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Charge-changing cross sections for H^- ions incident on a Na vapor target

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Measurements are reported for the total charge-changing cross sections σ_{-0} for 1–25-keV H^- ions incident on a Na vapor target and σ_{-+} for 7.5–25-keV H^- ions incident on a Na vapor target. The cross section σ_{-0} is 4.2×10^{-15} cm^2 at 1 keV and falls monotonically to 1.5×10^{-15} cm^2 at 25 keV. The cross section σ_{-+} is 9×10^{-18} cm^2 at 7.5 keV and rises to 4.0×10^{-17} cm^2 at 25 keV.

I. INTRODUCTION

In recent years there has been a surge of interest in charge-changing collisions involving negative ions. Measurement of negative-ion cross sections is essential for understanding the nature of negative-ion collision processes. In addition to their intrinsic interest, negative-ion charge-changing collisions play prominent roles in production of H^- and D^- ion beams, which is important for nuclear ion source research and controlled thermonuclear research. The production of H^- or D^- ions in Na has been studied previously.[1–7] For H^+ ions or H^0 atoms incident on Na, the total charge changing cross sections σ_{+0}, σ_{+-}, σ_{0+}, and σ_{0-} have been measured by a number of workers.[1,2,3,8,9] For H^- incident on Na, the total cross sections σ_{-0} and σ_{-+} have been measured in the energy range 30–200 keV.[8] In this paper we report the first measurements of the cross section σ_{-0} for H^- ions incident on a Na vapor target with energy in the range 1–25 keV and of the cross section σ_{-+} for H^- ions incident on a Na vapor target with energy in the range 7.5–25 keV. An H^- ion with 1–25 keV energy has the same velocity as an electron in the energy range of 0.5–12.5 eV which is comparable to the energy defects of the $H^-\to H^0$ and $H^-\to H^+$ conversion. Thus there is interest in the dependence of σ_{-0} and σ_{-+} on the energy of H^- in the 1–25-keV range.

II. APPARATUS

The apparatus used in this experiment is almost the same as that used in the experiments reported in Ref. 1 (see Fig. 1 of Ref. 1). An H^- ion beam is extracted directly from a duoplasmatron ion source using an off-axis extraction aperture. The H^- ion beam after focusing by an Einzel lens and a gap lens is momentum analyzed using a 10° bending magnet. The H^- ion beam is collimated using two 1.5-mm holes separated by 90 cm. Following collimation the ion beam passes between two parallel plates. The proper electric field between these plates deflects the H^- ion beam off axis into a suppressed Faraday cup. The incident H^- ion current, I_s, is measured in this cup. When the parallel plates are grounded the ion beam passes undeflected between the plates and enters the Na vapor target. The Na vapor target is very similar to the target described in Ref. 1. The Na target is constructed of stainless steel, is 2.54-cm internal diameter (i.d.), and is 16.5 cm long. The entrance and exit apertures of the target are 5.1 cm long and 0.64-cm i.d. The Na metal reservoir is located directly below the target and is connected to the target by a 1.8-cm-i.d. tube. The target is maintained about 150 °C above the temperature of the Na reservoir so that Na condensation in the target is avoided and hence the Na vapor density in the target is determined by the temperature of the liquid Na in the reservoir. The Na target density is determined using the measured temperature of the liquid Na in the reservoir, the known Na vapor-pressure curves, and the ideal gas law. The Na vapor density outside the target is very small. The Na vapor density inside the target is constant and falls linearly to zero along the entrance and exit tubes. Thus the target thickness π in atoms/cm^2 is given by $\pi = n\,[L + \frac{1}{2}\,(L_{ent} + L_{exit})]$ where n is the Na atom density in the target, L is the target length, L_{ent} is the length of the entrance tube, and L_{exit} is the length of the exit tube. We estimate the uncertainty in π to be about ±20% mostly due to uncertainty in the vapor pressure of Na as a function of the temperature.

After passage through the target the beam is separated into its charge components by a magnet that deflects the H^+ and H^- components of beam emerging from the target into suppressed Faraday cups located at plus and minus 4° to the incident-beam axis. The fast H^0 component passes undeflected through the magnet and is detected by the electrons ejected when the fast H^0 atoms hit a heated polished copper surface. The Faraday cups and the heated polished copper surface all subtend the same solid angle as seen from the center of the target. On axis with the two suppressed Faraday cups are annular detectors. The diameter of the hole in the annulus is slightly larger than the diameter of the Faraday cups. These annular detectors are used to assure that the system is correctly aligned so that the H^+ and the H^- beams are simultaneously centered on their detectors, and the annular detectors are used to estimate the fraction of the H^- and H^+ beams that are scattered through a large enough angle to miss the primary detectors. The Faraday cups and the neutral detector all intercept an angle of 0.7° as seen from the center of the target. The annular detectors each intersect particles scattered between the angles of 0.7° and 1.4°. The exit aperture of the target prevents particles from leaving the target if they have been scattered through an angle of more than 1.4°.

III. CROSS-SECTION MEASUREMENTS

In order to determine σ_{-0} and σ_{-+} we measure I_s, the H^- ion current incident on the Na target; I_-, the H^- ion current emerging from the Na target and reaching the H^- ion Faraday cup; I_+, the H^+ ion current emerging from the Na target and reaching the H^+ ion Faraday cup; and I_0, the neutral detector current. The currents I_-, I_+, and I_0 are measured as a function of π. The currents are given by $I_s=qN_s$, $I_-=qN_-$, $I_+=qN_+$, and $I_0=qN_0R$ where q is the electronic charge, N_s is the number of H^- ions incident on the Na target per second, N_-, N_+, and N_0 are, respectively, the number of H^- ions, H^+ ions, and fast-H^0 atoms emerging from the target and reaching their detectors per second, and R is the average number of electrons ejected from the heated polished Cu surface per incident H^0 atom. R depends on the energy of the incident H^0 atoms and on the condition of the Cu surface. The number of particles incident per second on the target must be equal to the number of particles per second emerging from the target plus the number of particles per second lost from the beam. Thus $N_s=(N_+/T_+)+(N_0/T_0)+(N_-/T_-)$ or $I_s=(I_+/T_+)+(I_0/T_0R)+(I_-/T_-)$ where T_+, T_-, and T_0 are factors that take into account losses from misalignment, stray fields, or due to the scattering of the particle through a sufficiently large angle that the particle misses its detector. The fractional yields of H^- ions, H^+ ions, and fast H^0 atoms are given by $F_-=I_-/T_-I_s$, $F_+=I_+/T_+I_s$, and $F_0=I_0/T_0RI_s$. It follows that $F_-+F_++F_0=1$. At small values of π the fractional yields are given by $F_-=1-(\sigma_{-0}+\sigma_{-+})\pi$, $F_+=\sigma_{-+}\pi$, and $F_0=\sigma_{-0}\pi$. From our measurements we obtain I_-/I_s, I_+/I_s, and I_0/I_s. It follows that for very small values of π:

$$I_-/I_s=T_-[1-(\sigma_{-0}+\sigma_{-+})\pi], \tag{1}$$

$$I_+/I_s=T_+\sigma_{-+}\pi, \tag{2}$$

and

$$I_0/I_s=T_0R\sigma_{-0}\pi. \tag{3}$$

For very low values of π ($\pi<5\times10^{13}$ atoms/cm^2) we find experimentally that I_-/I_s is a linear function of π. The linear function has an intercept T_- and a slope $T_-(\sigma_{-0}+\sigma_{-+})$. The intercept T_- is nearly 1. This is consistent with our measurement of very little current to the annular detector outside the negative-ion Faraday cup. We thus determine $\sigma_{-0}+\sigma_{-+}$. At low values of π we also find experimentally that I_+/I_s is a linear function of π. The slope of I_+/I_- is $T_+\sigma_{-+}$. We estimate T_+ from the ratio of the number of H^+ ions hitting the Faraday cup to the number of H^+ ions hitting the annular detector. T_+ is 0.85 at 7.5 keV and increases to 0.95 at 25 keV. Using these values of T_+ we obtain σ_{-+}. We obtain σ_{-0} as the difference between $\sigma_{-0}+\sigma_{-+}$ and σ_{-+}. Since σ_{-+} is much smaller than σ_{-0} the uncertainty in σ_{-+} (that arises from both statistical error in the small current I_+, and from systematic errors in obtaining T_+ and other systematic errors) does not introduce a large uncertainty in σ_{-0}. We estimate that the uncertainty in σ_{-0} is about ± 10% in the relative measurements and ± 22% in the absolute values of σ_{-0}. The primary uncertainty in the absolute value of σ_{-0} is due to uncertainty in π arising from the very rapid variation of the Na vapor pressure with temperature. The uncertainty in σ_{-+} is about ± 20% in the relative values and about ± 30% in the absolute values. The large uncertainty in σ_{-+} arises due to the uncertainty in obtaining T_+, the statistical uncertainty in the measurement of the small current I_+, and uncertainty in π due to

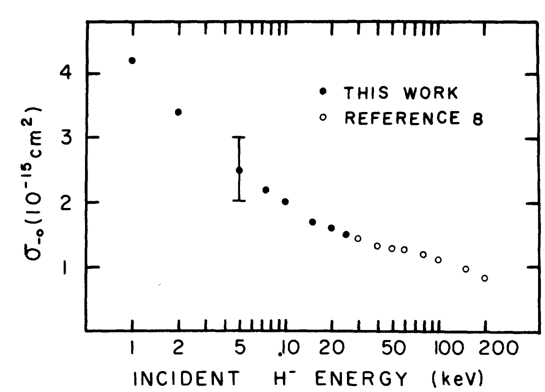

FIG. 1. The cross section σ_{-0} as a function of the energy. The cross sections from 1–25 keV are from our data. The cross sections from 30–200 keV are from Ref. 8. The error bar indicates the absolute error in σ_{-0}.

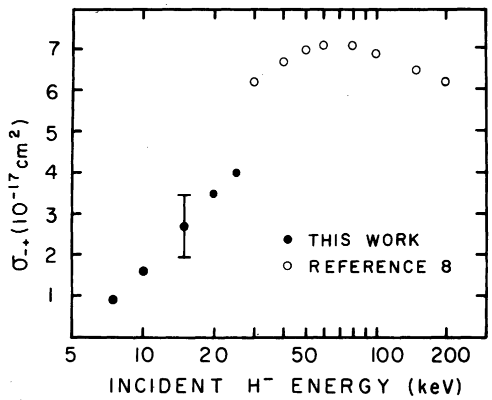

FIG. 2. The cross section σ_{-+} as a function of the energy. The cross sections from 7.5–25 keV are from our data. The cross sections from 30–200 keV are from Ref. 8. The error bar indicates the absolute error in σ_{-+}.

the rapid variation of the Na vapor pressure with temperature. At low values of π we observe that I_0/I_s is a linear function of π. The slope of I_0/I_s is $T_0R\sigma_{-0}$. Since we know σ_{-0} we obtain T_0R. We use the value of T_0R to check that $(I_-/I_sT_-)+(I_+/I_sT_+)+(I_0/I_sT_0R)=1$ is satisfied over the range of π used in our experiment. Although we obtain only the product T_0R from our experiment and not T_0 and R separately, we expect T_0 to be near 1 since the outgoing fast H^0 atom is not charged. The product T_0R ranges from 0.85 at 2 keV to 2.2 at 25 keV, and at a fixed energy varies in time by at most 15%.

Figures 1 and 2 show our results for σ_{-0} and σ_{-+} as a function of the energy. Also shown are the values of σ_{-0} and σ_{-+} at energies in the range 30–200 keV from Ref. 8. The values of σ_{-0} and σ_{-+} as a function of the energy are also tabulated in Table I. The data for σ_{-0} at 1 keV actually used D^- ions incident at the same velocity as 1-keV H^- ions (i.e., D^- at 2-keV energy). It is expected that the H^- and D^- charge-changing collisions have the same cross sections at the same incident-ion velocity.

The cross section σ_{-0} has the value 4.2×10^{-15} cm^2 at 1 keV and falls monotonically to 1.5×10^{-15} cm^2 at 25 keV. The values of σ_{-0} at higher energy from Ref. 8 are very consistent with values extrapolated from our low energy data.

TABLE I. The cross sections σ_{-0} and σ_{-+} as a function of the energy.

Energy (keV)	10^{-15} σ_{-0}(cm^2)	10^{-17} σ_{-+}(cm^2)
1	4.2	
2	3.4	
5	2.5	
7.5	2.2	0.9
10	2.0	1.6
15	1.7	2.7
20	1.6	3.5
25	1.5	4.0

The cross section σ_{-+} has the value 9×10^{18} cm^2 at 7.5 keV and rises to 4.0×10^{-17} cm^2 at 25 keV. At energies less than 7.5 keV, this cross section is too small to be measured meaningfully by this technique. Reference 8 reports values for σ_{-+} for H^- energy above 30 keV. The 30-keV data of Ref. 8 is about 30% higher than the value obtained by extrapolating our low-energy cross sections to 30 keV. We are not certain why our cross sections σ_{-+} do not agree better with those of Ref. 8. The cross section σ_{-+} is, however, small and hence difficult to measure. The two-step process $H^-+Na\rightarrow H^0$ followed by $H^0+Na\rightarrow H^+$ is not negligible as π increases. We separate the one-step cross section σ_{-+} from the two-step process using the dependence of F^+ on π. The single-step process is linear in π whereas the two-step process is quadratic in π. However, with significant errors in the data the separation of the linear and quadratic variation of F_+ with π at low values of π is subject to uncertainty. Another difficulty in measuring σ_{-+}, especially at low energies, results from the fact that the angular distribution of H^+ ions is large out to large angles. We correct for the H^+ ions that miss the Faraday cup and hit the annular detector, but there may be H^+ ions that are scattered into large enough angles that they strike the walls of the target and do not reach any detector. Considering these difficulties we believe that the agreement of our cross sections with those at higher energy is satisfactory.

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