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Angular-differential cross sections for H(2*p*) formation in intermediate-energy proton-helium collisions

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Angular-differential cross sections for charge transfer with simultaneous emission of a photon in collisions of protons with helium atoms have been measured. The incident proton energies were 25, 50, and 100 keV and the center-of-mass scattering angles were between 0 and 2.0 mrad. In the experiment, hydrogen atoms that scattered through an angle θ were detected in coincidence with photons emitted perpendicular to the scattering plane with a wavelength between 1140 and 1400 Å. Differential cross sections for capture into the $2p$ state of the hydrogen atom were determined from the variation in the coincidence signal with θ. The experimental results are compared with the results of a classical trajectory Monte Carlo (CTMC) simulation and with the results of a calculation for H($2p$) capture using the Coulomb-Brinkman-Kramers (CBK) approximation. The agreement between the experimental results and the CTMC calculation is good at all three energies while the agreement between the shape of the data and the CBK calculation is good at 50 and 100 keV.

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Electron-transfer processes in ion-atom collisions have been studied extensively over the last decades both experimentally and theoretically. In the intermediate-energy range (25 to 200 keV), there has developed a reasonably good agreement between theory and experiment for total cross sections for some collision systems. Experiments have become more sophisticated and increasingly reveal more detailed information about the collision process. There is generally poorer agreement between theory and experiment for angular-differential cross sections. Our understanding of these processes is far from being complete even for the simplest ion-atom collision systems ($H^+ + H$ or He).

Theoretical calculations for single-electron capture from multielectron atoms are difficult, in part because of the complicated models required to describe the target, and in part because the theoretical description of the collision is best accomplished by changing reference frames during the collision. The validity of the approximations used depends upon the charge and final *nl* state of the target and projectile and upon the projectile energy. Detailed experiments in which these parameters are "pinned down" are required to test the validity of the theory.

The study of single-electron capture in collisions between protons and helium has been the subject of numerous investigations, primarily because of the relative simplicity of the target, both theoretically and experimentally (see Refs. [1–3] and references therein). Only a few of these experiments, however, have investigated the angular distribution of H atoms with specific orbital angular momentum [4–6], and none of them have any overlap with the energy range (25 to 100 keV) and angular range (0 to 2 mrad) of the results reported here.

In the present experiment angular-differential cross sections for the collision process

$$H^+ + He \rightarrow H(2p,\theta) + [He^+]$$
$$\rightarrow H(1s,\theta) + [He^+] + \gamma(\text{Ly-}\alpha)$$

were measured with incident proton energies of 25, 50, and 100 keV where θ is the scattering angle. The square brackets indicate that the final state of the helium ion was not detected in the experiment. The measurements were made by time-correlating hydrogen atoms emerging from the collision region with photons emitted perpendicular to the scattering plane. These are the first state-selected measurements of angular-differential cross sections in this energy range.

The results reported here were obtained using the 200-keV variable-angle ion accelerator from the University of Missouri—Rolla ion energy-loss spectrometer (UMR-IELS). The apparatus is described elsewhere [7] and only additions which were required to perform this experiment are reported here. Protons were accelerated, collimated, and focused onto a gas cell. Hydrogen atoms resulting from electron capture were separated from scattered ions by a magnet located after the collision region. A focused mesh electron multiplier positioned approximately 1 m beyond the magnet was used to detect the fast neutrals. Crossed horizontal and vertical slits placed between the magnet and the detector defined the solid angle subtended by the neutral detector; these slits were 100 μm wide and were located 168 cm after the scattering center. Signals from the neutral detector were connected to the stop input of a time-to-digital converter (TDC).

Photons emitted perpendicular to the plane of the scattering were detected by a continuous dynode electron multiplier (CDEM). The multiplier was separated from the interaction region by a 1-mm-thick, 1-cm-diam magnesium fluoride window. A grounded fine wire mesh was placed over the window to prevent its surface from accumulating charge. The 1140-Å cutoff of the magnesium fluoride window ensured that photons from higher-energy transitions were not detected. The low-energy cutoff of the detector response at about 9 eV ensured limited response to photons with wavelengths longer than 1400 Å. The detector signal was connected to the start input of the TDC via a constant-fraction timing discriminator.

It was impossible to exclude radiation from $He^+(n=4 \rightarrow n=2)$ transitions, which occur at 1215.1 Å, from being detected by the CDEM. This radiation arises from the possible excitation of the target ion with simultaneous capture or ionization. Since emission cross sections for $He^+(n=4 \rightarrow n=2)$ transitions have not been measured, estimates of this transition rate were made using measured total emission cross sections for $He^+(n=4 \rightarrow n=3)$ to infer the population of the $n=4$ level [8,9]. This contribution is estimated to be less than 10% at all three energies [10]. Since our results are not absolute, the effect of this contribution is reduced still further, with the caveat that the angular dependence of the $He^+(n=4 \rightarrow n=2)$ differential emission cross sections are not drastically different from the shape of the H($2p$) differential cross sections.

Similarly, cascade contributions are small and have little effect on the results. An estimate of the first-order cascade contribution to the Lyman-α emission rate was made using H($3s$) and H($3d$) capture cross sections from Hughes *et al.* [11]. At all energies, this contribution is estimated to be less than 1% of the total signal [10].

Angular profiles of the incident beam with no gas in the target chamber were collected prior to and after a coincidence spectrum was acquired. This data was necessary to account for the effect of the apparatus geometry on the observed angular distribution of the coincidence signal. Angular profiles of the scattered neutral beam with gas in the chamber were also collected to check for consistency with the data previously reported by Martin *et al.* [12].

A representative time-interval histogram is shown in Fig. 1. This spectrum was acquired at zero scattering angle with 50-keV protons. The peak, which has a full width at half maximum value of about 8 nsec, arises from time-correlated photon–hydrogen-atom pairs. The location of the peak at channel 272 (corresponding to 0.680 μsec) is essentially determined by the flight time of the hydrogen atom between the scattering region and the neutral detector. The background is due to random uncorrelated photon-hydrogen atom pairs.

The general theory of photon-particle coincidences has been given by Macek and Jaecks [13]. McKnight and Jaecks [4] have given the general expression for the coincidence rate for Lyman-α photons and hydrogen atoms emerging in arbitrary directions. For a photon detector perpendicular to the scattering plane the coincidence count rate is proportional to the total H($2p$) differential cross section given by

$$\frac{d\sigma(2p)}{d\Omega}=\frac{d\sigma_0}{d\Omega}+2\frac{d\sigma_1}{d\Omega}\,, \tag{1}$$

where $d\sigma_0/d\Omega$ and $d\sigma_1/d\Omega$ are angular-differential cross sections for electron capture into the magnetic substates with $m_L=0$ and $m_L=1$, respectively. An integration of the general expression over the finite detector geometries yields a coincidence count rate which is given by

$$\dot{N}_c(2p,\theta)\propto A\frac{d\sigma_0}{d\Omega}+2B\frac{d\sigma_1}{d\Omega}\,. \tag{2}$$

For our experimental setup, A was 0.98 at all scattering angles and B was within 10% of unity except within 0.2 mrad of forward scattering [10]. Using the data of Hippler *et al.* [8] the ratio of the total cross sections, σ_0/σ_I, is estimated to be 2.8 in our energy range. If the

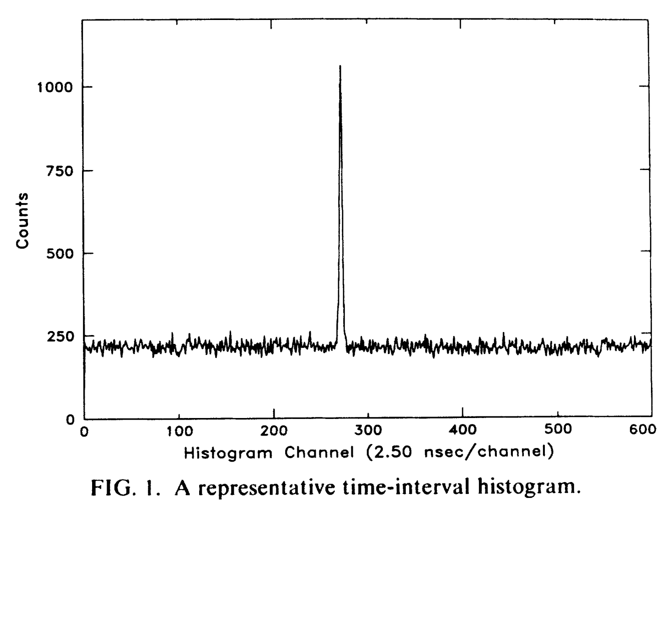

FIG. 1. A representative time-interval histogram.

same ratio is assumed to be the case for the differential cross sections, the correction for $d\sigma/d\Omega$ is estimated to range from 4% at 0.2 mrad to less than 0.05% at 2 mrad. Thus $\dot{N}_c$ is essentially proportional to the total H(2p) differential cross section except at the smallest scattering angles. However, no corrections have been made to the results presented here because the functional relationship between $d\sigma_0/d\Omega$ and $d\sigma_1/d\Omega$ is not known.

Each histogram was corrected for dead time [10] and the background was subtracted from the peak in the corrected spectrum to determine the total number of correlated events recorded during the acquisition time T. The number of counts "under the peak" was then normalized to the total number of photons detected during T. Relative differential cross sections were extracted from an angular sequence of normalized coincidence counts using angular deconvolution techniques described by Park *et al.* [14]. Differential cross sections obtained in this way were integrated to determine a relative total cross section which was normalized to known measured total cross sections for H(2p) capture [15]. The total cross sections given in Ref. [15] are an average of results from many different investigators. The results are quoted as having an accuracy of 30%. More recently Hippler *et al.* [16] have published total cross sections which are about 50% higher than the results given in Ref. [15] for 25- and 50-keV protons. The results of Ref. [15] were used because they encompass data from many different investigators.

The experimental results for H(2p) capture in the center-of-mass frame are presented in Fig. 2. The error in the data is derived from the combined error associated with determining the mean value of several measurements at the same angle and the error associated with separating the background component of the coincidence histogram from the peak [10]. Martin *et al.* [12] have measured electron capture to all states of hydrogen, H(Σ), as a function of H scattering angle. The variation of the differential cross section for H(2p) capture with scattering angle differs from the angular dependence of the H(Σ) capture cross sections at all three energies. This is not surprising since the H(Σ) cross sections are dominated by capture into the H(1s) state. At 25 keV, the structure evident in the H(Σ) differential cross sections is not observed in the H(2p) measurements. At zero angle the ratio of the H(Σ) angular cross section to the H(2p) cross section is nearly 200, but at a center-of-mass angle of 2 mrad this ratio drops to about 10. In general, the H(2p) cross sections are much flatter and do not exhibit the dramatic change in slope that the H(Σ) cross sections have at 0.8 mrad. At 50 keV, the H(2p) cross sections fall by about one order of magnitude over the first milliradian, while the H(Σ) cross sections drop by nearly 3 orders of magnitude over the same range. The H(Σ) cross sections again have a marked change in slope at about 1 mrad whereas the H(2p) cross sections do not. At 100 keV, the angular shapes of the H(Σ) and H(2p) differential cross sections are considerably more similar.

To our knowledge, no calculations of angular-differential cross sections have been reported for H(2p) capture in proton-helium collisions in the energy range between 25 and 100 keV. Burgdörfer [17] has reported analytical

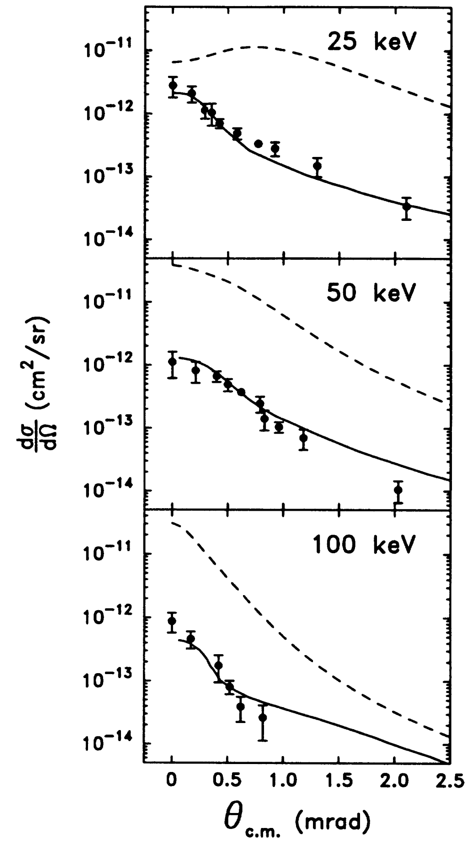

FIG. 2. Differential cross sections for electron capture to H(2p) in the center-of-mass frame for proton-helium atom collisions for the proton laboratory energies of 25, 50, and 100 keV. The solid circles are the present experimental results. The CTMC results (solid lines) and the CBK results (dashed lines) are also shown.

capture amplitudes as a function of impact parameter for charge transfer from a hydrogenic ground state (1s) into an arbitrary final (nlm) state of hydrogen within the Coulomb-Brinkman-Kramers (CBK) approximation. We have used his results for the capture amplitudes to calculate angular-differential cross sections for the proton-helium collision system. In our calculations we have used the experimental value for the ionization energy of helium, 24.6 eV, instead of the value one would obtain by using the variational results for the energy of one electron. The value used for the ionization energy of helium has more effect on the magnitude than on the shape of the differential cross section.

Another method, which has proven to be extremely useful in predicting and analyzing ionization and capture processes in ion-atom collisions, is the classical trajectory Monte Carlo (CTMC) technique, which has been described fully by Abrines and Percival [18], Bonsen and Banks [19], Olson and Salop [20], and others. In addition to the cross sections presented here for capture to the 2p state in p+He collisions, a companion study [21] has recently reported CTMC summed and state-selective (Σ,2s,2p,3s,3p,4s) total and differential cross sections along with a detailed description of the method and comparison with experiment.

The results of the CBK and CTMC calculations are shown for comparison. As expected, the CBK calculation grossly overestimates the total cross sections (and therefore the magnitude of the differential cross sections), but the agreement in the curve shape at 50 and 100 keV is excellent. At 25 keV, the angular variation of the H(2p) data is not reproduced by the CBK calculation. This is not surprising since the CBK is a high-energy approximation.

The CTMC results compare well with the experimental results at all energies. The agreement at 25 keV is very good. At 50 keV the agreement is excellent except at the largest scattering angles where the CTMC results are higher. At 100 keV the CTMC results are in fairly good agreement with the experimental results except at the largest scattering angles where again the CTMC results are higher.

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