PHYSICAL REVIEW VOLUME 177, NUMBER 1 5 JANUARY 1969

Charge-Exchange Collisions Between Hydrogen Ions and Cesium Vapor in the Energy Range 0.5-20 keV*

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(Received 1 July 1968)

Charge-exchange collisions have been studied when H^+ ions and ground state H^0 atoms are incident on Cs vapor. Measurements of the positive, neutral, and negative beam components after passage through the target were made as a function of the Cs target thickness at several energies between 0.5 and 20 keV. All three beam components were found to approach charge equilibrium monotonically. The maximum H^- equilibrium yield is $(21 \pm 4)\%$, which occurs at an H^+ energy of 0.75 keV. The H^- yield decreases with increasing energy, and is 0.4% at 20 keV. At energies below 4 keV the H^+ equilibrium yield is very small compared with the yield of H^0 and H^-. For energies greater than 10 keV the H^- equilibrium yield is very small compared with the yield of H^0 and H^+. The cross sections σ_{+0}, σ_{+-}, σ_{0+}, and σ_{0-} were measured. The subscripts + and − refer to the H^+ and H^- ions, 0 as an initial subscript refers to a ground-state H^0 atom, and 0 as a final subscript refers to an H^0 atom in the particular states produced. The cross section σ_{+0} decreases with increasing energy, and ranges from $(9.4 \pm 2.0) \times 10^{-15}\,\text{cm}^2$ at 1 keV to $(7.5 \pm 1.1) \times 10^{-16}\,\text{cm}^2$ at 15 keV. The cross section σ_{+-} decreases with increasing energy in the range 2–15 keV, and has the value $(2.1 \pm 0.6) \times 10^{-17}\,\text{cm}^2$ at 5 keV. The cross section σ_{0+} increases with increasing energy, having the value $(1.2 \pm 0.2) \times 10^{-17}\,\text{cm}^2$ at 2 keV, and $(1.74 \pm 0.26) \times 10^{-16}\,\text{cm}^2$ at 15 keV. The cross section σ_{0-} decreases with increasing energy, having the value $(1.5 \pm 0.3) \times 10^{-16}\,\text{cm}^2$ at 2 keV and $(1.4 \pm 0.2) \times 10^{-17}\,\text{cm}^2$ at 15 keV.

I. INTRODUCTION

Charge-exchange collisions of fast H^+ ions and H^0 atoms incident on Cs vapor are of considerable interest because the yield of H^- ions is very large, making Cs a good charge-exchange medium for negative-ion sources, and because the various cross sections yield information about the collision processes. In the present experiment, a momentum-analyzed, collimated beam of H^+ ions or fast ground state H^0 atoms at an energy in the range 0.5–20 keV was passed through a Cs vapor target of variable thickness. The beam emerging from the target was separated into its charge components, H^+, H^0, and H^- by a magnetic field, and all three components were measured simultaneously. Equilibrium yields were measured, as were the cross sections σ_{+0}, σ_{+-}, σ_{0+}, and σ_{0-}. The customary notation for cross sections is used in this paper. The two subscripts refer to the initial and final states, respectively, of the H atom or ion. The subscripts + and − refer, respectively, to H^+ and H^- ions. The subscript 0 refers to ground state H^0 atoms when used as an initial subscript. Because an H^0 atom can be created in various electronic states the subscript 0 refers to an H^0 atom in the particular states produced when used as a final subscript. The maximum yield of H^- ions was measured to be (21±4)% relative to the total beam after passage through the target, at a proton energy of 0.75 keV. Preliminary results of this experiment were reported earlier.[1]

Charge exchange of H^+ ions in alkali vapors has been studied in a number of experiments. Il'in *et al.*[2–4] have measured the total charge-exchange cross section σ_{+0} and the cross section for the production of highly excited H^0 atoms in collisions with alkali and other vapors, in the energy range 10–180 keV. The cross section σ_{+0} and the neutral equilibrium yield for H^+ ions incident on K and Na have been measured by Niemann and Donahue[5,6] in the energy range 4–30 keV. Schmelzbach *et al.*[7] have measured equilibrium fractions and the cross sections σ_{+0} and σ_{+-} for H^+ on K in the energy range 2.5–22 keV. Bohlen *et al.*[8] have measured the maximum yield of H^- for H^+ incident on Cs and K in the energy range 0.5–2 keV, and report an H^- yield of 15% at 0.5 keV in Cs and an H^- yield of 10% between 0.5 and 2 keV in K. Donnally and Becker[9] have reported an H^- yield of 10% in K at 1 keV. Drake and Krotkov[10] have reported an H^- yield of approximately 25% at 1 keV in Cs.

Discussion of a polarized-ion source using Cs as a target for $H^+ \to H(2s)$ and measurements of the cross section for this reaction have been presented.[11–16]

II. APPARATUS AND MEASUREMENTS

The apparatus, shown in Fig. 1, is essentially the same as was used for our study of collisions of He ions incident on Cs, and has been described in detail elsewhere.[17] In brief, the apparatus consists of an ion source and associated equipment, beam collimator, charge-exchange target, and beam-measuring equipment. There is also a gas neutralizer for converting the incident H^+ ion beam into a fast ground state H^0 atom beam.

H^+ ions from the radio-frequency ion source are accelerated by a voltage between 1 and 20 keV, measured to ±3%. Since it was difficult to obtain sufficient beam intensity at lower energies, the experiments were extended to lower velocities by using deuterium ions instead of hydrogen ions. The beam passes through a unipotential lens (einzel lens), two vertical trim magnets, and a

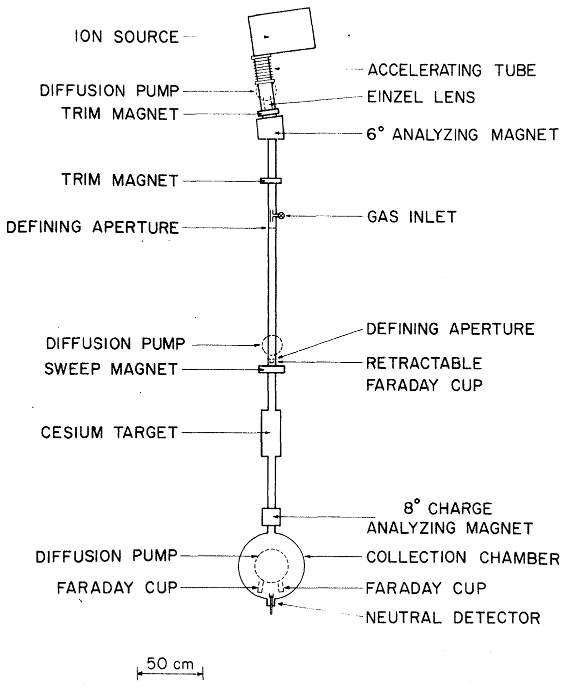

FIG. 1. Schematic diagram of apparatus.

momentum analyzing magnet.

The beam collimation consists of two 0.15-cm-diameter apertures separated by a drift tube one meter long. This collimation assures that the beam will pass through the Cs target and enter the collection chamber without striking the entrance or exit apertures of the Cs target, except when high Cs densities cause multiple scattering. Following the collimation section is a retractable, suppressed Faraday cup (hereafter called the source cup) which is used to measure the positive beam incident on the Cs target.

A horizontal coil which surrounds the entire apparatus is used to compensate for the vertical component of the earth's magnetic field. The horizontal component of the earth's field is nearly along the beam axis and hence does not affect the beam.

In front of the Cs oven is a coil producing a transverse magnetic field of sufficient strength to sweep charged particles out of the beam. This coil is used to determine the contribution to the measured beam currents by unwanted fast neutral atoms formed in the collimation section. This contribution is subtracted as background.

A beam of fast neutral ground-state atoms can be prepared by passing the H^+ beam through an argon gas target. The remaining charged particles are swept away by the field of a permanent magnet which replaces the sweeping coil used to measure background. This magnet produces a transverse magnetic field of sufficient strength to also quench most metastable H^0 atoms,[18] so that the beam of H^0 atoms incident on the Cs target is almost entirely in the ground state. The gas target for neutralization is a tube 0.3 cm inside diameter and 10 cm long located along the beam axis just before the first collimating aperture. Argon gas is admitted at the center of this tube.

The Cs target, which is described in detail in Ref. 17, is a copper lined stainless steel container, maintained at a temperature of approximately 225°C. Cesium vapor is admitted through a bakeable valve. The Cs density in the target can be varied by changing the temperature of the reservoir or by operation of the valve between the reservoir and the target. There is also provision for admitting argon into the oven for calibration measurements.

The gauge used to measure the Cs density in the target is a surface ionization detector (see Ref. 17). This detector is located in an auxiliary heated chamber connected to the Cs target by a 0.1 cm diameter aperture in a thin plate. The Cs is pumped by a liquid nitrogen-cooled trap. The pumping of Cs vapor by the cold surface and the low conductance of the inlet aperture combine to attenuate the Cs density in the auxiliary chamber relative to the Cs density in the target. The Cs gauge was calibrated against the known vapor pressure of Cs by having Cs vapor in equilibrium with liquid Cs in the target.[17]

After leaving the Cs target, the beam passes through a magnetic field and enters the collection chamber where the separated charge-component beams are measured. The positive and negative ion beams are each measured with a suppressed Faraday cup. The neutral atoms are measured with a detector which utilizes secondary electron emission from a copper surface, as described in Ref. 17. The magnetic field of the charge analyzing magnet is sufficient to quench most metastable H^0 atoms emerging from the Cs, so that most H^0 atoms incident on the secondary emitting surface are in the ground state.

In order to calibrate the neutral detector, it is necessary to determine the secondary electron current emitted from the copper surface per incident H^0 atom. Calibration using an H^+ beam of known intensity is not sufficient because the secondary emission ratio may be different for incident H^0 and H^+. Rather, we assumed that at low Cs densities, the increase in the neutral beam which results from an increase in Cs density is equal to the decrease in positive-beam current. The plot of positive-beam current as a function of secondary electron current (both divided by the source cup current) for various Cs target densities is a straight line whose slope is the secondary emission ratio. This statement is correct because the fraction of negative ions is small, and because the angular distribution of H^0 atoms formed by electron attachment in a gas is known to be such that almost all the fast atoms will exit from the target in a solid angle small enough to hit the neutral detector.

A similar procedure is followed when H^0 atoms form the beam incident on the Cs target, except that the secondary emission ratio is measured using an argon target. The secondary emission ratio cannot be measured directly using the incident H^0 beam because there are no source cup readings, which are necessary to account for changes in the beam intensity, and because the number of H^+ ions created in the Cs target for low Cs densities is not sufficient to permit an accurate determination of the secondary emission ratio. The secondary emission ratios determined using H^+ incident on Cs and on argon agree to within 5%.

The fractions of the beam emerging from the charge exchange target in the positive, neutral and negative charge states are hereafter referred to as F_+, F_0, and F_-. By definition, $F_+ + F_0 + F_- = 1$. The total beam measured after passage through the target is generally greater than 90% of the beam measured before the target, except at very low energies or at very high Cs densities, where multiple scattering in the target causes loss of beam. The loss in beam occurs on passage of a beam through the target chamber with no Cs present due to a small misalignment of the apparatus.

III. DATA

Typical data are shown in Fig. 2 for 15-keV H^+ ions incident on a Cs vapor target. Shown are F_+, F_0, and F_-, which are the fractions of the beam in charge states +, 0, and −, after passage through a Cs vapor target of thickness π measured in atoms/cm^2. Also shown is the transmission through the Cs target, which is the ratio of the total beam measured after passage through the target to the beam incident on the target.[19] The transmission is approximately 90% for thin Cs targets, and decreases monotonically with increasing target thickness, due to multiple scattering of atoms and ions from the beam. In this experiment we measure all three beam components after passage through the target, which permits correction to be made for multiple scattering. This correction is believed to be valid because the mean scattering angle of an H^+ or H^0 atom in an electron attachment or stripping collision is small. Consequently an H atom or ion undergoes several changes of charge before being scattered through an angle large enough to collide with the walls of the target chamber and hence be lost from the beam. Therefore all three charge components of the beam are reduced in the same ratio by multiple scattering. Thus the data shown in Fig. 2 are thought to be independent of apparatus geometry. Note that all three beam fractions approach charge equilibrium monotonically, i.e., the fractions are independent of Cs target thickness π for large values of π. This is in clear constrast to our measurements[17] for collisions of He on Cs, where F_- has a maximum before charge equilibrium, because the fraction of metastable He^0 atoms from which the He^- ions are produced is changing with Cs target thickness.

That the beam fractions reach charge equilibrium indicates that metastable H^0 atoms in the beam after passage through a thick Cs target are a constant fraction of the neutral atoms, or that the appropriate cross sections[20] are the same for metastable and ground state H^0 atoms in collisions with Cs.

Fig. 3 shows the beam fractions F_0 and F_- for 15 keV H^+ ions incident on a thin Cs target.[21] Note that F_0 and F_- are linear with π, indicating single and double electron pickup, respectively, in a single collision. The slopes of the linear portion of F_0 and F_- are proportional to the cross sections σ_{+0} and σ_{+-}, respectively. Fig. 4 shows the beam fractions F_+ and F_- for fast ground state 15 keV H^0 atoms incident on a thin Cs target. The linear portion indicates single-electron stripping and pickup, respectively, and the slopes are proportional to σ_{0+} and σ_{0-}.

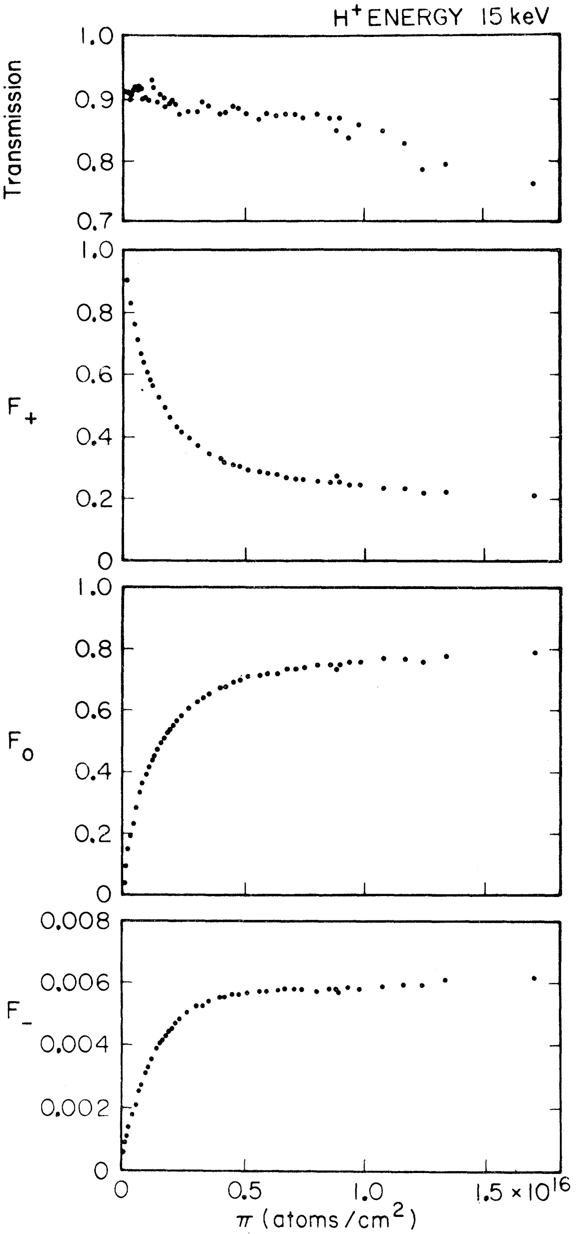

FIG. 2. The fractions F_+, F_0, and F_- of beam in positive, neutral, and negative charge states after passage of a 15 keV H^+ ion beam through a Cs vapor target, as a function of Cs target thickness, π. Also shown is the transmission through the target.

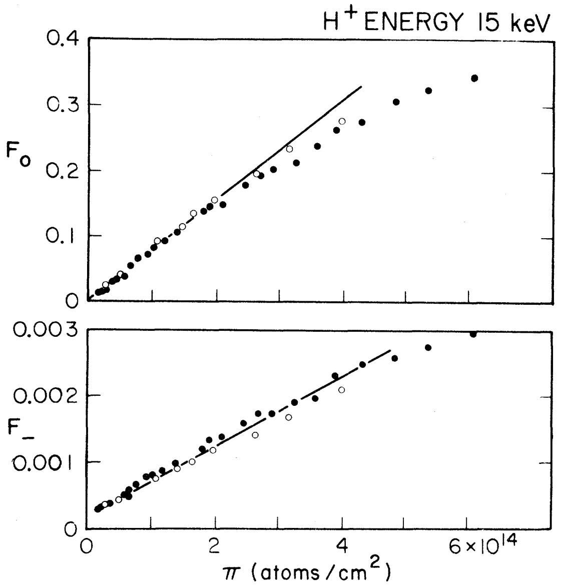

FIG. 3. The fractions F_0 and F_- of beam in neutral and negative charge states as a function of Cs target thickness π for a thin Cs target. The incident beam is 15-keV H$^+$ ions. The closed and open circles show data taken when Cs density is increasing and decreasing. The straight line indicates the linear portion of the data (i.e., one-step process).

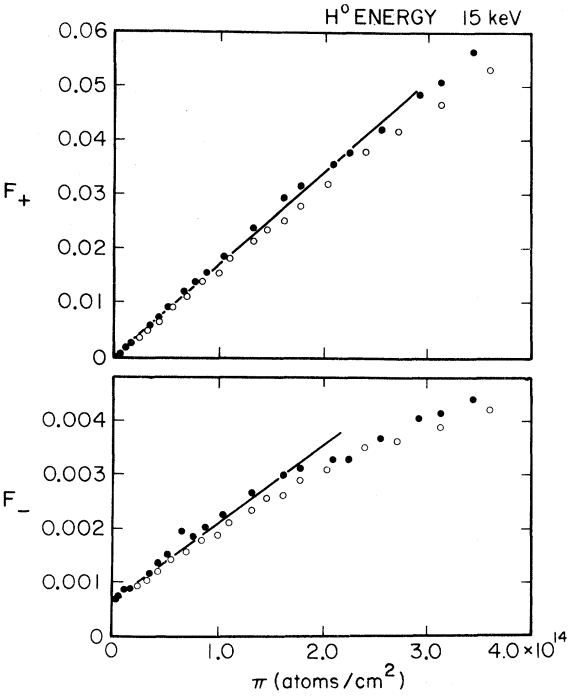

FIG. 4. The fractions F_+ and F_- of beam in positive and negative charge states as a function of Cs target thickness π for a thin Cs target. The incident beam is 15 keV ground-state H^0 atoms. The closed and open circles show data taken when Cs density is increasing and decreasing. The straight line indicates the linear portion of the data.

IV. RESULTS AND DISCUSSION

Equilibrium fractional yields are shown in Fig. 5 and are summarized in Table I for H$^+$ energies in the range 0.5–20 keV. The lines in Fig. 5 are drawn for clarity. Multiple points at some energies indicate the repeatability of the data. The equilibrium values of F_+, F_0, and F_- are labeled F_+^∞, F_0^∞ and F_-^∞. They were determined from data like that shown in Fig. 2. Note that for ion energies greater than 10 keV, the equilibrium H$^-$ component, F_-^∞, is small compared with F_+^∞ and F_0^∞. Note also that for ion energies less than 4 keV, the equilibrium H$^+$ component, F_+^∞, is small compared with F_0^∞ and F_-^∞.

The H$^-$ equilibrium yields are shown on a logarithmic scale in Fig. 6. The maximum value of F_-^∞ is (21±4)%, which occurs at an energy of 0.75 keV.

Bohlen *et al.*[8] have measured the negative-ion current emerging from a Cs target divided by the incident positive-ion current, $I_-/I_{\rm inc}$. Maximum values of $I_-/I_{\rm inc}$ measured by them are also shown on Fig. 6, and are in satisfactory agreement with our measurements. However, a comparison of our data and their data indicates that their data is not corrected for multiple scattering, because their $I_-/I_{\rm inc}$ yield of negative ions as a function of Cs density passes through a maximum and then decreases with increasing density. From such data it is difficult to determine the equilibrium value F_-^∞, since one does not know whether multiple scattering has attenuated the beam at the particular target thickness at which $I_-/I_{\rm inc}$ reaches a maximum. This is the reason why measurement of the neutral-beam component (or detailed knowledge of angular distribution of scattered particles) is vital for a

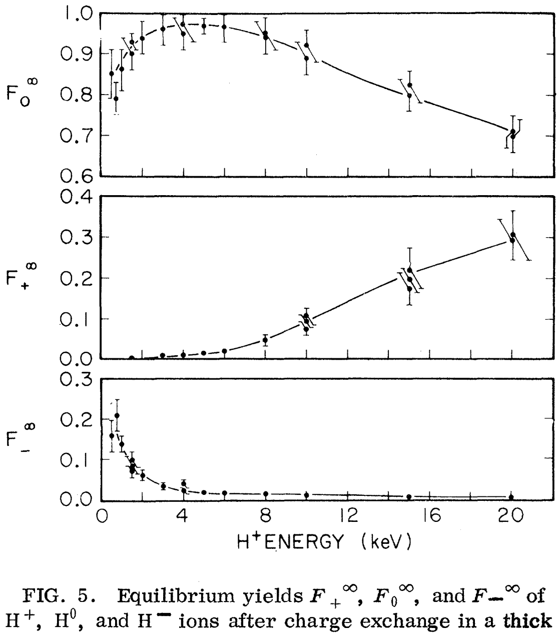

FIG. 5. Equilibrium yields F_+^∞, F_0^∞, and F_-^∞ of H$^+$, H^0, and H$^-$ ions after charge exchange in a thick Cs vapor target, in the energy range 0.5–20 keV.

TABLE I. Equilibrium yield F_+^∞, F_0^∞, F_-^∞ of H^+, H^0, and H^- ions (D^+, D^0, D^-) after charge exchange of H^+ (D^+) ions in Cs vapor.

Incident ion	Energy (keV)	F_+^∞	F_0^∞	F_-^∞
H^+	1.5	0.0010 ± 0.0002	0.92 ± 0.03	0.080 ± 0.015
	2	0.0021 ± 0.0005	0.94 ± 0.04	0.063 ± 0.013
	3	0.0043 ± 0.0011	0.96 ± 0.04	0.034 ± 0.007
	4	0.0060 ± 0.0030	0.96 ± 0.04	0.030 ± 0.012
	5	0.010 ± 0.003	0.97 ± 0.02	0.020 ± 0.006
	6	0.015 ± 0.003	0.97 ± 0.04	0.017 ± 0.004
	8	0.042 ± 0.010	0.94 ± 0.04	0.014 ± 0.003
	10	0.087 ± 0.025	0.90 ± 0.03	0.009 ± 0.003
	15	0.19 ± 0.04	0.80 ± 0.04	0.0065 ± 0.0020
	20	0.29 ± 0.05	0.71 ± 0.04	0.0038 ± 0.0005
D^+	1.0	a	0.85 ± 0.06	0.16 ± 0.04
	1.5	a	0.79 ± 0.04	0.21 ± 0.04
	2	0.0008 ± 0.0003	0.86 ± 0.05	0.14 ± 0.02
	3	0.0023 ± 0.0007	0.92 ± 0.03	0.085 ± 0.025

[a] Not measured.

TABLE II. Cross sections for charge exchange of H^+ (or D^+) in Cs vapor, in units of $10^{-17} cm^2$. Subscripts + and − refer to positive and negative ions, 0 as an initial subscript refers to a ground state atom, and 0 as a final subscript refers to an atom in the particular states produced.

Incident ion	Energy (keV)	σ_{+0}	σ_{0+}	σ_{+-}	σ_{0-}
H	2	680 ± 140	1.17 ± 0.20	3.7 ± 1.1	15.4 ± 2.5
	5	520 ± 100	5.4 ± 0.8	2.1 ± 0.6	7.0 ± 1.3
	10	220 ± 45	12.3 ± 2.2	0.87 ± 0.26	2.3 ± 0.5
	15	75 ± 11	17.4 ± 2.6	0.52 ± 0.16	1.43 ± 0.23
D	1	580^{+400}_{-200}			
	2	940 ± 200	0.31 ± 0.20		27.2 ± 5.0
	4		3.5 ± 2.0		22.2 ± 5.0
	10		6.3 ± 1.3		7.2 ± 1.4

reliable determination of equilibrium charge-component fractions.

The cross sections, which were determined from the initial slope of the charge-component fractions as a function of Cs target thickness, π, are given in Table II. Thin targets were used, so that single-collisions are the dominant processes.

The cross section σ_{+0} for H^+ incident on Cs is shown in Fig. 7. Also shown are measurements by Il' in *et al.* [2,3]; their measurements and ours are in significant disagreement. The cause of the disagreement is not known.

Cross sections have been reported[11–16] for $H^+ + Cs \rightarrow H(2s) + Cs^+$. Some of the cross sections reported for this reaction are larger in magnitude than our measured value for σ_{+0}, which is the cross section for electron pickup into all the states of the H^0 atom. One possible problem with some of the experiments measuring electron pickup into the 2s state is the difficulty of calibrating the Lyman-alpha detector. Sellin,[13] for example, assumed as a rough guide that electron pickup into the $n=2$ states dominates at an H^+ energy of 10 keV, and further assumed that 1/4 of the atoms produced in the $n=2$ state were in the 2*s* state. Obviously these assumptions are open to question.

The cross sections σ_{0+} and σ_{0-} for collisions of fast ground state H^0 atoms incident on Cs vapor

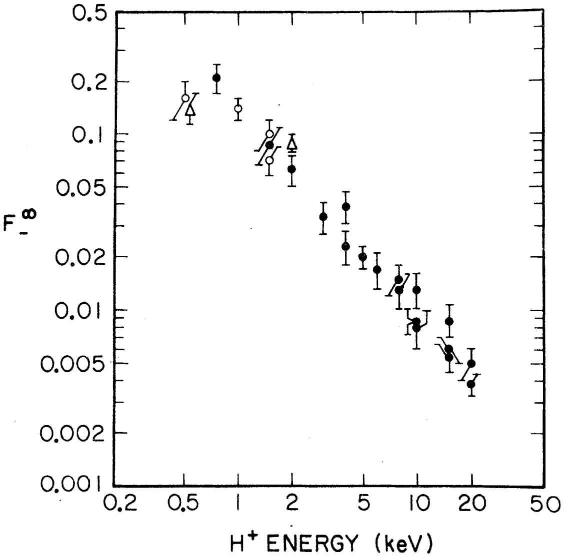

FIG. 6. Logarithmic plot of F_-^∞, the equilibrium yield of H^- (or D^-) ions after passage of H^+ (or D^+) through a thick Cs vapor target. Closed circles are data with H^+ as the incident beam. Open circles are data with D^+ as the incident beam, plotted at half their energy. Triangles are representative of measurements by Bohlen *et al.*

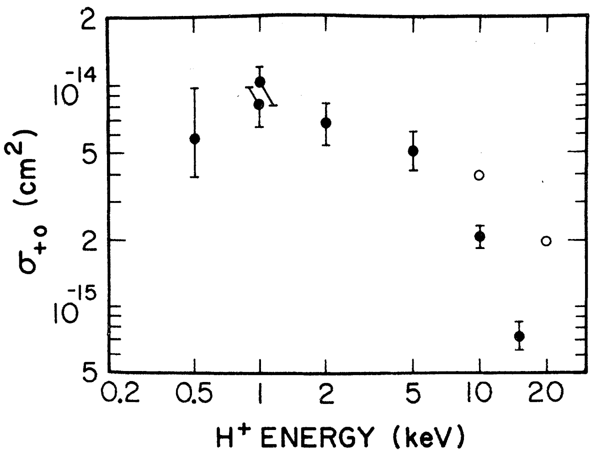

FIG. 7. The cross section σ_{+0} for H^+ ions incident on Cs vapor. The open circles are measurements by Il'in *et al.* (Refs. 2 and 3).

are shown in Figs. 8 and 9. The cross section σ_{+-} for two-electron pickup by H$^+$ in Cs vapor is shown in Fig. 10; this cross section was difficult to determine at energies below 10 keV because of the difficulty in determining the slope of the linear portion of F_- vs π.

It is interesting to note that a possible check on the consistency of the data is to calculate the neutral equilibrium yield, F_0^∞, from σ_{+0} and σ_{0+}, at a sufficiently high H$^+$ energy that two charge components, F_+ and F_0, are so much larger than F_- that F_- can be neglected. If one ignores the fact that there are two long-lived neutral states, then it is easily shown that $F_0^\infty = \sigma_{+0}/(\sigma_{+0} + \sigma_{0+})$.[22] For H$^+$ ions of 15 keV and 20 keV, the values of F_0^∞ calculated from the cross sections are 0.80 and 0.69 respectively, which are in satisfactory agreement with the measured values of 0.79 and 0.71. Similarly, for a sufficiently low H$^+$ energy, F_0 and F_- are large relative to F_+ for a thick Cs target, and F_+ can be neglected. Then it can be shown that $\sigma_{-0} = \sigma_{0-}(1/F_-^\infty - 1)$. If the role of metastables can be neglected, then our measured values of σ_{0-} and F_-^∞ can be used to calculate σ_{-0}. This calculation gives σ_{-0} values of 2–6 $\times 10^{-15}$ cm^2 at energies from 1–3 keV. We do not know whether these calculations are meaningful since the existence of metastable atoms has been ignored.

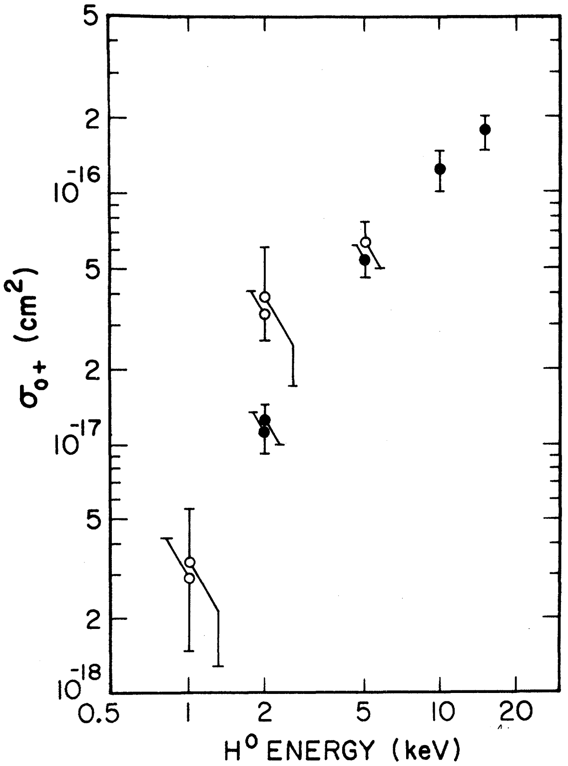

FIG. 8. The cross section σ_{0+} for ground state H^0 (or D^0) atoms incident on Cs vapor. Closed circles are for ground-state H^0 atoms incident. Open circles are for ground-state D^0 atoms incident, shown at half their energy.

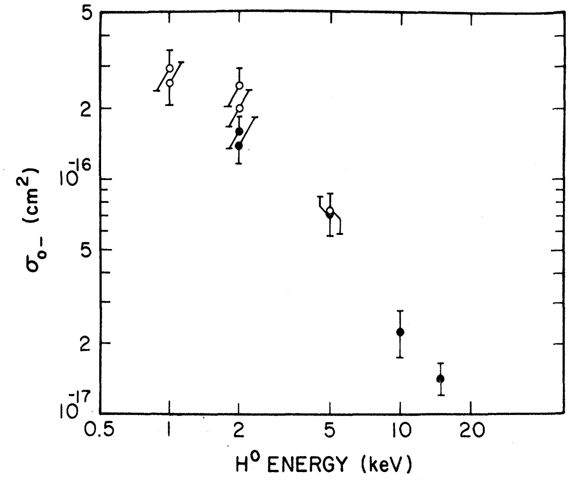

FIG. 9. The cross section σ_{0-} for ground-state H^0 (or D^0) atoms incident on Cs vapor. Closed circles are for ground-state H^0 atoms incident. Open circles are for ground-state D^0 atoms incident, plotted at half their energy.

The primary uncertainty in the measurements of the equilibrium charge fraction yields is the uncertainty in the value of the secondary-electron emission ratio in the neutral detector. This ratio could be determined to an accuracy of 5%, but the ratio could change as much as 10% within the period of a particular set of measurements, due to changes in the surface conditions of the secondary emitter.

The primary uncertainty in the cross section values arises from the uncertainty in the calibra-

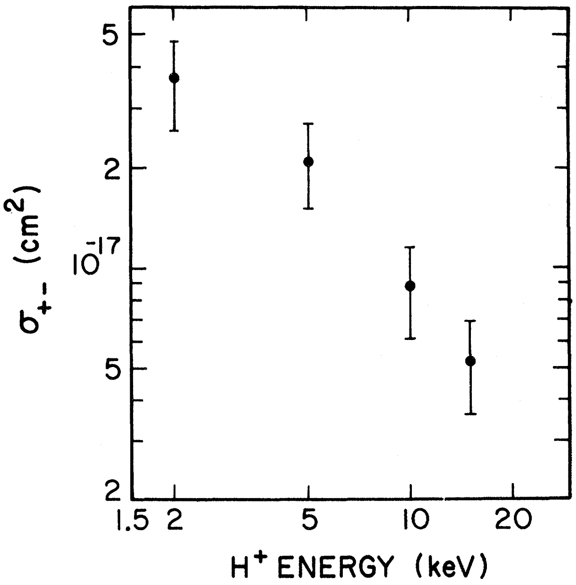

FIG. 10. The cross section σ_{+-} for H$^+$ ions incident on Cs vapor.

tion of the Cs gauge. The absolute calibration of the Cs gauge to the Cs vapor pressure has an uncertainty of ±20%.[17] In addition to this, there were two systematic effects: (1) data taken with the Cs density increasing differs systematically from that taken with the Cs density decreasing by approximately 10% (see Figs. 3 and 4), and (2) the calibration constant of the Cs gauge changed slowly with time. The calibration constant was measured periodically, and drift of the calibration constant contributes no more than a ±10% error to most of the cross sections. One further uncertainty is that the slope of the linear portion of the data could generally be determined only to approximately 5–10%. This is included in the error bars. The only error not shown in the error bars is the 20% absolute calibration uncertainty. The 20% uncertainty in the calibration of the Cs gauge must be added to the quoted error in order to obtain the precision of the absolute cross section.

When the Cs gauge is used at high Cs densities the calibration constant changes. This of course does not affect the equilibrium yield values, but is the reason why cross section measurements with thin Cs targets were made independently of high Cs density equilibrium yield measurements.

One point of interest is the comparison of measurements made with hydrogen ions and deuterium ions of the same velocity. Measurements of σ_{0+} and σ_{0-} for H^0 and D^0 of the same velocity are shown in Figs. 8 and 9. The apparent difference between the cross sections measured with H^0 and D^0 at an H^0 energy of 2 keV probably arises from systematic experimental uncertainties which result because the positive-ion currents are very small at this energy. For the same reason, the measurements of F_+^∞ at an H^+ energy of 1.5 keV and D^+ at 3.0 keV (see Table I) are not in good agreement. The values of F_0^∞ and F_-^∞ are in agreement to within the stated accuracy.

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[*] This research was supported by U. S. Army Research, Durham, North Carolina; The U. S. Atomic Energy Commission; and The University of Wisconsin Research Committee with funds provided by a NASA institutional grant and with funds for computer use.

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[19] The currents measured are (1) I_s, the H^+ current in the source cup located before the Cs target, (2) I_+ and I_-, the H^+ and H^- ion currents after passage of the beam through the Cs target, and (3) I_0, the equivalent neutral current after passage of the beam through the Cs target. The total current measured after passage of the beam through the target is called $\sum I$, where $\sum I \equiv I_+ + I_0 + I_-$. In general, $\sum I$ is less than I_s, due to misalignment of the apparatus and loss through multiple scattering. The transmission is defined as $\sum I/I_s$. The charge fractions are F_i, where $F_i \equiv I_i/\sum I$, and where i stands for +, 0, or −. In experiments where H^0 is the beam incident on the target, there are no values for I_s. Note that I_s values are not needed once the secondary-emission ratio has been determined.

[20] The appropriate cross sections are σ_{+0} and σ_{0+} for H^+ energies greater than 10 keV, σ_{-0} and σ_{0-} for H^+ energies less than 4 keV, and all cross sections at energies in between.

[21] Figure 3 is intended to show an expanded view of the low-density portion of the data shown in Fig. 2. For experimental reasons the data for thin and for thick Cs targets were not taken at the same time.

[22] This is a solution to the pair of differential equations:

$$dF_+/d\pi = \sigma_{+0}F_+ + \sigma_{0+}F_0$$

$$dF_0/d\pi = -\sigma_{0+}F_0 + \sigma_{+0}F_+ .$$