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Cross sections and equilibrium charge fractions when D_2^+ is incident on Cs vapor*

F. W. Meyer and L. W. Anderson
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706
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The total cross section for charge exchange or breakup when D_2^+ is incident on Cs has been measured in the energy range 3.0–23 keV. The cross section has a value of $(1362 \pm 80) \times 10^{-17}$ cm^2 at 3 keV and falls rapidly with increasing energy, reaching a value of $(594 \pm 40) \times 10^{-17}$ cm^2 at 23 keV. The equilibrium fraction of D^- obtained when D_2^+ is incident on Cs has also been measured. The equilibrium fraction of D^- is $(10.5 \pm 2.0)\%$ at 3 keV, $(7.3 \pm 1.6)\%$ at 5 keV, $(3.4 \pm 0.7)\%$ at 11.5 keV, $(2.0 \pm 0.4)\%$ at 17.3 keV, and $(1.5 \pm 0.3)\%$ at 23 keV. The equilibrium fraction of D^- obtained when D_2^+ is incident on Cs at an energy E is shown experimentally to be the same as the equilibrium fraction of D^- obtained when D^+ is incident on Cs at an energy $\frac{1}{2}E$. The angular distribution of the reaction products when D_2^+ ions are incident on Cs includes appreciable scattering into angles which are larger than 1°. An explanation of these large scattering angles is offered.

I. INTRODUCTION

An understanding of the atomic collision processes involved in the formation of D^- ions is of great interest in the areas of accelerator technology and controlled thermonuclear reaction research. In the production of high-energy D^+ beams by tandem accelerators, for example, an intense D^- ion source is required. In the controlled thermonuclear reaction (CTR) program, the injection of fast D^0 atoms has been proposed as a method of heating plasmas. The fast D^0 beam can be obtained in the following sequence: (i) production of D^- ions at low energy, (ii) subsequent acceleration of the D^- ions to high energy, and (iii) formation of D^0's by electron stripping of the fast D^- ions.

One method of producing D^- ions is by charge exchange with a D^+, D_2^+, or D_3^+ ion beam incident on a gas target. The total and differential cross sections involved in producing D^- ions, and the equilibrium fraction of D^- ions emerging from the target determine in part the intensity and emittance of the D^- ion beam produced in the target.

The total charge-exchange cross sections and equilibrium fractions for the reactions that occur when D^+ (or H^+) are incident on Cs vapor have been measured by numerous workers.[1–8] These experiments have shown that the equilibrium fractions of D^- (or H^-), when D^+ (or H^+) is incident on Cs vapor at energies less than 5 keV, are very large. Cs vapor is thus an attractive charge-exchange medium for the production of D^- (or H^-) ions. Similar experiments have not previously been reported for D_2^+ or D_3^+ incident on Cs.

The Barnett report[9] on the atomic and molecular data needs for the CTR program points out the immediate need for measurements of the total cross sections, differential cross sections, and equilibrium fractions for the formation of D^- when D_2^+ and D_3^+ are incident on Cs vapor. The present paper reports experimental values of the total charge-exchange cross sections and equilibrium fractions for D^- when D_2^+ is incident on Cs vapor. An interpretation of the results is offered in the final section of the paper.

II. EXPERIMENTAL APPARATUS AND ANALYSIS

The experimental setup used is identical to that used previously by Meyer and Anderson[10] except that the number of suppressed Faraday cups in the detection chamber downstream of the Cs target has been increased from two to four, to permit simultaneous measurement of the currents of the D_2^+, D^+, D^-, and D_2^- ions produced in the target. The Faraday cups each subtend an angle of approximately 1° as seen from the target, and are positioned symmetrically to the left and right of the beam axis at ±4° and ±8° with respect to the center of the analyzing magnetic field located between the Cs target and the detection chamber. The magnetic field momentum analyzes the beam emerging from the target, thus spatially separating the beam into its constituent ionic species. Since all the ions leave the target with very nearly the same velocity, the magnetic field which is required to deflect the D_2^+ beam component emerging from the target into the Faraday cup located at +4° with respect to the magnet center, also deflects each of the D^+, D^-, and D_2^- beam components into the remaining Faraday cups located at +8°, −8°, and −4°, respectively. The fast D^0 and D_2^0 particles emerging from the target strike a secondary emission detector also located in the detection chamber along the beam axis. The electrons ejected by the incidence of the fast neutral particles on the secondary emission detector are collected by a positively biased ring.

The Cs density in the target is measured by two hot wire gauges, one inside the target and the other in an auxiliary chamber as described in Ref. 10. The gauge in the target (called hot wire gauge 2 in Ref. 10) is used to measure directly the Cs density at low densities. The gauge in the auxiliary chamber (called hot wire gauge 1 in Ref. 10) is used to measure the Cs density at high densities where the hot wire gauge 2 is space charge limited. The gauge in the auxiliary chamber is calibrated against the gauge inside the target as described in Ref. 10.

Experimentally, at a particular energy of the incident D_2^+ beam, we measure the D_2^+ ion current before the Cs target, the ion currents to the various Faraday cups in the detection chamber downstream of the Cs target, and the electron current in the secondary emission detector for various values of the Cs ion current in the hot wire detector (i.e., for various values of the Cs target thickness).

The currents measured in the Faraday cups downstream of the Cs target are $I_1 = N_1 e$, $I_2 = N_2 e$, and $I_3 = N_3 e$, where I_1, I_2, and I_3 are respectively the D_2^+ ion current, the D^+ ion current, and the D^- current; N_1, N_2, and N_3 are respectively the number of D_2^+ ions, D^+ ions, and D^- ions emerging per second from the target and being collected in the Faraday cups; and e is the electronic charge. We observe no D_2^- current for any values of the energy and Cs-target thickness investigated in this paper. The current in the D_2^- Faraday cup is less than 10^{-5} of the incident ion current and was not measurable with a Keithley electrometer. The current to the neutral detector is $I_0 = I_4 + I_5 = R_4 N_4 e + R_5 N_5 e$, where I_4 and I_5 are respectively the secondary electron currents in the neutral detector produced by the incidence of fast D^0 and D_2^0 particles on the neutral detector, N_4 and N_5 are respectively the number of D^0 and D_2^0 particles emerging per second from the target and striking the neutral detector, and R_4 and R_5 are respectively the number of secondary electrons emitted from the neutral detector per incident D^0 and D_2^0 particle. The current to the Faraday cup located before the Cs target is $I_s = N_s e$, where N_s is the number of D_2^+ particles incident on the target.

The total number of deuterium atoms incident on the target is $2N_s$. These atoms must either be detected after the target or be scattered in the target so that they do not strike the detectors downstream of the target. Stray electric and magnetic fields may also deflect the charged particles so that they do not strike the detectors. Thus we find that

$$2N_s = \frac{2N_1}{T_1} + \frac{N_2}{T_2} + \frac{N_3}{T_3} + \frac{N_4}{T_4} + \frac{2N_5}{T_5}, \qquad (1)$$

where T_{1-5} are factors that take into account that a particle may acquire a sufficient amount of transverse velocity in the production process, by scattering, or by deflection due to stray electric and magnetic fields that it misses the Faraday cup. Thus the different T's are all less than or equal to one. We shall call T_1, T_2, T_3, T_4, and T_5 transmission factors for the D_2^+, D^+, D^-, D^0, and D_2^0 particles, respectively. The factors of 2 stem from the fact that the deuterium molecule contains two atoms. T_{1-5} may all be different since the angular distribution of each of the reaction products when D_2^+ collides with Cs may be different. Rewriting Eq. (1) in terms of the currents, we obtain

$$2I_s = \frac{2I_1}{T_1} + \frac{I_2}{T_2} + \frac{I_3}{T_3} + \frac{I_4}{R_4 T_4} + \frac{2I_5}{R_5 T_5}. \qquad (2)$$

The fractions of the total number of incident deuterium atoms at the end of the target in the forms D_2^+, D^+, D^-, D^0, and D_2^0 are given respectively by

$$F_1 = \frac{I_1}{T_1 I_s}, \quad F_2 = \frac{I_2}{2T_2 I_s}, \quad F_3 = \frac{I_3}{2T_3 I_s},$$

$$F_4 = \frac{I_4}{2T_4 R_4 I_s}, \quad \text{and } F_5 = \frac{I_5}{T_5 R_5 I_s}.$$

From Eq. (2) it follows that $F_1 + F_2 + F_3 + F_4 + F_5 = 1$. The total neutral beam fraction is $F_0 = F_4 + F_5$.

The differential equation describing the beam fraction F_1 is given by

$$\frac{dF_1}{d\pi} = -(\sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 + \sigma_5) F_1 + \sigma_6 F_5, \qquad (3)$$

where π is the target thickness in atoms per cm^2. The cross sections σ_{1-6} refer to the reactions

$D_2^+ + Cs \rightarrow D^0 + D^+ + Cs$ (σ_1),

$D_2^+ + Cs \rightarrow D^+ + D^- + Cs^+$ (σ_2),

$D_2^+ + Cs \rightarrow 2D^+ + Cs + e^-$ (σ_3),

$D_2^+ + Cs \rightarrow D_2^0 + Cs^+$ (σ_4),

$D_2^+ + Cs \rightarrow 2D^0 + Cs^+$ (σ_5),

$D_2^0 + Cs \rightarrow D_2^+ + Cs + e^-$ (σ_6).

We ignore charge-exchange reactions which involve two or more electron pick up such as $D_2^+ + Cs \rightarrow D^0 + D^- + Cs^{++}$, and we recognize explicitly in the differential equation that once the molecule or molecular ion is broken up the probability for two fast deuterium atoms or ions reuniting is negligible. Thus the reaction $D^+ + D^0 \rightarrow D_2^+$ does not occur in the fast beam. There are similar differential equations for the beam fractions F_2, F_3, F_4, and F_5.

III. EXPERIMENTAL RESULTS AND INTERPRETATION

The transmission factor T_1 of the D_2^+ beam through the target is greater than 95% when $\pi = 0$ for all the energies of the incident D_2^+ ions investigated in this paper. This indicates that deflection of the ions by stray electric and magnetic fields is negligible. The value of I_1/I_s falls from one to zero almost exponentially as π increases from zero to large values as shown in Fig. 1. We interpret this as indicating that any fast D_2^0 molecules formed are broken up into fast D^0 atoms or into D^+ and D^- ions before they can be stripped of an electron and regenerate a D_2^+ ion [i.e., the term $\sigma_6 F_5$ in Eq. (3) is negligible]. We believe that the elastic scattering of the D_2^+ ion into an angle not accepted by the D_2^+ ion Faraday cup (i.e., an angle greater than 1°) is small. The angular spread of the beam can be estimated from the variation of the current to the Faraday cup as a function of the analyzing magnetic field. If the beam is broad the current will change gradually as a function of the magnetic field. The measured D_2^+ ion current is observed to be insensitive to the analyzing magnetic field when this field is varied by as much as ±10% about the value required to center the D_2^+ beam into its Faraday cup. The ion current falls sharply to zero outside this range in magnetic field indicating that the D_2^+ beam is deflected so that it entirely misses the Faraday cup. Therefore we conclude that the effect of elastic scattering on the angular divergence of the D_2^+ beam is small. Furthermore,

$$I_1/I_s = T_1 F_1 = T_1 e^{-\pi(\sigma_1+\sigma_2+\sigma_3+\sigma_4+\sigma_5)}.$$

Here we recognize that $F_1 = 1$ at $\pi = 0$. From the experimental linear dependence (see Fig. 1) of $\ln(I_1/I_s)$ upon π for all values of π, we obtain T_1 and the total cross section for charge exchange or breakup of D_2^+ ions in Cs, $\sigma_T = \sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 + \sigma_5$. Experimentally we observe that the fraction of D^+ or D^- ions emerging from the target at low values of π is much smaller than the neutral fraction emerging so that $\sigma_T \simeq \sigma_4 + \sigma_5$. The values obtained for σ_T at the energies investigated are shown in Fig. 2.

We now discuss the beam fractions in the limit of high Cs density, i.e., when π is large. The beam fractions in the limit of very thick targets are called the equilibrium fractions and we denote them by F_1^∞, F_2^∞, F_3^∞, F_4^∞, and F_5^∞. There are numerous processes by which a D_2^+ ion or a D_2^0 molecule may be broken up. However, the probability of two fast atoms or ions recombining to produce a fast D_2^+ or D_2^0 particle is essentially zero. Thus after passage through a thick target there remain only atoms and atomic ions (i.e., $F_1^\infty = 0$ and $F_5^\infty = 0$). Consequently the equilibrium fractions for D_2^+ incident on Cs are expected to be the same as the equilibrium fractions when D^+ is incident on Cs, provided that the velocity of the incident D^+ ions is the same as that of the incident D_2^+ ions. In addition, for a thick target, each emerging particle will have undergone several charge changing collisions so that the transmission factor of each charge component will be the same (i.e., $T_2 = T_3 = T_4 = T$). The total fraction transmitted T is a function of the energy E of the incident particle and the target thickness π. Thus when π is suffi-

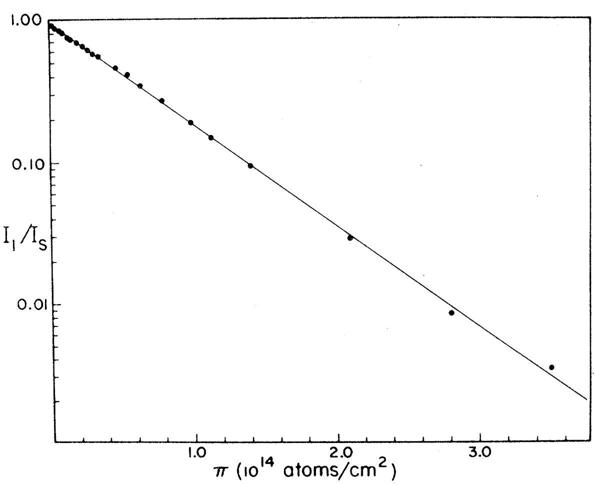

FIG. 1. Ratio of the D_2^+ current emerging from the target I_1 and the source current I_s as a function of the target thickness π for D_2^+ incident on Cs at 3 keV. The curve through the data points is drawn for clarity only.

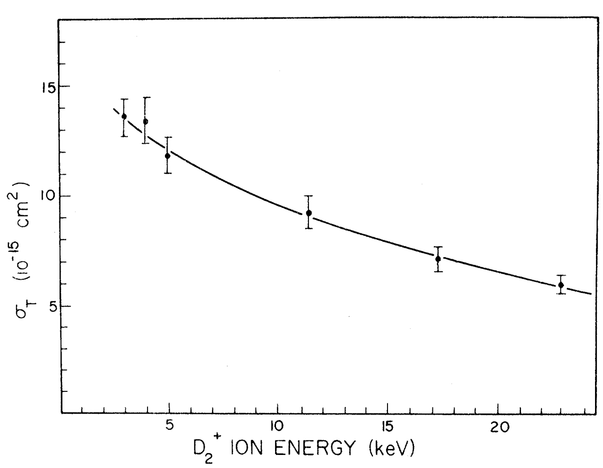

FIG. 2. Total cross section for charge exchange or breakup σ_T for D_2^+ incident on Cs as a function of the incident ion energy. The curve through the data points is hand drawn for clarity only.

ciently large

$$I_0 = I_4 = TR_4 N_4 e$$

and

$$2I_s = \frac{1}{T}\left(I_2 + I_3 + \frac{I_0}{R_4}\right).$$

The equilibrium beam fractions then are

$$F_2^\infty = \frac{I_2}{2TI_s}, \quad F_3^\infty = \frac{I_3}{2TI_s}, \quad \text{and } F_0^\infty = \frac{I_0}{2R_4 TI_s}.$$

Turning now for a moment to the case where D^+ ions are incident on a very thick Cs target at an energy $\frac{1}{2}E$, we have, by arguments similar to those presented in the previous paragraph,

$$I_s' = \frac{1}{T'}\left(I_2' + I_3' + \frac{I_0'}{R_4}\right),$$

where I_s' is the current of D^+ ions incident on the Cs target, I_2', and I_3' are the currents of D^+ and D^-, respectively, emerging from the target and entering the "+" and "−" Faraday cups, I_0' is the electron current to the neutral detector, and T' is the fraction of the incident ion beam transmitted through the target and into the detector Faraday cups. R_4 is the number of electrons emitted from the neutral detector per incident D^0 atom and thus R_4 is the same for D_2^+ incident at an energy E and for D^+ incident at the energy $\frac{1}{2}E$. The equilibrium beam fractions when D^+ is incident on a very thick Cs target are

$$F_2^\infty = \frac{I_2'}{T'I_s'}, \quad F_3^\infty = \frac{I_3'}{T'I_s'}, \quad \text{and } F_0^\infty = \frac{I_0'}{R_4 T'I_s'}.$$

If our assertion that the equilibrium fractions are the same when D_2^+ is incident on Cs at an energy E as when D^+ is incident at an energy $\frac{1}{2}E$ is correct, we should find that when π is very large $I_3/I_0 = I_3'/I_0'$. As a test of our theory, the following experiment was performed. Using a very thick Cs target we have measured I_3 and I_0 with D_2^+ incident at an energy E. We then rapidly switch to a D^+ ion beam of energy $\frac{1}{2}E$ and measure I_3' and I_0'. This experiment was carried out at energies $E = 3$, 5, 11.5, 17.3, and 23 keV. At all these energies we find that $I_3/I_0 = I_3'/I_0'$ with reasonable accuracy. For example with $E = 23$ keV ($\frac{1}{2}E = 11.5$ keV) we find $I_3/I_0 = 0.00739$ and $I_3'/I_0' = 0.00732$ and with $E = 11.5$ keV ($\frac{1}{2}E = 5.75$ keV) we find $I_3/I_0 = 0.0255$ and $I_3/I_0' = 0.0236$. The results of this experiment indicate experimentally that to a reasonable degree of accuracy the equilibrium fractions for D_2^+ incident at the energy E on Cs are the same as the equilibrium fractions when D^+ is incident on Cs at the energy $\frac{1}{2}E$. This experiment is consistent with the result that $T = T_2 = T_3 = T_4$ and that R_4 is the same for both sets of measurements. This experiment is especially important since it does not depend on knowing T, T', or R_4.

We observe R_4 to change slowly with time. The measurements of I_3, I_0, I_3' and I_0' are made very quickly (~2 min. for measurement of I_3, I_0, I_3', and I_0' at a given energy). On this time scale R_4 does not change significantly. In order to know the actual values of F_2^∞, F_3^∞, and F_0^∞ one must measure R_4. This measurement requires more time and R_4 may change somewhat on this time scale. Thus the actual values of F_3^∞ we obtain are somewhat less accurate than our determination that the equilibrium fractions are the same when D_2^+ and D^+ are incident on Cs with the same velocity.

In order to measure R_4 we use D^+ incident on a very thin target of Cs at an energy $\frac{1}{2}E$, and measure I_2'/I_s', I_3'/I_s', and I_0'/I_s' as a function of π. Since $\sigma_{+-} \ll \sigma_{+0}^1$, I_3'/I_s' is much smaller than I_2'/I_s'. Consequently we can use the equations $I_2'/I_s' = T'(1 - \sigma_{+0}\pi)$ and $I_0'/I_s' = R_4 T'\pi\sigma_{+0}$ to determine R_4, σ_{+0}, T' from the variation of I_2'/I_s' and I_0'/I_s' with π. The values of σ_{+0} obtained in this manner are consistent with those obtained by Schlachter *et al.*[1]

Having determined R_4, we subsequently use a D_2^+ ion beam incident on a very thick Cs target at an energy E. We determine T using the equation $2I_s = (1/T)(I_2 + I_3 + I_0/R_4)$. Knowing R_4 and T we obtain the equilibrium fractions $F_2^\infty = I_2/2T_sT$, $F_3^\infty = I_3/2TI_s$, and $F_0^\infty = I_0/2R_4TI_s$ from measurements of I_2/I_s, I_3/I_s, and I_0/I_s when π is very large. Using this procedure we have measured F_3^∞ for D_2^+ energies 3, 5, 11.5, 17.3, and 23 keV and for D^+ energies of 1.5, 2.5, 5.75, 8.65, and 11.5 keV. The values of F_3^∞ for both D_2^+ and D^+ incident on Cs are shown in Fig. 3 and are tabulated in Table I for the energies investigated. The value of π necessary to obtain the value of F_3 which is 90% of the F_3^∞, is called π^∞. We find that for D_2^+ incident on Cs, π^∞ is in the range 5×10^{15}–10^{16} atoms/cm² for all the energies investigated. It should be noted that, while the equilibrium fractions with D_2^+ incident on Cs are equal to the equilibrium fractions when D^+ is incident on Cs with the same velocity, the values of π^∞ can not be determined from measurements using D^+ incident on Cs, but instead must be measured using D_2^+ incident on Cs. It is observed that the maximum negative fraction occurs at high density and is the equilibrium fraction. The equilibrium fractions F_3^∞ when D_2^+ is incident on Cs with an energy E are in reasonably good agreement with the results of Schlachter *et al.*[1] and Gruebler *et al.*[2] on the equilibrium fractions of H^- when H^+ is incident on Cs at an energy $\frac{1}{4}E$. It seems reasonable to assume that if D_3^+ ions were incident on Cs with an energy E, the equilibrium fractions would be

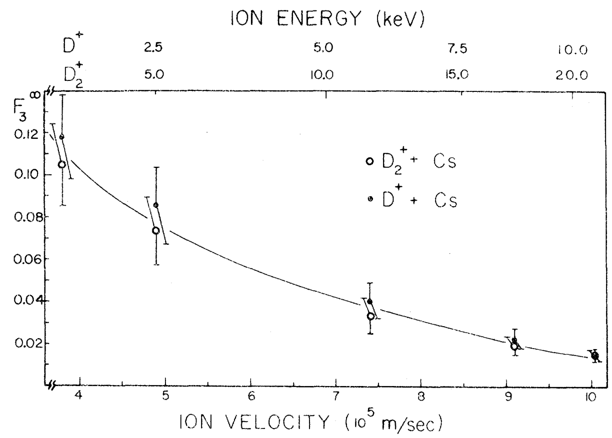

FIG. 3. Equilibrium fraction of D^-, F_3^∞, for $D_2{}^+$ incident on Cs (open circles), and for D^+ incident on Cs (solid circles) as a function of the incident ion energy. The curve through the data points is hand drawn for clarity only. Note that within experimental uncertainty the equilibrium fraction of D^- when $D_2{}^+$ is incident on Cs at an energy E is equal to the equilibrium fraction of D^- when D^+ is incident on Cs at an energy $\frac{1}{2}E$.

the same as those for D^+ incident on Cs at an energy $\frac{1}{2}E$.

The measurements of T when $D_2{}^+$ is incident on a very thick target of Cs show that T is small and that T decreases as π increases. Also T is smaller when the incident beam has a low energy than when the incident beam has a high energy. The small value of T implies that the range of angles into which the reaction products are scattered exceeds the 1° angle which the Faraday cups in the detection chamber subtend as seen from the center of the Cs target. We speculate that the cause of this large angular scattering is twofold. The first cause is the transverse velocity acquired by the product atoms or ions when a fast $D_2{}^0$ molecule breaks up; the second is the additional transverse velocity acquired in numerous small angle scatterings of the atomic products formed when the molecular ion breaks up. This causes T to fall as π increases.

TABLE I. Equilibrium fractions of D^- for $D_2{}^+$ and D^+ incident on Cs as functions of the incident ion energy (keV) and velocity (10^5 m/sec). The equilibrium fraction of D^- is denoted by F_3^∞ (in percent).

	D^+		$D_2{}^+$	
v	Energy	F_3^∞	Energy	F_3^∞
3.79	1.5	11.8 ± 2.0	3.0	10.5 ± 2.0
4.89	2.5	8.5 ± 1.8	5.0	7.3 ± 1.6
7.44	5.8	4.1 ± 0.8	11.5	3.4 ± 0.7
9.08	8.6	2.3 ± 0.4	17.3	2.0 ± 0.4
10.5	11.5	1.5 ± 0.2	23.0	1.5 ± 0.3

The ion source in our experiment is a duoplasmatron. The $D_2{}^+$ is extracted directly from the ion source. If the $D_2{}^+$ is produced in an ionizing collision of an electron and a ground-state $D_2{}^0$ molecule in the ion source plasma, the Franck-Condon principle indicates that most of the $D_2{}^+$ should be in vibrational levels with $\nu = 2, 3$, or 4. The $D_2{}^+$ incident on the target might make a collision with a Cs atom and be neutralized producing a fast $D_2{}^0$ molecule. The $D_2{}^0$ could be in the repulsive $b^3\Sigma_u^+ 2p\sigma$ state or in a state such as the $a^3\Sigma_g^+ 2s\sigma$ state that can radiatively decay to the $b^3\Sigma_u^+$ state.[11] In either case the Franck-Condon principle indicates that the two deuterium atoms would come apart with a total energy of about 6–8 eV or 3–4 eV per atom produced. The atoms would therefore acquire a transverse velocity and be distributed in angle about the incident direction up to angles like

$$\theta = \frac{v_\perp}{v_\parallel} = \left(\frac{4}{E/2}\right)^{1/2},$$

where E is the energy of the incident $D_2{}^+$ particle in eV so that $\frac{1}{2}E$ is the energy of each individual D^0 atom. As a numerical example if $E = 3$ keV, then $\theta \simeq 3°$. If the fast $D_2{}^0$ molecule is produced in a singlet state, then a subsequent spin exchange collision may leave the molecule in the repulsive $b^3\Sigma_u^+$ state. The $D_2{}^+$ ion may also pick up two electrons in a single collision. The resulting $D_2{}^-$ ion might be in the repulsive $b + e^{-2}\Sigma_g^+$ state[11] producing a D^- ion and a D^0 atom. We observe a few D^+ ions produced at low Cs density. In the energy range 3–23 keV we find $F_2 \lesssim 0.01F_0$ when π is low. At 3 keV F_2^∞ is very small so that F_2 increases, reaches a maximum of less than 1%, and then falls to almost zero as π increases from 0 to 5×10^{15} atoms/cm². The D^+ ions may arise by collision of a $D_2{}^+$ ion with a Cs atom such that the Cs atom hits one end of the $D_2{}^+$ ion and leaves the ion in a high enough vibration rotation state to dissociate the molecular ion into a D^+ and D^0 pair. Another possibility is that the collision of a $D_2{}^+$ ion is such that the center of mass of the Cs atom passes between the two nuclei of the $D_2{}^+$ ion snapping the bonding orbital. Both of these processes might produce a large angular deflection. After the molecule breaks up the atomic products formed undergo subsequent charge exchange collisions which produce further small angle scattering.

In general we see there are many ways of breaking up the fast incident $D_2{}^+$ ion or a fast $D_2{}^0$ molecule into two atoms or ions. Most of these processes will produce an appreciable angle of scattering (i.e., $\theta \simeq 3°$). Thus it is clear why the transmission is low. This interpretation is strengthened by the experimental observation that the beam components D^+ and D^- both have broad distributions in angle. The existence of these distributions is determined by varying the magnetic field that deflects these beams into their Faraday cups. However, the exact angular distribution was not obtained. The currents to these Faraday cups show broad peaks and drop to zero slowly as the D^+ and D^- beams are swept across their respective Faraday cups. The slow drop to zero indicates a beam width appreciably greater than the 1° angle subtended by the Faraday cups. The beam divergence of greater than 1° for the D^+ and D^- beams was observed for all values of π and for all the energies investigated. This distribution in angle is not observed at any values of π for the D_2^+ particles emerging from the Cs target.

IV. CONCLUSIONS

We have measured the total cross sections for charge exchange and breakup when D_2^+ is incident on Cs. The equilibrium fractions when D_2^+ is incident on Cs at an energy E are experimentally very large and in fact are equal to the equilibrium fractions when D^+ is incident on Cs at an energy $\frac{1}{2}E$. This result is encouraging for making D^- ion sources since a higher extraction energy generally gives more beam intensity with less space charge blow up. We also observed that the transmission of the reaction products out of our target is low. We explain this result in terms of the large scattering angles resulting from the break up of D_2^0 molecules produced in a repulsive state and other processes. If one wishes to use D_2^+ incident on Cs to make a beam of negative ions, one probably should focus the D_2^+ beam, forming a cross over in the Cs target. The Cs target should be dense but short and permit particles to leave at large angles (a few degrees). A lens following the Cs target can focus the emerging beam and helps prevent excessive spreading. The emittance of the D^- beam leaving the Cs target will be somewhat poorer than the emittance of the D_2^+ beam entering the target because of the angular scattering $[\theta \simeq (4/\frac{1}{2}E)^{1/2}]$ unless the scattering all occurs at a point. However, for an actual ion source the higher energy (and hence higher intensity) of the incident D_2^+ beam may more than compensate for the poorer final D^- emittance. The ion current from a space charge limited source is proportional to $E^{3/2}/m^{1/2}$, so that for the same velocity of extraction the D_2^+ current from a space charge limited source is twice as intense as the D^+ current. The D_2^+ beam thus contains four times as many D atoms as the D^+ beam. Also even for the same extraction voltage many ion sources yield larger outputs of D_2^+ or D_3^+ than D^+. Thus a D^- ion source using D_2^+ incident on Cs may have some advantages over a D^- ion source using D^+ incident on Cs.

Note added in proof. Two additional references concerning D_2^+ incident on Cs are the following: Carmen Cisneros, C. F. Barnett, and J. A. Ray, Bull. Am. Phys. Soc. 19, 911 (1974), and C. F. Barnett (private communication). In these two references differential scattering cross sections and equilibrium fractions of D^- when D_2^+ is incident on Cs in the energy range 0.5–5 keV are reported. The equilibrium fraction reported in the above references are in satisfactory agreement with the results of our research.

ACKNOWLEDGMENTS

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