

For the Period May 1993 to March 1995

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Abstract: Trapped H^- has been produced from trapped H^+ , H_2^+ , and H_3^+ in an ICR trap. The initial positive ions collide with a cesiated trap surface and are recaptured as H^- by fast reversal of the trapping potential.

All work in this period has been towards study of the conversion of trapped H^+ , H_2^+ , H_3^+ into trapped H^- ions. The first two-third of the time period was devoted to improvement of the yield of H^- .

The key feature in production has been the state of the surface to be cesiated. This was dealt with by constructing one electrode of the ICR trap from a HAVAR^{TM} (alloy) foil so that it could be cleaned by resistive heating to 800 C. The features of the relative contributions of H^+ , H_2^+ , H_3^+ are described in appendix A and B.

The latter one-third of the period was directed to vacuum considerations.

Our production and decay curves for H^+ , H_2^+ , and H_3^+ have been interpreted assuming that the only contribution to the total pressure is H_2 . Although this is very plausible in view of the history and construction materials of the vacuum system, it would be prudent to verify this in some way. A residual gas analyzer is not available and in any case would necessitate breaking vacuum, thus changing the system conditions. Therefore we use the ICR trap itself in its classic mode as a mass analyzer. This was not anticipated when the system was first chosen. In particular, the marginal oscillator detection of hydrogen ions was chosen for sensitivity, not mass range, and the combination of magnetic field and operational frequency was optimized for hydrogen ions.

New coils were wound with larger inductance, the feedback level was modified, and the feedback step-up ratio was changed. After these changes the new operation frequency of the oscillator is 243 kHz at a trap voltage $V_0=2.5$ V. Now

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the mass range from 20 to 38 was accessible for singly charged ions, which spans the important species N_2^+ , O_2^+ , NO^+ , CO^+ , HCO^+ , N_2H^+ . Masses below 20 are not trapped stably and the upper mass limit is determined by the magnet power supply. A standard magnetic field scan is drawn in figure 1. The new circuit is shown in figure 2. First scans showed nothing in this mass range. To get a better look we turned on the heater tape around the vacuum shell between the trap chamber and the ion pump and gradually increased the temperature of the system. Two masses which differ by one atomic unit appeared ($M_Y=M_X+1$), and a typical scan for each is shown in Figure 3a and 3b. The dependence of these peak areas on temperature is shown in figure 4. Actually these are not shown directly as functions of temperature but only versus total pressure, which itself depends on temperature. However their area (ion numbers) vary in a different way from the total pressure reading. This must mean that the total pressure has a very small contribution from these species at normal conditions. The total pressure was previously shown to be mostly hydrogen since it tracks very reliably with the H_2^+ ion production. The production and decay of these species is shown in Figures 5a and 5b. One of the peaks shows only decay, interpreted as $M^+ + H_2 \rightarrow$ many whereas the other has a growth and decay. However the production time constant and the total signal do not match well with the decay of the other species, and we conclude that it does not grow in from the other observed mass. This signals a secondary production mechanism from light masses beyond our range.

The fraction of partial pressure for these heavy species can be extrapolated back to the conditions of the primary data (i.e. no heaters on) and is negligible. Then we see that we have strong evidence that our interpretation of the decays of the hydrogen ions as just due to hydrogen ions reacting with neutral hydrogen in the trap is correct.

Technical details of the process are in appendix B which is a summary of this work which was compressed to 2 1/2 pages of the text and 1 1/2 pages of figures for submission to *The Journal of Applied Physics* as a "Communication". However, the manuscript was criticized by the referee as unclear and unsuitable

for the JAP. We tend to agree that the extreme brevity required for a "Communication" might have eroded the presentation and we are preparing a much more lengthy and detailed publication based on the forthcoming Ph.D. dissertation of Kiki Hosea (August 1995). The abstract for a poster presentation of this work is included as appendix C.

FIGURE CAPTIONS

Figure 1. : The temporal response of the B sweep field from wobble coils. Total span was 0.006 T. An unsymmetric output profile is due to hysteresis and circuit impedance.

Figure 2. : A Marginal Oscillator in which the feedback circuit has been modified from step-up capacitors to step-up inductors (L_1 and L_2). A typical operation of the oscillator are: frequency = 243 kHz, output level = 20 mV(peak to peak) and $Q=7000$ to 9000.

Figure 3a: Trapping conditions are: $B_0=0.473$ T, $P=8.0 \cdot 10^{-8}$ Torr, $f_0=243$ kHz, $V_0=20$ mV, $Q_{\text{circuit}} = 7500$, $V_t=2.5$ V and $I_e = 0.28 \mu\text{A}$ (3 sec. duration). $B \uparrow$ means field sweep up.

Figure 3b : Trapping conditions are: $B_0 = 0.425$ T, $P = 2.4 \cdot 10^{-8}$ Torr, $f_0=209$ kHz, $V_0=18\text{mV}$, $Q_{\text{circuit}} = 8700$, $V_t=2.5$ V and $I_e = 0.2 \mu\text{A}$ (10 sec. duration). $B \downarrow$ and $B \uparrow$ means field sweep down and up respectively. The up-slope is approximately twice the down-slope, which causes the difference in width.

Figure 4 : The dependence of RF peak areas (ion numbers) on pressure which is related to the temperature. The normal pressure condition (room temperature) is $4.0 \cdot 10^{-9}$ Torr. The extrapolation of the heavy species to the lower pressure, indicates that their partial pressure are negligible at room temperature. The trapping conditions are: $f_0=243$ kHz, $V_0=20$ mV, $Q_{\text{circuit}} = 7500$, $V_t=2.5$ V and $I_e = 0.28 \mu\text{A}$ (3 sec. duration). $B_0(\text{mass X})=0.473$ T and $B_0(\text{mass Y})=0.487$ T.

Figure 5a: The production and decay of the mass X and Y ($X+1$). It seem that the mass X and mass Y has no relation since the production raise time of mass Y differ than the decay time of mass X. The time on the horizontal axis was started at the end of ion production (electron beam off). The trapping conditions are: $f_0=243$ kHz, $V_0=20$ mV, $Q_{\text{circuit}} = 7000$, $V_t=2.5$ V and $I_e = 0.20 \mu\text{A}$ (3 sec. duration). $B_0(\text{mass X})=0.473$ T and $B_0(\text{mass Y})=0.487$ T.

Figure 5b: The production and decay of the mass Y. The time on the horizontal axis was started at the end of ion production (electron beam off). The trapping conditions are: $f_0=209$ kHz, $V_0=18$ mV, $Q_{\text{circuit}} = 6300$, $V_t=2.5$ V, $I_e = 0.20 \mu\text{A}$ (3 sec. duration) and $B_0(\text{mass Y})=0.425$ T

Figure 1.

Figure 2.

Figure 3a.

Figure 3b.

Figure 4.

Figure 5a.

Figure 5b.

APPENDIX A

Observation Of Trapped H^- From Trapped Positive Hydrogen Ions

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ABSTRACT

Relatively efficient *in situ* production of H^- in an ion trap has been demonstrated. Electron impact ionization of H_2 produces trapped H^+ and H_2^+ and $\text{H}_2 + \text{H}_2^+$ produces trapped H_3^+ . H^- is produced by surface charge exchange of the trapped positive hydrogen ions at a cesiated Havar^{TM} trap electrode. Proper timing of switched trapping potentials projects the positive ions to the cesiated surface and traps the H^- ions. Hydrogen ions with energies of 0.5 to 6.0 eV are detected with high sensitivity at $\nu_c^+ = 2$ to 4 MHz by a marginal oscillator with a synthetic Q of 6000 - 8000. H^- yields from H^+ , H_2^+ and H_3^+ are under study.

INTRODUCTION

Production of H^- from surface charge exchange of fast positive hydrogen ions at a cesiated surface has been previously observed. Most experiments were performed by using energetic positive hydrogen ions of hundreds to thousands of eV and the energetic H^- ion current was measured. An efficiency conversion of 8 to 40% has been reported [1,2,3]. Several models of the H^- ion generation have been developed. Recently, preliminary results with H^+ beams in the eV range on cesiated electrodes show a yield of 4-10% H^-/H^+ incident [4].

In our experiment, the trapped H^- ion yield also have relatively low energy (0.5 to 6.0 eV) so in principle they can be manipulated for further use such as calibration particles for antiprotons. A rectangular Ion Cyclotron Resonance (ICR) trap has been chosen for this experiment because of its favorable relatively simple wall collision geometry.

In terms of the area of the ion resonance signals for a slow magnetic field scan, the efficiency of conversion and trapping of H^- was $\sim 4\%$ for H^+/H^- and $\sim 0.7\%$ for H_2^+/H^- for unoptimized delay interval of switched trapping potentials. H^- yield also depends on the controllable work function of the cesiated Havar electrode and the amplitude of the switched trapping potentials. Our data are preliminary at the present time.

METHOD

H^+ and H_2^+ ions in the ICR trap are produced by electron impact ionization of H_2 molecules. Sequential ionization of H_2^+ ions also contributes to H^+ production. H_3^+ ions are created through collisions of H_2^+ ions and H_2 molecules.

By fast programming of the trapping potentials, ions are allowed to approach a trap wall (Havar trap electrode) which has been cesiated to approximately a monolayer. A fraction of positive hydrogen ions can surface charge exchange to H^- and be recaptured in the trap by fast programming of the trap voltages. The program consists of:

- a. grounding a cesiated electrode which then draws trapped ions into collision.
- b. electron transfer to produce H^- ions
- c. fast switching of the opposite electrode (reflector plate) to repel H^- ions
- d. lowering after $\sim 1.2 \mu s$ the cesiated electrode to the same potential as the reflector plate.

A schematic of the apparatus is shown in Fig.1 and the switching process is shown in Fig.2.

APPARATUS

Our overall experimental set up is shown in Fig. 3. The ICR is 5.1 cm x 1.4 cm x 1.4 cm and is constructed of OHFC copper plates (except for the cesiated electrode which is a Havar foil) supported by an assembly of Macor plates.

A marginal oscillator with a very weakly coupled rf drive is used for ion detection [4]. Typical rf injection levels are 0.2 to 0.8 mVpp through a 10 Megohm resistor to the tank circuit. In this way, a stable low level rf excitation can be maintained. After reducing mechanical vibrations the trap was found to support a Q of 6,000 to 8,000. At this condition, the marginal oscillator is quite immune to instability from pickup noise.

Total volume of the UHV system is ~ 1 liter and baseline pressure approaches 1×10^{-9} torr with filament off. Background hydrogen serves as the gas supply in this experiment.

Thermionic emission from a 0.04 mm diameter tungsten wire, produces an electron beam accelerated to ~ 85 eV at the trap entrance. At this energy, the maximum yield of H^+ and H_2^+ is obtained [6]. The beam pulse duration is varied to control total number of trapped ions.

Fig. 1. H^+ and H_2^+ are produced by electron impact ionization of H_2 , and H_3^+ is produced by collision of $H_2^+ + H_2$. When V_{Cs} is lowered (time $\equiv t_0$) the positive hydrogen ions can approach the cesiated electrode and surface charge exchange to H^- . They are then repelled toward the reflector plate. Potentials reversed during trapping are indicated by an arrow (near V_{Cs} , V_{ref} and V_{trap}).

Fig. 2a. Produce and trap positive hydrogen ions. ($V_t = 13.5$ Volt)

Fig. 2b. Grounding the cesiated electrode at time $t = t_0$. The positive ions are projected to the cesiated electrode. Positive ions charge exchange to H^+ and leave the cesiated electrode.

Fig. 2c. Fast switching of reflector electrode to repel H^- ions at time $t = t_{ref} - t_0$.
 $t_{ref} - t_0 = 0.8 \mu s$ has been used.

Fig. 2d. Lowering the cesiated electrode to the same potential as the reflector plate at time $t = t_{cs} - t_0$. For $t_{ref} - t_0 = 0.8 \mu s$ we set $t_{cs} - t_0 = 1.2 \mu s$.

Fig. 3. A block diagram of the experiment configuration. The generator voltage of 0.2 to 0.8 mV is injected through 10 M Ω resistor to the tank circuit. The tank capacitance is ~ 8 pF. The main field is 0.168 T and wobble field is typically 0.003 T. The rf is continuous and 13 volt is a typical trap voltage.

A magnetic field is generated by an iron dipole with 18 cm diameter poles and a gap of 7.5 cm. A field of 0.7 T can be achieved at 10 A excitation, limited by the power supply. For $\nu^+(H^+) = 2.6$ MHz, a field of only 0.168 T was employed. The sweep field from wobble coils is $\Delta B = 0.003$ T and the temporal response is shown in Fig. 4. An unsymmetric output profile is due to hysteresis and circuit impedance. In addition, a phase shift is observed in the Hall probe since its finite area senses an induced emf as the field is swept.

The Havar electrode is cleaned at 800 C by Joule heating for 24 hours after system baking and prior to the deposition of Cs atoms. The Cs source is from SAES GETTER. As Cs evaporation occurs the work function of the Havar electrode was monitored over several mm² by a visible diode laser for which $h\nu = 1.83$ eV (Fig.5).

DISCUSSION

Our lifetime for positive hydrogen ions is shown in Fig. 6. Positive hydrogen ions in the trap are initially lost by evaporation and later mostly to ion-neutral collisions [7]. The H_2^+ ions lifetime is shorter than the H^+ and H_3^+ lifetime due to the reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$

Fits to the ion resonance signal areas yield relative ion numbers and lifetimes as in Fig. 6. We solve the rate equations for possible processes using known cross-sections [6,8]. Since the background H_2 pressure parameter is determined by the decay curves, the production rates can be calculated. The ion creation data for H_2^+ and H_3^+ and the fits using known cross-sections are shown in Fig. 7. This determines the absolute number of H_2^+ ions as 2×10^5 for 4 μ Coulomb (1 μ A e^- beam at 4 seconds creation time).

A representative signal sweep for H^+ and H^- is shown in Fig. 8. The different numbers of H^- ions observed in each measurement are due to the changing fraction of H^+ , H_2^+ and H_3^+ as in Fig. 6.

The hydrogen ions are detected by resonating a marginal oscillator through a swept magnetic field.

In the sweeps analyzed in Fig 9 the switching intervals were $t_m - t_0 = 0.8 \mu s$ and $t_{cs} - t_0 = 1.2 \mu s$. From these data, a typical efficiency of H^- ions trapped was $\sim 4\%$ and 0.7% for H^+ and H_2^+ , respectively. Since the efficiency of conversion of H^- is seen in other

SWEPT B FIELD PROFILE

Fig. 4. Swept ΔB field of 27 gauss typically was employed. The unsymmetric profile is due to hysteresis and circuit impedance.

Fig. 5. Geometry for cesiation: Cs source is activated by 5.5 to 6.5 A current heating. The work function change on the cesiated wall is monitored by a diode laser. A typical voltage of -9 V is applied to the cesiated wall. A photocurrent of up to 15 nA was observed from the area illuminated by the laser.

POSITIVE HYDROGEN ION LIFETIME

Fig. 6. The ion signals detected by varying the time of resonance after the electron beam is switched off. The H_2^+ ions lifetime is shorter due to the collision process $H_2^+ + H_2 \rightarrow H_3^+ + H$. The solid lines are fits based on rate equations of possible processes. The dispersion of the data points from the smooth curves is not due to statistics but is due rather to e^- beam intensity fluctuations and to drift of the high Q oscillator system. Statistical uncertainty is smaller than the point size.

Fig. 7. The ion signal during creation for e beam of $1 \times 10^{-6} \text{ A}$. The solid lines are fits by solving production and loss equations. For $t > 5$ seconds space change effects dominate.

H⁺ AND H⁻ ION SIGNALS

Fig. 8. A typical spectrum of H⁺ and H⁻ ion signals. The trapping switched potentials cause a glitch in the rf envelope. However, it does not destabilize the detection system. The H⁺ signal is broadened and the rf level is loaded down by positive ion space charge.

H⁻ ION LIFETIME

Fig. 9. H⁻ signals detected as a function of time delay after creation. The lifetime is due to collision of H⁻ with H₂. The error bar represents the uncertainty of background subtraction, and not the statistics of the peak area.

experiments to be constant per hydrogen atom [1], we believe that the variation in the H^- yield here is just due to trapping efficiency. A dominating factor in the efficiency is the speed of the ions relative to the switching interval. For the switching times used, so far the H^- production from H_3^+ is completely suppressed. In subsequent tests we will optimize the switching times for H_2^+ and H_3^+ .

In order to measure the lifetime of H^- the B sweep timing is varied relative to a fixed t_0 switching start time. The relative areas of the H^- signal versus the resonance-crossing time relative to t_0 is shown in Fig. 9. H^- ion lifetime (~ 6 seconds) is completely determined by the reaction of H^- ions with H_2 and is an independent check of the H_2 pressure.

FUTURE WORK

By lengthening the switching intervals, the H^- production from H_2^+ and H_3^+ will be maximized. These relative yields will also depend on the positive ion energy as determined by trap well depth.

The different production and decay time dependences of the H^+ , H_2^+ , H_3^+ ion numbers will be exploited to clarify their relative contributions to the H^- production.

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APPENDIX B

Production of Trapped H^- Ions From Low Energy Trapped Positive Hydrogen

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Relatively efficient *in situ* production of H^- in an ICR trap has been demonstrated. H^- is produced from trapped H^+ , H_2^+ and H_3^+ by electron transfer near a cesiated Havar trap electrode by sequenced switching of trapping potentials which projects the positive ions to the cesiated surface and then traps the H^- ions. Hydrogen ions with energies of 0.5 to 6.0 eV are detected by a marginal oscillator with synthetic Q of ≈ 7000 .

Production of H^- from surface charge exchange of fast positive hydrogen ions at a cesiated surface has been previously observed. Most experiments were performed for fast positive hydrogen ions of hundreds to thousands of eV and the fast H^- ion current was measured. An efficiency conversion of 8 to 40% has been reported^{1,2,3}. Several models of the H^- ion generation have been developed⁴⁻⁹. More recently, preliminary results have been reported for H^+/H^- conversion for H^+ beams in the eV range on cesiated electrodes¹⁰ which show a yield of 4-10% for H^- .

In our experiment, the trapped H^+ and H^- ions also have relatively low energy (0.5 to 6.0 eV) and can be manipulated for further use as calibration particles for antiprotons. A rectangular Ion Cyclotron Resonance (ICR) trap has been chosen for this experiment because of its favorable relatively simple wall collision geometry. H^+ and H_2^+ ions in the ICR trap are produced by electron impact ionization of H_2 molecules and sequential ionization of H_2^+ ions also contributes to H^+ production. H_3^+ ions build up through collisions of H_2^+ ions and H_2 molecules. Grounding of the cesiated electrode draws to the cesiated electrode trapped ions which pick up two electrons and are repelled. Then fast switching of the opposite electrode repels the H^- ions and is followed in less than a transit time by lowering the cesiated electrode to this same potential.

A schematic of the apparatus is shown in Fig. 1a and our general experimental set up is shown in Fig. 1b. An account of the development of this apparatus has been given previously¹¹. The ICR trap has dimensions of 5.1 cm x 1.4 cm x 1.4 cm and is realized by 1 mm thick OFHC copper plates except for a HAVAR^{TM} foil cesiated electrode. The plates are supported by MACOR^{TM} blocks. The marginal oscillator is lightly coupled through a 10 M Ω resistor to an RF injection level of 0.2 to 0.8 mV(p-p)¹². This maintains a stable low level of

oscillation and with damping control of mechanical vibrations the trap was operable at a Q of 6,000 to 8,000 with good stability. Total volume is ~ 1 liter and baseline pressure approaches 1×10^{-9} torr (filament off). Background hydrogen serves as gas supply in this experiment. Thermionic emission from a 0.04 mm diameter tungsten wire produces electrons which are accelerated to 85 eV at the entrance aperture in a trap wall and the pulse duration determine the total number of trapped ions. The magnetic field is generated by an iron dipole with 18 cm diameter poles, and a gap of 7.5 cm gives a field of 0.5 T for resonant detection of H_3^+ and 0.168 T for H^+ . The Havar electrode is cleaned at 800 C by Joule heating for 24 hours after system baking and again just prior to the deposition of Cs atoms¹³. During evaporation the work function of the Havar electrode is monitored by a diode laser ($h\nu = 1.83$ eV).

Observed ion losses versus time as in Fig. 2a are mostly due to ion-neutral collisions; the H_2^+ ion lifetime is shorter than H^+ and H_3^+ lifetimes due to the reaction $H_2^+ + H_2 \rightarrow H_3^+ + H$. We use known¹⁴ ion-atom cross sections to find the background H_2 pressure from the decay curves; then the production rates are calculated from known¹⁵ electron cross-sections. A consistency check of the calculated pressure was also made from our observed lifetime for H^- ions. The observed creation for H_2^+ and H_3^+ and their fits shown in Fig. 2b. These determine a typical initial number of trapped H_2^+ ions as $\sim 2 \times 10^5$ for 4 μ coulomb ($1 \mu A$ e^- beam on for 4 seconds).

A typical H^+/H^- signal for a slow magnetic scan is shown in Figure 3a. Using absorption area as proportional to ion number and the ratio of H^+/H_2^+ for this individual run's creation time, the limits of efficiency of conversion and trapping of H^- would be $\sim 4\%$ if all H^- were due to H^+/H^- or $\sim 0.7\%$ if all H^- were due to H_2^+/H^- . For this run the trapping depths were ± 9 Volts and the switching intervals were: $T_{r,fl} = 0.8 \mu s$ and $T_{c,0} = 1.2 \mu s$. In Fig. 3b a limited

exploration of switching intervals begins to show how yields may be assigned to individual trapped hydrogen species. This indicates that (1) for the particular switching times of Fig. 3a the H^- production from H_3^+ is highly suppressed (2) a much larger yield of H^- is achievable. Although the total H^- yield depends strongly on the work function of the cesiated Havar electrode and the total trap potential depth, the factor driving these dependences is the ion speed.

Since the efficiency of conversion of H^- is seen in other experiments at higher energy to be constant per hydrogen atom¹, we make a working hypothesis that departures from this rule here are just due to trapping efficiency. We are currently mapping out and optimizing the switching times for H_2^+ and H_3^+ . Other experiments being carried out at the present time exploit the different production and decay dependences of the H^+ , H_2^+ , H_3^+ to more exactly determine their relative contributions to the H^- production.

We wish to thank the machine shop and electronics shop of the Texas A&M physics department for their support of this experiment. Encouragement came from Nelson Jarmie and Michael Holtzscheiter of Los Alamos National Laboratory. This work was supported by the Department of Energy under Contract W7405-Eng 36.

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Figure Captions

FIG. 1 Schematic of the experimental setup

(a) Electrical and physical schematic of the experiment. H^+ and H_2^+ are produced by electron impact ionization of H_2 , and H_3^+ is produced by collision of $H_2^+ + H_2$. When V_c is lowered (at time $\equiv t_0=0$) the positive hydrogen ions will approach closely the cesiated electrode and transfer electrons, forming H^- which is attracted toward the reflector plate. During this flight period the cesiated and reflector electrodes are switched at T_c and T_{refl} respectively to equal negative potentials for completion of the trapping process.

(b) A block diagram of the experiment configuration. The RF drive voltage of 0.2 to 0.8 mV is injected through a 10 M Ω resistor to the tank circuit (~ 8 pF). The main field is 0.168 T and wobble field is typically 0.003 T. RF drive is continuous and 13.5 Volts is a typical trap voltage.

FIG. 2 Positive ion absorption signals

(a) Absorption area versus delay after the electron beam is switched off. The H_2^+ ions lifetime is shortened by the process $H_2^+ + H_2 \rightarrow H_3^+ + H$. The solid lines are based on known reaction rates. Dispersion of the data points from the smooth curves is not statistics but is due to imperfect logging of e^- beam intensity fluctuations and drift of the very high Q oscillator system.

(b) Absorption area during creation by a fast e^- beam. The solid lines are fits by solving production and loss equations. For $t > 4$ seconds space charge effects start to dominate.

FIG. 3 Ion signals for H^- production by potential switching.

(a) A typical spectrum of H^+ and H^- ion signals for trap voltage ± 9 Volts. The trapping switched potentials cause a glitch in the rf envelope. However, this does not destabilize the detection system. The H^+ signal is broadened, and the rf level is loaded down, due to the positive ion space charge before, but not after, the switch from positive to negative trap potentials.

(b) A limited exploration of the variation of negative ion yield as a function of switching times. Trapping voltage was ± 13.5 Volts. The strong dependence is due to fairly narrow trapped energy distributions for the positive ions and their $m^{1/2}$ scaling factors in transit times for equal trapped kinetic energies. Parentheses around H^+/H^- , H_2^+/H^- , H_3^+/H^- means that these are plausible choices which could account for the peak structures.

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