Ionization of Atomic Hydrogen by 30–1000 keV Antiprotons

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(Received 13 February 1995)

Ionization in collisions between antiprotons and atomic hydrogen is perhaps the least complicated and most fundamental process that can be treated by atomic-collision theory. We present measurements of the ionization cross section for 30–1000 keV antiprotons colliding with atomic hydrogen.

PACS numbers: 34.50.Fa

Pointlike charged particles colliding with atomic hydrogen isotopes (H or D) constitute some of the most fundamental three-body systems available for study. Ionization is one of the most important collision processes, and a detailed understanding of its basic mechanisms underpins many applied areas of physics. Furthermore, ionization reactions are of particular importance since the final state contains three bodies which mutually interact via the Coulomb force, and they are prime examples of situations for which no exact solution of the Schrödinger equation can be found.

During the last decade, it was realized that measurements employing equivelocity electrons (e^-), positrons (e^+), antiprotons (p^-), and protons (p^+) as projectiles are especially fruitful in disclosing the various mechanisms that affect the probability for single or multiple ionization of target atoms and molecules, as well as in testing the theories that describe these processes. For a comprehensive discussion of this topic, see Knudsen and Reading [1]. Measurements of single and multiple/dissociative ionization have been performed with all four particles impinging on He and H_2 [1,2]. A more fundamental and important target is atomic hydrogen where there are no uncertainties due to the incomplete knowledge of the static-target wave function or the dynamic interplay of the target electrons during the collision, which are inherent to the situation for multielectron targets.

For a test of the theory for ionization of atomic hydrogen, it is especially important to have experimental data for antiproton impact. This is due to the following: (i) The electron-transfer channel is a great complication for the case of impact of the positive projectiles e^+ and p^+; (ii) the light projectiles e^- and e^+ do not allow the theoretical simplification of a straight-line, constant-velocity projectile path; and (iii) electron projectiles demand a treatment of exchange phenomena. Therefore, the reaction $p^- + \mathrm{H} \rightarrow p^- + p^+ + e^-$ is, from a theoretical viewpoint, the simplest one and is thus the most fundamental of all atomic-collision ionization phenomena.

For the atomic hydrogen target, the ionization cross section has been known for several years for impact of protons [3,4] and electrons [5]. Recently, two groups published corresponding measurements for positron impact [6,7]. Unfortunately, there are large differences between these two sets of data. The present measurements offer guidance as to which set is the more reliable.

Until now, there have been no experimental investigations of the ionization of atomic hydrogen by p^- impact. This was due both to the very low intensity of the only existing low-energy p^- beam and its limited availability for atomic physics and to the very low density of useful atomic hydrogen targets. Nevertheless, we have recently succeeded in measuring this cross section for impact energies between 30 keV and 1 MeV.

For experimental reasons, we used atomic deuterium, D, instead of atomic hydrogen as a target. It is not expected that there should be any isotope effect in the ionization cross section on the percentage level of accuracy which we are concerned with in this field. This has recently been confirmed by Krishnakumar and Srivastava [8] who found the cross sections for single and dissociative ionization of H_2 and D_2 for 16–1000 eV electron impact to be identical.

The experimental setup was based on the apparatus used in our previous work (see Ref. [2] and references therein) with one important difference. Instead of a static-gas

0031-9007/95/74(23)/4627(4)$06.00

target, we used a broad jet of D and D_2 emitted from a Slevin-type [9] source. A beam of $\sim 10^5$ s^{-1} 5.9 MeV p^- was obtained from the Low-Energy Antiproton Ring (LEAR) at CERN. The antiprotons were slowed down in a Be foil, a few mm of atmospheric air, an interchangeable Be degrader, and a thin Mylar foil. They then passed through a 100 μm plastic scintillator prior to entering the target region. Finally, they were detected downstream by a 1 mm thick plastic scintillator. The two scintillators were covered with thin Al foils which block out photons emitted from the deuterium source. The signals from the two scintillators define the time of flight (TOF) of each p^-. The thicknesses of the Be degrader and the air gap were adjusted to give a broad distribution of p^- energies between 30 keV and 1 MeV.

In the target region, the p^- beam crossed a broad jet of D and D_2 emitted from the nozzle of the Slevin-type, RF-discharge source. To minimize the emission of photons (Lyman α) from the deuterium plasma, an UV-photon trap was built into the nozzle, and, furthermore, to prevent photons from reaching the detectors, all inner surfaces of the apparatus were covered with Aquadag where possible.

The ions created in the target region were extracted by a 400 V/cm static electric field perpendicular to both the p^- and the deuterium beam. The ions were then temporally and spatially focused by a gap lens onto a channeltron detector, the cone of which was held at -1.85 kV. The time between the arrival of an ion and the detection of the corresponding p^- defines the ion TOF and hence its mass-to-charge ratio. Figure 1 shows such ion TOF spectra integrated over all p^- energies. With RF off [Fig. 1(a)], we observe a $D_2{}^+$, a D^+, and a H^+ peak. The latter stems from water of the rest gas and is the only remaining peak when the deuterium supply is cut off. The presence of these H^+ ions is the reason deuterium was chosen as a target gas since the $H_2{}^+$ yield is negligible from the dissociation of water. The D^+ peak in Fig. 1(a) stems from dissociation of D_2. In Fig. 1(b) it can be seen that when RF is on, the jet from the Slevin source contains a large fraction of D atoms.

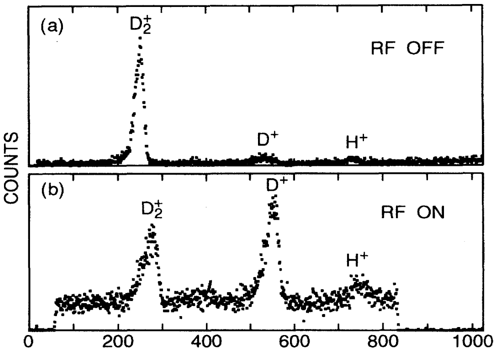

FIG. 1. Time-of-flight spectra for ions extracted from the interaction region when the RF supply was (a) off and (b) on.

All data were accumulated event by event by a Camac system connected to a PC. The ion TOF spectra corresponding to various antiproton-energy bins were extracted, and from each of these spectra, the number of D^+ was found. This number was corrected for overall background and for the D^+ yield stemming from the dissociation of D_2 in the jet. This latter correction, which was always smaller than 10%, was obtained from the content of $D_2{}^+$ in the spectra and the known fragmentation ratio of H_2 ionized by p^- impact [2]. The correction for overall background was generally considerably smaller than 10%, but below 60 keV it increased with decreasing energy and it reached a magnitude of 32% for our lowest-energy data point. This is reflected in the given experimental uncertainty. The ratio between the corrected number of D^+ and the number of p^- in the energy bin gives the relative cross section for ionization of D. The absolute cross section was obtained through a normalization in the energy interval between 0.5 and 1 MeV to the p^+ impact on H data of Shah and Gilbody [3] which, in turn, were normalized to first Born calculations at 1.5 MeV by Bates and Griffing [10]. We believe this to be a valid procedure since we have shown previously that the cross sections for p^+ and p^- impact on H_2 as well as on He are identical in this energy range.

It remains to discuss the overlap between the D jet and the p^- beam. The detected ions stem from the ion-extraction volume, which is defined by an aperture in the upper extraction electrode as well as by the width of the "usable" p^- beam. This width was given by the size of the end scintillator detector and was made to fit the size of the extraction-electrode aperture. In a separate experiment at the Aarhus tandem accelerator, we scanned a needle beam of 2 MeV protons vertically and horizontally across the jet. We found the density of D atoms (as well as of D_2 molecules) integrated along the beam in the ion-extraction region to be constant within 10% such that all usable p^- sample the same integrated number of target atoms, and no correction is needed for different overlaps. This is additionally confirmed by the fact that the cross section for single ionization of D_2 from the present p^- data agrees (within the experimental error of 10–20%) with our previously measured cross section for the single ionization of H_2 [2].

From the tandem-experiment ion signal rate and the known cross section for 2 MeV p^+ ionization of D, we found the target density to correspond to a D pressure of 4×10^{-6} Torr, which is ~ 100 times less than the target densities used in our previous experiments on antiproton impact on static gases.

In Fig. 2, the present experimental data for ionization of D by p^- are compared with the data of the Belfast group [3,4] for p^+-impact ionization of H. In the latter case, the cross section is for the creation of a free electron—i.e., electron capture is excluded. As can be seen, the two cross sections agree within experimental uncertainty

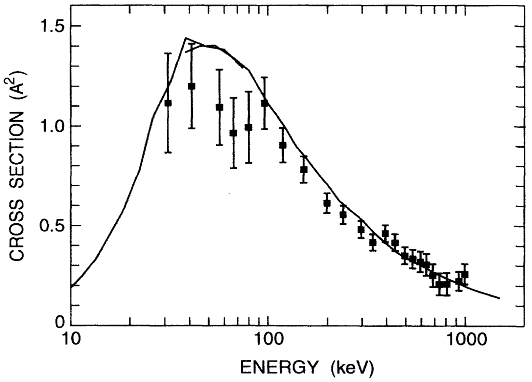

FIG. 2. The cross section for the creation of a free electron for p^+ impact on H as measured by the Belfast group [3,4] (—), and the present data for p^- impact on D (■).

for the highest energies. This is as expected from the first Born approximation, which scales as the square of the projectile charge, and which is usually assumed to be valid at asymptotically high impact velocities (however, see the discussion below). For projectile energies below ~350 keV, the p^- cross section is smaller than the p^+ cross section; the more so, the lower the projectile velocity. This is due to the polarization of the target atom during the first part of the collision. At the lowest p^- energy used here, however, there is an indication that the p^- cross section crosses the p^+ cross section. This may be attributed to the so-called binding/antibinding effect in the close collisions which dominate ionization at low velocities. Here, the presence of p^- close to the target nucleus decreases the binding of the target electron, whereas the reverse is true for p^+.

In Fig. 3 a comparison is shown between the p^+, p^- results and data for equivelocity e^+, e^- impact. It should be noted that the e^- data [5] and the e^+ data of Jones *et al.* [7] merge smoothly at high velocity with the data for heavy projectiles. (For decreasing velocity, the ratio between e^+ and p^+ cross sections and that between the e^- and p^- cross sections decrease mostly due to the limited kinetic energy carried by the light particles as compared to equivelocity heavy particles.) It is clear from Fig. 3 that the revised e^+ data of Weber *et al.* [6] do not follow this smooth trend, suggesting that they are erroneous.

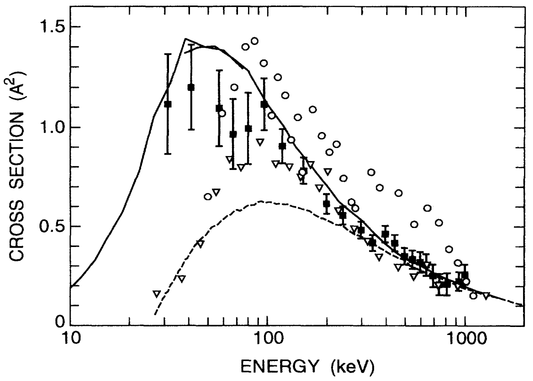

FIG. 3. The p^+ (—) and p^- (■) data of Fig. 2 are compared with corresponding measurements for equivelocity e^- (- - -) [5] and e^+ (o) [6], (▽) [7] colliding with H.

There exists an abundance of theoretical calculations of the p^+- and p^--impact ionization of atomic hydrogen. We compare our results with the most recent and advanced quantal calculations. Figure 4(a) shows a comparison between the present p^- data, the p^+ data of the Belfast group [3,4], and the continuum distorted wave–eikonal initial state (CDW-EIS) calculations of Fainstein [11]. As can be seen, the theory agrees well with the p^- data. However, there seems to be a systematic shift along the energy axis of the p^+ theoretical curve relative to the experimental data.

In Fig. 4(b), the recent two-center atomic orbital close coupling (TCAOCC) calculations of Toshima [12] are shown. To the surprise of the community, Toshima found a p^+-impact cross section which at 1.5 MeV was 1.17 times larger than the first Born result [10]. The difference was attributed to the creation of projectile continuum states which allegedly were not properly accounted for in the earlier calculations [10,11,13]. In Fig. 4(b),

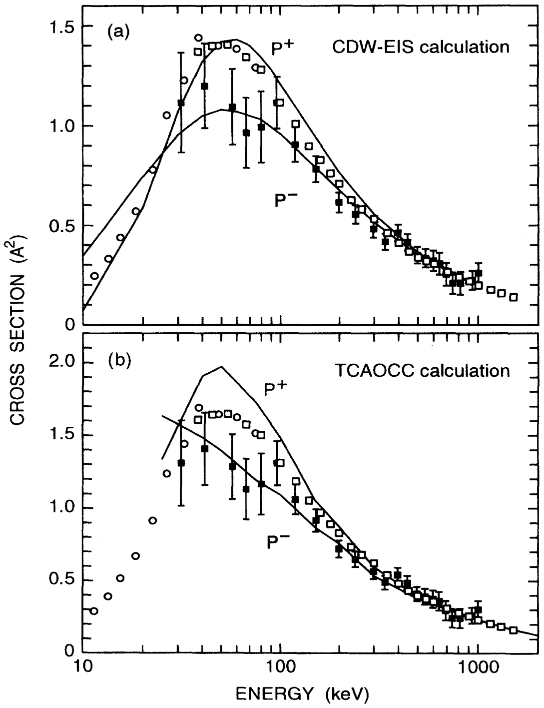

FIG. 4. Comparison among the present p^- data (■), the p^+ data of the Belfast group [3,4] (o, □), and theory (—): (a) CDW-EIS calculations of Fainstein [11]; (b) TCAOCC calculations of Toshima [12].

we show the experimental data multiplied by 1.17 and compare them with Toshima's results. There is a very good agreement between theory and experiment for the p^- case. However, the theory does not agree with the p^+ experimental data.

These disagreements between theory and experiment for p^+ impact confirm, we believe, that this case is more complicated to address theoretically, mostly due to the electron-capture channel. The agreement between theory and the experimental results in the more basic p^--impact case is encouraging.

It is interesting to note the very different trend toward lower energies of the two theoretical p^- calculations presented in Fig. 4. It would clearly be of importance to perform p^- measurements at energies below the energy values reached in this work. This seems, however, not possible with our present degrader foil scheme for reaching low p^- energies, and further technical development is needed to reach this goal.

The authors would like to thank P. D. Fainstein and E. Krishnakumar for supplying us with their as yet unpublished results. We are grateful for the enthusiastic technical support supplied by P. Aggerholm, B. Lanigan, and N. Murphy.

This project has been supported by the Danish Natural Science Research Council and the EPSRC, U.K.

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