Differential scattering and total cross sections of hydrogen and deuterium atoms in nitrogen*

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Absolute differential cross sections for stripping of hydrogen and deuterium atoms in nitrogen have been investigated in the energy range 0.5 to 2 keV for hydrogen and 1.03 to 4.12 keV for deuterium. The interactions were observed over scattering angles from 0 to 9°. Total cross sections for these processes were calculated by integration of the experimentally determined differential cross sections. Angular distributions were identical in shape for both D^+ and H^+ but different in magnitude at the same center-of-mass energy. The integrated cross sections were equal at equal velocities. The total H stripping cross sections were approximately 30% higher than those reported in previous work.

I. INTRODUCTION

In a recent paper, Fleischmann *et al.*[1(a)] measured the relative differential scattering cross sections for electron stripping collisions when H atoms were passed through eight gases. In this work the measured scattering cross sections were normalized to the total stripping or loss cross section measured previously. The present paper reports on the results of determining the differential scattering cross section absolutely, and by integrating over the scattering angles the total stripping cross section was obtained for H^0 and D^0 passing through N_2.

Classical calculations exist for predicting the ionization or stripping cross section. Using a statistical treatment, Firsov[2] starts with the Thomas-Fermi model of the interacting atoms. Firsov's formulation predicts the energy dependence and derives the total electron stripping cross section for heavy atoms of equal mass. On the other hand, a two-state model developed by Fleischmann and co-workers[3] sought to obtain a scaling law for absolute cross sections and beam energies. In this model, ionization of the atoms occurs by direct transition between the ground state and continuum states. They treated the collision as a time-dependent perturbation of the projectile by the gas target atom. Using a simple electrostatic potential, the probability of a transition from a bound state to a continuum state was determined for a fixed impact parameter. Integration over all impact parameters and continuum states yielded the total stripping cross section. Comparison of Firsov's method with experimental data reveals a high- and low-energy falloff for the experimental curves which was not predicted by the model. Comparison of previous data with the two-state model indicates better agreement of the cross sections over the full energy range (particularly at low energies) than that predicted by Firsov's model. On the other hand, Firsov's model predicts cross sections for rare-gas–rare-gas collisions with a greater degree of reliability than does the two-state model.

The present experiment was done to (1) obtain an accurate stripping cross section of H and D in N_2 to determine whether the Firsov or two-state model was appropriate; (2) develop techniques of obtaining accurate total cross sections from differential scattering cross sections such that other reactions of interest in the controlled thermonuclear program could be measured at low energies where scattering is severe; and (3) look for an isotope effect in stripping collisions of H and D in N_2. This paper describes the results of this investigation.

II. APPARATUS

The experimental arrangement was similar to that described in Ref. 1(a) and described in detail in the preceding paper.[1(b)] Ions were formed in a Von Ardenne-type ion source, accelerated to the desired energy, magnetically focused, and mass analyzed before passing through an oxygen neutralization gas cell. Charged particles emerging with netural particles from the oxygen cell were removed by application of a transverse electric field. Energetic atoms of H and D were incident on a nitrogen gas cell, a cylinder 2.5 cm long and 2.5 cm in diameter. Gas-cell pressures were measured with a calibrated mks capacitance manometer. The molybdenum entrance aperture was 1 mm in diameter; the exit slit was 2 mm high and 8 mm long. The cell was mounted in a chamber such that the detector assembly rotated about the center of the gas cell. Located 0.54 m from the gas cell was the detector assembly with a 1-

mm aperture. The assembly consisted of a 45° parabolic electrostatic energy analyzer, as described by Harrower.[4] The energy resolution of the analyzer was approximately 10%, so that all particles within the distribution of energy losses were counted by one voltage setting of the electrostatic analyzer. The protons or deuterons were counted by a funnel-type channel electron multiplier.[5] An aperture was placed in the rear plate of the analyzer such that the total scattered beam could be measured by a second multiplier as a function of the scattering angle. Careful calibration was made for the multiplier counting efficiency, which was approximately 100% for H^+ or D^+ when a negative 3000-V potential was applied to the front of the multipliers. Provisions were made to move the detector assembly in the vertical direction to ensure that the detector aperture was centered on the scattered beam. A secondary-emission type of Faraday cup measured the total neutral beam.

III. EXPERIMENTAL PROCEDURE AND ERRORS

The differential scattering cross section is given by the formulation

$$d\sigma_{0+} = I(\theta, \phi)\, d\Omega / I_0 n l \ ,$$

where $I(\theta)$ is the positive-ion current measured at angles θ and ϕ, $d\Omega$ is the solid angle subtended by the detector aperture, I_0 is the total neutral-particle current, n is the N_2 gas target density, and l is the length of the gas cell. The total stripping cross section is found by integration over angles θ and ϕ, and since the scattering is symmetrical about the scattering angle ϕ, we have

$$\sigma_{0+} = 2\pi \int_0^{\pi} \frac{d\sigma_{0+}}{d\Omega} \sin\theta \, d\theta \ .$$

In the measurement a proton or deuteron beam was converted to an atomic beam which was then stripped by the N_2 target. Path lengths and apertures were chosen such that the root-mean-square angular resolution of the system was 2.7 mrad, or 0.15°. The pressure in the scattering cell was maintained below 1.6×10^{-3} Torr to ensure single collisions.

The secondary-emission detector used to measure the neutral flux was calibrated by determining the secondary emission of protons or deuterons and assuming that neutral H or D atoms have the same secondary-emission coefficient. Both protons and deuterons had the same secondary emission at equal velocities. The secondary-emission coefficient was measured frequently and was found to remain constant to within a few percent over long intervals of time.

Before and after each angular scan the neutral-beam flux was measured. If the two measurements did not agree to within 5%, the data were discarded.

Several sources of error are present: (1) the absolute length of the gas cell, (2) measurements of neutral and ion currents, (3) collision chamber absolute density, (4) convolution of the detector resolution, (5) ionization along the path length outside the collision chamber, and (6) multiple collisions. No correction has been made to the length of the gas cell. Gas streaming from the exit aperature of the collision cell should decrease the cross section by at most 12%. Great care was taken in calibrating the channel multipliers and secondary-emission detectors. The assumption of equal secondary electron emission for protons and neutrals is probably incorrect. Previous measurements[6] have shown that the ratio $\gamma(H^0)/\gamma(H^+)$ was 1.1 at an energy of 20 keV. Extrapolation of these results to 1 keV results in a ratio of 1.05. Thus the measurement of I_0 is overestimated by 5%. The estimated probable error of determining the proton or deuteron flux is ±5%. The collision chamber density was measured with a mks manometer calibrated against a McLeod gauge, using H_2 as a gas. No attempt has been made to correct the results by the process of convoluting the detector resolution. This source of error has not been estimated, but from Saures and Thomas's[7] work the deconvolution leads to a correction of about 10% for angles greater than 0.5°. The pressure outside the collision cells was maintained in the region of 10^{-6} Torr. Increasing the pressure in these regions produced no change in the angular distributions. To eliminate slit scattering and residual gas scattering, a background distribution was obtained with the collision cell evacuated. This distribution was subtracted from the scattered distribution and in all cases was less than a few percent. To ensure that multiple collisions were not present, angular distributions were taken at several pressures, and the pressure was always below that which produces the broadened distribution characteristic of multiple scattering. Distributions were made on both sides of the forward direction to assure us that the distributions were symmetric. The estimated root-mean-square error is 17%, while the cross sections were reproducible to within 15% from day to day.

IV. RESULTS

The angular distributions of protons and deuterons scattered by stripping collisions with N_2 are shown in Fig. 1. The energies of the scattering curves are labeled in the laboratory system

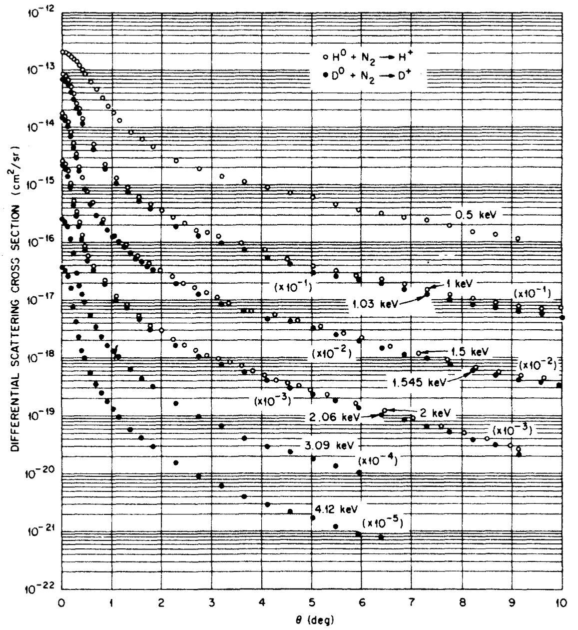

FIG. 1. Differential stripping cross sections of H^0 and D^0 at the same center-of-mass energy.

and have the same center-of-mass energy. The shape of the distributions agree well with those found in Ref. 1, and scattering is predominantly in the forward direction. Although the shape of the angular distribution was the same for H and D, the absolute magnitudes were different. Smith *et al.*[8] have shown that the impact parameter $\phi(b)$

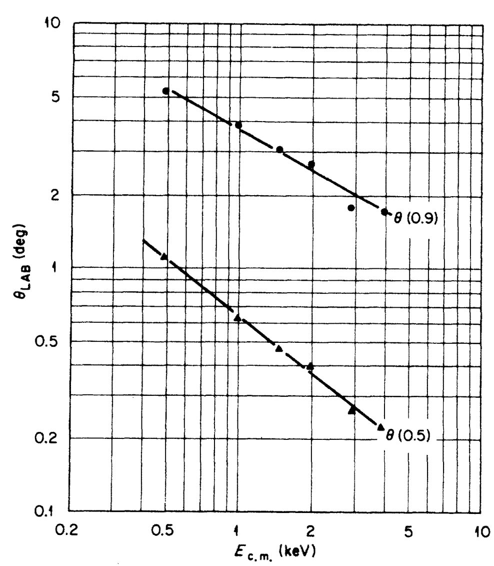

FIG. 2. Cone angles at which 50% and 90% of the total intensity of H^+ and D^+ ions formed are scattered as a function of the neutral-particle energy.

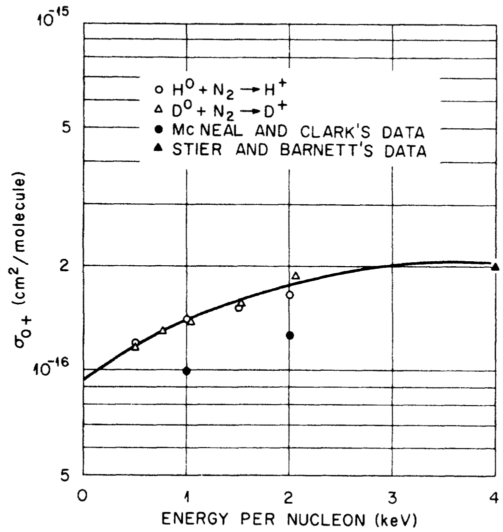

FIG. 3. Stripping cross sections of H^0 and D^0 in N_2 as a function of the particle energy. The energy is given as energy/nucleon.

to the first order is equal to the product of energy and scattering angle. Thus H and D with the same center-of-mass energy scatter at the same angle, as indicated in Fig. 1. Integrating the differential cross sections yields the stripping cross section, which scales as the H and D velocity.

Shown in Fig. 2 are the cone angles into which 50% [$\theta(0.5)$] and 90% [$\theta(0.9)$] of the particles are scattered as a function of the particle energy. Points are plotted for both H and D atoms. Again, since the scattering shape is the same, the cone angle into which H^+ or D^+ scatters is the same. The slopes of $\theta(0.5)$ and $\theta(0.9)$ are not the same; however, the energy dependence is between $1/E$ and $1/E^2$.

The differential scattering cross-section curves have been integrated, and the total stripping cross sections are shown in Fig. 3, where σ_{01} cross sections are plotted as a function of the energy per nucleon. Also shown are the data obtained by McNeal and Clark[9] and by Stier and Barnett.[10] The data of McNeal and Clark are low by approximately 40% compared with the present measurements. This discrepancy may have arisen from some of the reaction products (H^+) being intercepted by the target-gas-cell exit aperture, which in McNeal and Clark's experiment corresponded to a scattering angle of 1.8°. Our angular measurements indicate that for an energy of 0.5 keV, 64% of the H^+ lie within a 1.8° cone angle, while at 2.5 keV, 93% are within this same angle. Stier and Barnett[9] used an attenuation method to measure the total stripping cross section. This method is indepen-

TABLE I. Comparison of theoretical calculations with experimental results for the stripping cross sections of H^0 and D^0 in N_2.

E_H (keV)	E_D (keV)	Velocity (10^7 cm/sec)	σ_{OBF} [a] (10^{-16} cm^2)	σ_{HHF} [b] (10^{-16} cm^2)	σ_{RJMC} [c] (10^{-16} cm^2)	σ_D [d] (10^{-16} cm^2)	σ_H [d] (10^{-16} cm^2)
0.5	1.03	3.7	1.106	0.234		1.17	1.19
	1.54	3.79	1.574	0.417		1.3	
1.0	2.06	4.38	2.0	0.636	1.0	1.38	1.40
1.5	3.09	5.37	2.72	1.14		1.56	1.51
2.0	4.12	6.2	3.26	1.706	1.25	1.88	1.65

[a] σ_{OBF} was obtained by Firsov's approximation (Ref. 2).
[b] σ_{HHF} was obtained by two-state approximation (Ref. 3).
[c] σ_{RJMC} was measured by R. J. McNeal *et al.* for hydrogen projectiles (Ref. 9).
[d] σ_H, σ_D were calculated by integrating the differential results up 9° at each energy with hydrogen and deuterium projectiles, respectively.

dent of exit slit geometry if elastic scattering is assumed to be small. The present data extrapolate very well to the total cross section at 4 keV, as measured by Stier and Barnett. Within the experimental accuracy, the D^0 and H^0 stripping cross sections are equal at the same velocity.

The numerical values of the experimental measurements and the theoretical predictions of Firsov[2] and Fleischman *et al.*[3] are given in Table I. By assuming the nitrogen molecule to be two independent atoms (i.e., $Z_T = 7$), the theoretical values were calculated. The calculated cross sections were multiplied by 2 in order to compare them with the present values. Cross sections calculated with Firsov's formalism agree well in magnitude with the experimental value at 0.5 keV. As the energy per nucleon increases, the Firsov cross sections increased much more rapidly with energy than did the experimental values, which are different by a factor of 2 at 2 keV. Using the two-state approximation, the experimental cross section is a factor of 5 greater than that calculated. The two-state values increase rapidly with energy and are equal to the measured cross section at 2 keV. Clearly, both theoretical approximations fail to predict the energy dependence of the measured cross section in the energy range 0.5–2.0 keV per nucleon. These data suggest that other models must be proposed, probably taking into account molecular effects and curve crossing. Additional experimental data should be extended to include lighter target gases (He) as well as argon.

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