PHYSICAL REVIEW A VOLUME 1, NUMBER 4 APRIL 1970

Coincidence Measurements of Close H^+-on-He Collisions*

William Keever and Edgar Everhart†
Physics Department, University of Connecticut, Storrs, Connecticut 06268

(Received 20 November 1969)

Differential measurements are made for close encounters of protons with helium atoms, measuring the charge state after collision of both particles in coincidence. Incident proton energies range from 5 to 170 keV and the scattering angle is 10°. The probabilities versus energies of three reactions are studied: electron transfer P_{01}, scattering without change of charge of either particle P_{10}, and ionization of the target (so that both particles are singly ionized after the collision) P_{11}. Here P_{01} is found to exhibit a damped resonant structure plotted versus energy and P_{10} shows a complementary oscillatory structure. The ionization probability P_{11} increases smoothly with energy.

I. INTRODUCTION

These measurements concern encounters of keV-energy protons with helium atoms at such small impact parameters that the incident particle is scattered to an appreciable angle θ, here set at 10°. The charge states of both the scattered hydrogen and the recoil helium are examined in coincidence. The data extend from 5- to 170-keV incident proton energy.

Several authors have reported noncoincident measurements of the H^+-on-He collisions wherein only the scattered incident particle is detected. Thus, Ziemba *et al.*[1] and Helbig and Everhart[2] measured a quantity P_0 in these collisions, where P_0 is the fraction of the incident protons that capture an electron during the collision and emerge neutral. When P_0 is plotted versus incident energy there is seen a resonant structure that is damped more as the energy decreases. Dose and Meyer[3] and Jaecks, McKnight, and Crandall[4] have made differential probability measurements of electron capture into the 2*s* state of hydrogen for this collision. None of these previous studies have examined the charge state of the target particle after the collision.

The present study looks at the relative probabilities versus energy for the following processes, neglecting states of excitation:

$$\begin{aligned} H^+ + He &\to H + He^+, && P_{01} \\ &\to H^+ + He, && P_{10} \qquad (1)\\ &\to H^+ + He^+ + e^-, && P_{11}. \end{aligned}$$

The first subscript is the charge of the hydrogen after the collision, the second that of the helium. Three other reactions P_{12}, P_{-12}, and P_{02} would be possible if the collision resulted in He^{++}. The first two of these reactions are not seen here, and the P_{02} reaction is seen so rarely that it is negligible.

The process P_{01} is termed charge transfer; P_{10} is scattering without change of charge; and P_{11} may be called ionization. A time-delayed coincidence measurement of both particles measures P_{01}, P_{10}, and P_{11}. In the earlier work[1,2] a single subscript indicated the charge of the scattered hydrogen. Thus

$$\begin{aligned} &P_0 = P_{01}, \\ \text{and} \quad &P_1 = 1 - P_0 = P_{10} + P_{11}. \end{aligned} \qquad (2)$$

Since this earlier work determined P_0 and P_1, the contribution of the present study lies in the separate measurement of P_{10} and P_{11}. Theoretical studies of close H^+-on-He collisions include those of Lichten,[5] Green,[6] and Sin Fai Lam,[7] though none of these examine P_{10} and P_{11}.

II. EXPERIMENT AND PROCEDURE

The theory of the measurement, a description of the apparatus, and the procedure for taking data have been described in detail[8] in connection with coincidence measurements of Ar^+-on-Ar collisions and other combinations. It is only necessary to describe here the special problems encountered in the H^+-on-He combination.

A. Inelastic Energy

Ordinarily a detailed examination of the scattering angle θ and the recoil angle ϕ would allow a calculation of the inelastic energy loss Q. However, for H^+-on-He at the rather high incident energies T_0 under study, Q is so small compared to T_0 that this measurement is impractical. That is, the angular relationship between θ and ϕ is practically the same as it would be for an elastic collision.

B. Scattering Angle

Experience with this collision[1,2] has shown that the data are almost independent of the scattering angle θ. The reason is that, over the energy range of the experiment, the impact parameter is small compared to atomic dimensions for all angles greater than a fraction of a degree. For practical reasons, having to do with the geometry of the scattering chamber available, the angle θ is set at 10°. This relatively large angle for the scattered hydrogen has the important advantage that the recoiling helium particle, whose energy varies approximately as $\sin^2\theta$, is correspondingly easier to detect. A 20-keV proton scattered at 10° results in a 152-eV helium recoil at $\phi = 83.75°$, and this helium (whether neutral or ionized) is sufficiently energetic to be counted with our secondary-electron multipliers. If the proton angle had been set to 5°, the helium energy would have been only 38 eV, creating problems for detection.

The angle 10° is a compromise. With a larger angle the recoil heliums would be still easier to detect, but the differential scattering cross section drops so precipitously with angle that relatively few events would be counted.

C. Use of Deuterons

The collision D^+ on He is considered to be equivalent to H^+ on He, provided that the incident velocity and impact parameter are the same. For example, 10-keV deuterons scattered at 10° are equivalent to 5-keV protons scattered at 20°. Since there is no angular dependence on the probabilities between 10° and 20°, the 10-KeV deuterons scattered to 10° give the same data as would 5-keV protons scattered to 10°.

The most important advantage of using deuterons is that their greater mass (for a given scattering angle) imparts more kinetic energy to the recoil helium. In practice, a 10-keV deuteron beam scattered to 10° (equivalent to a 5-keV proton beam) results in a 152-eV helium recoil, whereas it required a 20-keV proton beam at 10° to give a 152-eV recoil. Thus use of deuterons in place of protons allowed the equivalent proton energy of the data to be lowered from 20 to 5 keV, while maintaining sufficient recoil-particle kinetic energy for detection.

The D^+-on-He data, appropriately scaled in energy, overlap smoothly with the H^+-on-He data.

D. Procedure

As shown in Eq. (2), a measurement of P_{01} is here entirely equivalent to a measurement of P_0. Thus the neutral scattered component is detected in coincidence with the "total" (independent of charge state) recoil component, and then the "total" scattered component is detected in coincidence with the "total" recoil component. The ratio of these two count rates is $P_0 = P_{01}$. The recoil counts serve as a beam time monitor to connect these two counts.

Probabilities P_{10} and P_{11} are measured by determining the relative number of He and He^+ coincidences with scattered protons. Here the protons serve as a beam time monitor. The counts are normalized so that $P_{10} + P_{11} = 1 - P_{01}$.

E. Correction for Secondary Collisions

The differential cross section for scattering of H^+ on He at 10° is so small that target gas pressures of 3 to 7 mTorr were necessary in order to obtain reasonable counting rates with good statistics (100 events/h).

The scattered fast H or H^+ particle and the much slower He or He^+ particle must traverse about 0.43 cm of helium target gas at these pressures before they can reach the evacuated detector chambers. There is negligible change of charge for the H^+, H, and He particles under these conditions, but, unfortunately, there is a 6–10% probability of neutralization for the He^+ in its own gas at this path length and pressure. Such neutralization depletes the count of He^+ and increases the count of He.

The techniques used to measure P_{01} make the result independent of this complication, but the data taken for P_{10} and P_{11} require correction. To first order, this is accomplished by adding $\sigma x n N_1$ counts to the apparent number N_1 of He^+ coincidence counts and by subtracting the same number of counts from the He recording. Here x is the 0.43-cm path, and n is the helium-target-gas number density at the pressure in question. Values of total cross section σ for charge transfer are read from Hayden and Utterback[9] at low recoil energies, and from Nagy, Savola, and Pollack[10] at the higher recoil energies.

III. DATA AND DISCUSSION

The charge-exchange probability P_{01} (often called P_0) is plotted versus incident proton energy T_0 in Fig. 1. Although measured on different apparatus the present 10° data agree well with Helbig and Everhart's data[2] taken at 0.7–3.0° as shown on the figure. The D^+-on-He data, properly scaled, are consistent with the H^+-on-He data. The coincidence data show a somewhat higher scatter than the previous noncoincidence data. Apparently the advantages of freedom from spurious counts and freedom from the possible effects

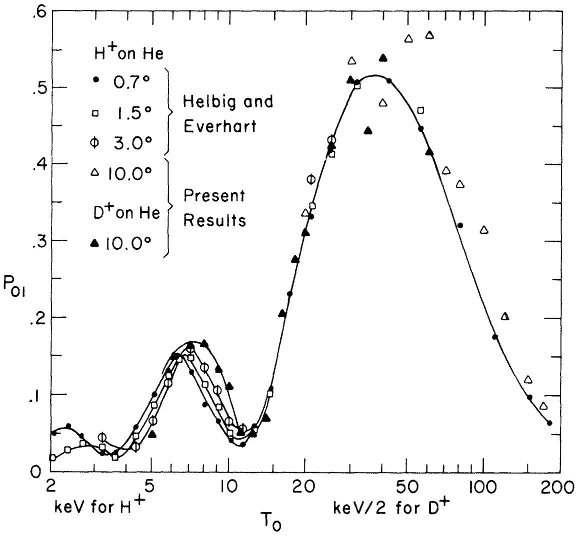

FIG. 1. For close H$^+$-on-He collisions the charge-exchange probability P_{01} is plotted versus incident proton energy T_0. The proton is scattered at 10° in these data, and a comparison is made with similar data taken at 0.7°–3° by Helbig and Everhart (Ref. 2). Data for the D$^+$-on-He collision are included, scaled as explained in the text.

of target gas impurities are canceled by the much lower counting rates in the coincidence experiment.

Of more interest are the results for P_{10} and P_{11} shown plotted versus energy T_0 in Fig. 2, since these data can only be attained by the coincidence method.

The curve for P_{10}, scattering without change of charge, is complementary to the charge-exchange data of Fig. 1, the one having a maximum where the other has a minimum. Oscillations are not seen in the P_{11} data. There is a threshold at about 7 keV, and above this there is a linear dependence of P_{11} on the logarithm of P_0. Over the energy range between 7 and 170 keV an empirical expression

$$P_{11} = 0.276 \log_{10} (\tfrac{1}{7} T_0) \tag{3}$$

fits these 10° differential scattering data.

The fact that the P_{11} data do not partake of the oscillations is significant, and leads the authors to speculate on the mechanism. The P_{11} reaction could occur in several steps:

$$H^+ + He \rightarrow H\,He^{+*} \rightarrow H^+ + He^* \rightarrow H^+ + He^+ + e^- . \tag{4}$$

An intermediate doubly excited state of the H He^{+*} ion breaks up into a proton plus He*, this latter also being doubly excited. Later an auto-ionization transition occurs, leaving He$^+$ and e^-. Apparently when the H He^{+*} state is formed, it is created independently of the phase of the oscillations, and no further oscillations occur afterwards. In other words, the ionization reaction appears to take precedence over the charge-exchange oscillations.

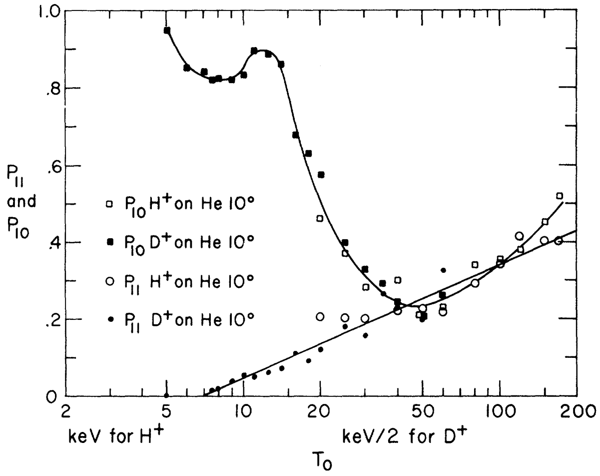

FIG. 2. The probabilities P_{10} and P_{11} are plotted versus incident proton energy for measurements of the H$^+$-on-He and the D$^+$-on-He collisions wherein the incident particle is scattered at 10°.

---

[*] Work sponsored by the U. S. Army Research Office, Durham.

[†] Present address: University of Denver, Denver, Colo.

[1] F. P. Ziemba, G. J. Lockwood, G. H. Morgan, and E. Everhart, Phys. Rev. 118, 1552 (1960).

[2] H. F. Helbig and E. Everhart, Phys. Rev. 136, 674 (1964).

[3] V. Dose and V. Meyer, Phys. Letters 23, 69 (1966).

[4] D. H. Jaecks, R. H. McKnight, and D. H. Crandall, in Proceedings of the Sixth International Conference on the Physics of Electronic and Atomic Collisions (The MIT Press, Cambridge, Mass., 1969), p. 862.

[5] W. Lichten, Phys. Rev. 139, 27 (1965).

[6] T. A. Green, Phys. Rev. 152, 9 (1966).

[7] L. I. Sin Fai Lam, Proc. Phys. Soc. (London) 92, 67 (1967).

[8] Q. C. Kessel and E. Everhart, Phys. Rev. 146, 16 (1966).

[9] H. C. Hayden and N. G. Utterback, Phys. Rev. 135, 1575 (1964).

[10] S. W. Nagy, W. J. Savola, Jr., and E. Pollack, Phys. Rev. 177, 71 (1969).