Double ionization of helium by He^{+} projectiles

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The ratio of the cross section for double ionization to the cross section for single ionization of helium produced by 25- to 625-keV/amu He^{+} projectiles has been measured. The results reported here are consistently higher than the values reported by Dubois *et al.* Above 400 keV/amu, where charge capture is small, the ratios are about the same as those reported for He^{2+} projectiles.

I. INTRODUCTION

The double ionization of helium has been studied to determine the importance of electron-electron correlation in ion-atom collisions.[1,2] In the limit of high projectile velocities a single electron is removed from the target by the projectile and the other relaxes to the continuum through the shake-off process. The relaxation process is strongly dependent on the electron-electron correlation in both the initial[3] and final states[1] of the target atom. Assuming a shake-off process dominates the interaction, one should be able to express the double ionization cross section as a constant times the single ionization cross section. This expectation has lead to the standard practice of measuring the ratio R of double to single ionization cross sections and observing the dependence of the ratio on projectile velocity.

At lower projectile velocities the interaction between the projectile and the target electrons becomes stronger and double ionization occurs through a double collision mechanism where the projectile interacts directly with each target electron. This double collision process has a different dependence on projectile velocity than does the shake-off process.[4] At still lower velocities charge capture by the projectile plays an important role in the double ionization of helium.[2] In the case of the double ionization of some other rare gases, it can be the dominant process.[5]

Several investigators[1,2,6–8] have measured the ratio R of double- to single-ionization cross sections using the bare projectiles H^{+}, He^{2+}, and Li^{3+}, and the projectile He^{+}. The results of these measurements have been in general agreement except for those of Dubois *et al.*[8] who measured R for H^{+} and He^{+} projectiles. Their results for H^{+} on He were lower than those of the other investigators, but there were no other He^{+} results with which to compare. We have measured R for 25- to 625-keV/amu He^{+} projectiles in order to check their He^{+} on He results and also to provide a comparison of R for He^{2+} projectiles to that for He^{+} projectiles.

II. EXPERIMENTAL PROCEDURE

Figure 1 is a schematic of the collision region. A pulsed beam (31 kHz) of He^{+} projectiles passes midway between two parallel plates and is collected in a Faraday cup. A timing signal signifying the arrival of a beam pulse is produced by a capacitive beam pick-off (BPO) unit. The back plate of the parallel-plate arrangement is biased at $+20$ V while the front plate is grounded. The ions repelled from the collision region pass through a small aperture in the front plate, and are then focused into a hemispherical analyzer set to pass positive ions of 10 eV/q. The ions are detected with a channel electron multiplier with its front end biased at 4500 V. The times of flight of the ions from the collision region to the detector are recorded.

The thermal motion of the target gas coupled with the small electric field (10.5 V/cm) used to extract the target ions means that the He^{2+} ions are more likely to pass through the small front plate aperture than are the He^{+} ions. A correction factor to the ratio R can be estimated by considering the source of the target ions to be a point source centered over the exit aperture with an initial Maxwell-Boltzmann velocity distribution. These assumptions lead to a correction factor of 1.34 that should be divided into the measured R. Since the incident beam produces a line source rather than a point source, however, a correction factor was measured and then compared to the simple calculation. R was measured at several beam energies for D^{+} on He collisions and compared to equal velocity H^{+} on He measurements of Shah and Gilbody.[2] (D^{+} was selected for our measurements rather than H^{+} in order to minimize the $m/q=2$ background signal from the

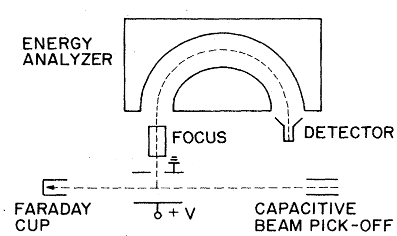

FIG. 1. Schematic of the experimental apparatus. The pulsed ion beam passes midway between the parallel plates. The target ions are accelerated at low energy toward a hemispherical analyzer and detector. Their time-of-flight is recorded.

ion source gas.) The comparison yielded a correction factor of 1.42 that had to be divided into our measured values of R. It was assumed that this correction was independent of the projectile and the same value was used for the He^{+} projectiles.

Pulses produced by the detector were sent to a time-to-amplitude converter (TAC) as START pulses. The BPO signals were used as the STOP pulses. The output of the TAC was collected in a multichannel analyzer and its contents were displayed in order to see the various mass (m/q) peaks. The total number of counts in the peaks of interest were determined, background was subtracted, and corrected ratios were calculated.

III. RESULTS

The velocity dependence of the ratio of double to single ionization cross section for He^{+} on He collisions is shown in Fig. 2. Also shown are the results of Dubois *et al.*[8] and of two other groups of experimenters for He^{2+} on He collisions.[1,2] The results of Dubois *et al.*[8] are lower in magnitude than ours, but both data sets peak near the same beam velocity.

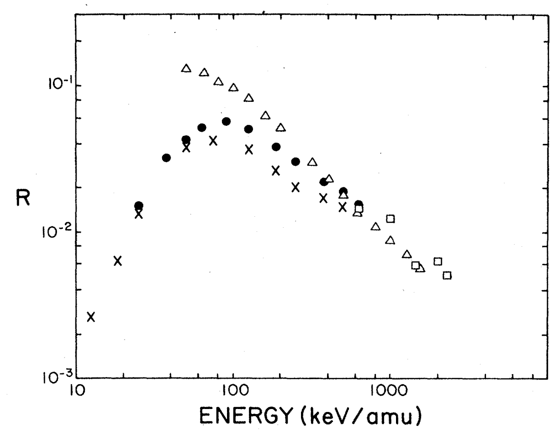

FIG. 2. Ratio of doubly- to singly-charged helium ions produced by He^{+} and He^{2+} projectiles on a helium target. He^{+} projectiles: ● shows present results, × shows results of Dubois *et al.* (Ref. 8); He^{2+} projectiles: △ shows results of Shah and Gilbody (Ref. 2), □ shows results of Knudsen *et al.* (Ref. 1).

Shah and Gilbody[2] measured the cross sections for direct ionization, both double and single, and for ionization plus charge capture. These have been combined and plotted in Fig. 2 in order to compare our values of R for He^{+} projectiles to their values of R for He^{2+} projectiles with charge capture included. As seen in Fig. 2 the values of R are comparable for the higher energies where the charge capture cross section is small. The measurements of Shah and Gilbody[2] show that the process of charge capture plays an important role in ionization at projectile energies below about 400 keV/amu. Our measurements do not monitor the charge state of the projectile after the collision, and therefore charge capture contributions are not excluded in our measurements.

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