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Further studies of double ionization of He, Ne, and Ar by fast and slow antiprotons

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Measurements of the ratio R between double- and single-ionization cross sections for antiproton impact on He, Ne, and Ar targets are reported for impact energies ranging from 65 keV to 20 MeV. At high energies the results are found to merge with proton results at around 20 MeV, and the high-energy limit of the common ratio is in good agreement with recent first-Born-calculation results for the helium target. The large difference previously observed in the ratio R for protons and antiprotons at energies between 0.5 and 5 MeV is found to persist down to the lowest energies investigated here.

I. INTRODUCTION

In recent years, high-quality, low-energy beams of the antiparticles e^+ and $\bar{p}$ have become available. This situation makes attractive atomic collision experiments that compare the effect of projectiles having the same mass but opposite charge.

Our first experiments with antiprotons from the low-energy antiproton ring LEAR at CERN were primarily aimed at the study of double ionization of He, but other gases (Ne and Ar) were investigated as well.[1,2] It was demonstrated that the already known difference in double ionization of He by electrons as compared to protons is a charge effect rather than a mass effect. This finding initiated a theoretical activity which has not yet ceased,[3–10] and experimentally the finding was recently[11] confirmed by measurements of the double ionization of He by fast equivelocity electrons and positrons. The comparison of ionization by protons and antiprotons was done via measurements of the ratio $R=\sigma^{++}/\sigma^{+}$ where σ^{++} and σ^{+} are the double- and single-ionization cross sections, respectively.

The R values obtained with antiprotons were much larger (a factor of 2) than those obtained with equivelocity protons in the energy interval between 0.5 and 5 MeV. This difference was discussed[2] in terms of interference between two collision mechanisms which both result in double ionization. This interference effect is now understood, at least qualitatively, in a narrow energy interval, but as discussed later, much theoretical effort is devoted to extensions of this energy interval, and by doing so, other effects are also included.

Thus, further measurements of R both at lower and at higher energies were well motivated. In the work presented here, we have investigated the ratio R for antiprotons impinging on He, Ne, and Ar in the energy interval from 65 keV to 20 MeV.

II. EXPERIMENT

Antiproton beams were extracted from LEAR through a 100-μm Be window. The two energies of the antiprotons after the Be foil were $\sim$5 and $\sim$20 MeV, respectively. Lower-energy beams were obtained by inserting aluminum degrader foils in front of the mylar entrance window to the vacuum chamber.

The experimental arrangement was very similar to the one described in Ref. 2. The energy of each antiproton in the beam was determined by measuring the time-of-flight (TOF) of the particles in the beam between a 100-μm-thick "start" scintillator and a 1-mm-thick "stop" scintillator $\sim$50 cm downstream. The time resolution obtained was 2.4 ns (full width at half maximum), corresponding to an energy resolution of 1.2 keV at 50 keV and 300 keV at 2 MeV. A typical TOF spectrum for the lowest energies used in this experiment is shown in Fig. 1. The broad velocity distribution is obtained from a 5-MeV antiproton beam and a degrader of $\sim$100-μm aluminum, as well as the 100-μm start scintillator itself.

The calibration of these TOF spectra was performed in two ways: (1) with light emitting diodes placed near the scintillators, allowing us to obtain beam-independent "time-zero" information as well as a channel-to-nanosecond calibration, and (2) by recording TOF spectra for two positions of the stop scintillator, 500 mm apart, for several of the high antiproton energies. Together with the calibration of the electronics, this allows us to deduce the mean energy of the degraded antiproton beam, and hence the "time-zero" knowing the distance between the start and stop scintillators. These two methods gave consistent values of the "time-zero." In

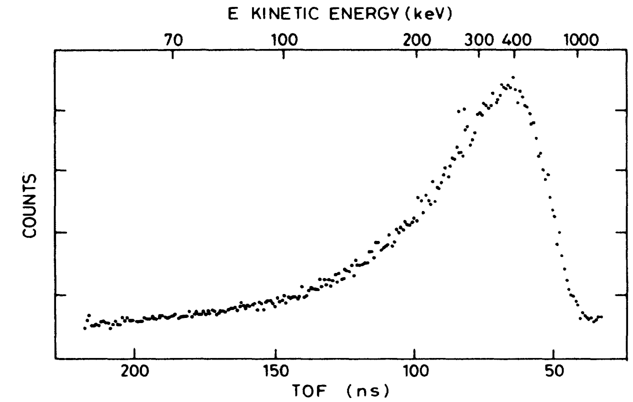

FIG. 1. TOF Spectrum for 5.9-MeV $\bar{p}$ after passage of a 99.2-μm aluminum degrader foil.

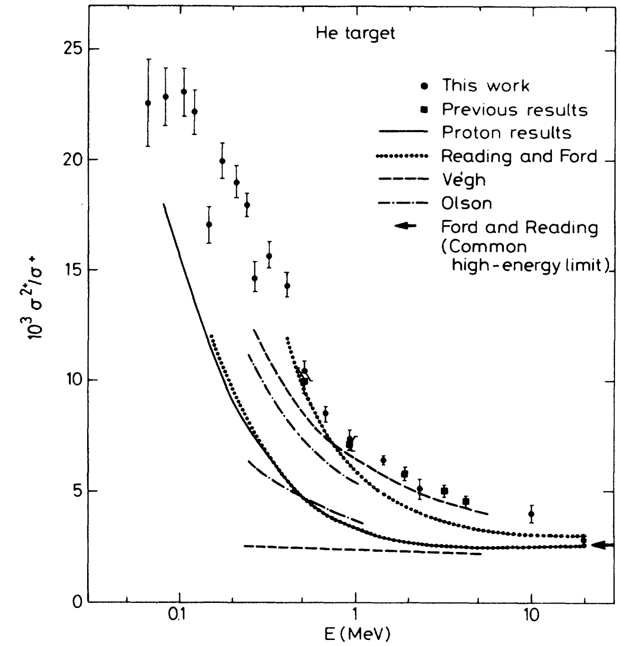

FIG. 2. The experimental ratio $R=\sigma^{2+}/\sigma^{+}$ in a He target as a function of energy for antiprotons [filled squares (Ref. 2) and points] and for protons [solid line (Ref. 2)]. Theoretical estimates are drawn for comparison. Upper curves relate to antiprotons and lower curves to protons.

this way the absolute velocity, and hence the kinetic energy, of the antiprotons could be accurately determined.

The ions (e.g., He^{+} and He^{2+}) produced in a low-pressure (a few mTorr) gas cell were accelerated towards a channeltron and identified through their TOF with respect to an antiproton signal in the scintillators (for details, see Ref. 2). For each ion detected, both the ion TOF and the corresponding antiproton TOF were recorded event by event. This enabled us to evaluate the ratio R of double-to-single ionization associated with "slices" in the antiproton TOF spectrum (Fig. 1), corresponding to different impact energies. Thus, data were obtained down to antiproton energies of 65 keV. The gas cell was closed at the exit with a 0.2-μm aluminum foil. The lowest antiproton energies were corrected for the energy loss in this foil.

The 10-MeV (degraded 20-MeV antiprotons) and 20-MeV experiments were performed in the more conventional technique with an ion-antiproton TOF spectrum recorded by a multichannel analyzer.

III. RESULTS ON He

The measured ratio $R=\sigma^{2+}/\sigma^{+}$ for antiprotons on He is presented as a function of impact energy in Fig. 2. Also shown are experimental proton data as a curve fitted to the results listed in Ref. 2 and various theoretical estimates for both protons and antiprotons.

The present measurements confirm our previous results and extend the data both towards lower and higher energies. In the high-energy region, an expected common high-energy limit is found at energies $\sim$20 MeV. At low energies, the large differences between $\bar{p}$ and p data persists. It should be noted that at low energies, R does not relate directly to a difference in double ionization since also single ionization and charge transfer depend on the projectile charge, as discussed by, e.g., Fainstein *et al.*[3] However, R is easier to obtain experimentally, even under more difficult experimental conditions, and this observable now has its own integrity in so far that theorists also report on calculations of R at low energies.

Since our first results were published, a number of theoretical interpretations of R for He target atoms have appeared. In short, Reading and Ford[4,5] applied the so-called forced-impulse method, where a series of time-frozen amplitudes, which include electron correlation, are connected by time evolution operators. Their results, normalized to high-energy proton data, are shown in Fig. 2. It should be noted that only 50% of the measured effect has been accounted for at the higher energies. The authors argued that this lack of agreement is probably caused by the neglection of higher-order partial waves in their calculations.

In a recent article, Ford and Reading[6] calculated the high-energy value of R applying the first Born approximation, but now also including d waves in their expansion. Their result is shown in Fig. 2, and very good agreement with the experimental common high-energy value of R is found.

McGuire[7] was the first who suggested that the observed effect is caused by interference between two different double-ionization mechanisms. This idea was further developed by Sørensen[2] who argued that the observed difference of R for protons and antiprotons could be explained as an interference effect involving two different types of two-step processes.

Our new data on He at low energies are of special interest in connection with the theoretical estimates of Olson[9] and Végh.[10] Classical-trajectory Monte-Carlo calculations by Olson at energies between 250 keV and 1 MeV predict a $\bar{p}/p$ difference in R being mostly due to a difference in double ionization but, especially at the lower energies, also partly to a difference in single ionization

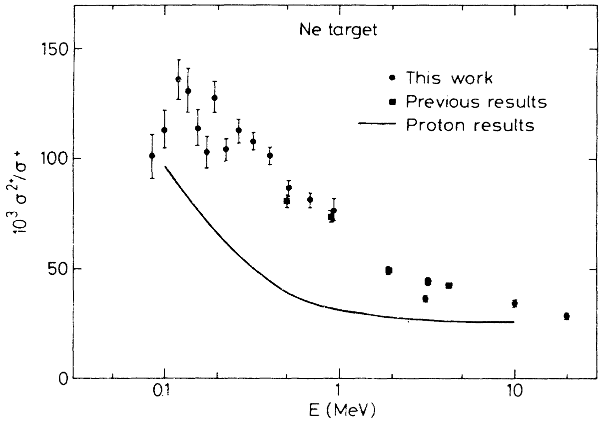

FIG. 3. The experimental ratio $R=\sigma^{2+}/\sigma^{+}$ in a Ne target as a function of energy for antiprotons [solid squares (Ref. 2) and points] and for protons [solid line (Ref. 2)].

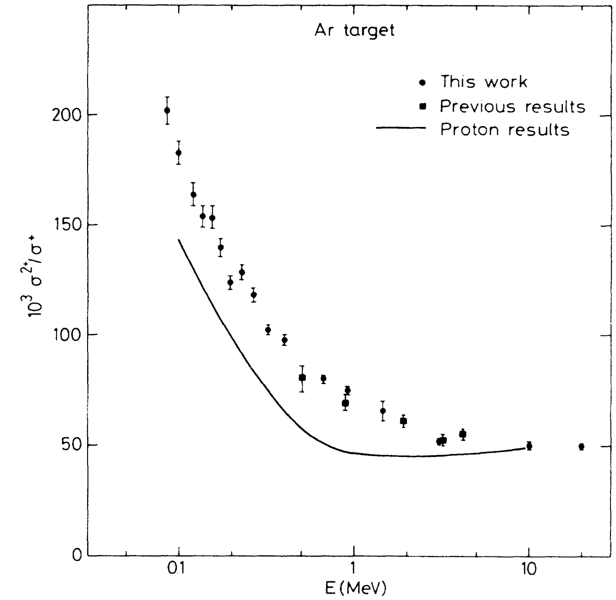

FIG. 4. The experimental ratio $R=\sigma^{2+}/\sigma^{+}$ in an Ar target as a function of energy for antiprotons [solid squares (Ref. 2) and points] and for protons [solid line (Ref. 2)].

and charge transfer. As can be observed from Fig. 2, these calculations are only in fair agreement with our medium-energy results. The model proposed by Végh[10] explains the observed $\bar{p}/p$ differences as a result of correlated motion of the target electrons during the collision. In Ref. 2 it was argued that the collision time needed for such effects to be important was so long that this mechanism is important only at very low energies. Végh's theoretical curves are shown in Fig. 2. It should be mentioned that these R curves are obtained by dividing Végh's double-ionization cross sections by experimental single-ionization cross-section values for protons. Also these estimates are only in fair agreement with our latest experimental results at the lowest energies, but $\bar{p}/p$ differences in single-ionization cross section could hamper such a comparison.

IV. RESULTS ON Ne AND Ar

The experimental R values for Ne and Ar are presented in Figs. 3 and 4. Also here, good agreement with previous results is found, and common high-energy limits for R are established. It was argued in Ref. 2 that single and double ionization in Ne are dominated by processes taking place in the outer (L) electronic shell and thus being similar to the ionization processes for the He target. The large difference between the proton and the antiproton results continues down to the lowest projectile energies although the two points at the lowest energies could indicate a reduction in the R values for antiprotons. A maximum in R for protons at around 80 keV for a He target and around 100 keV for a Ne target can be obtained from the work of DuBois and Manson.[12] A more detailed discussion of the low-energy behavior, however, must await more precise measurements.

In Ar it was found[2] that double ionization at MeV energies is partly an outer-shell effect and partly a result of inner-shell ionization followed by autoionization. It was also argued that for protons the relative importance of inner-shell ionization decreased with decreasing energy below ~ 1 MeV. The fact that the $\bar{p}/p$ difference in Ar seems to be more persistent at the lowest energies compared to He and Ne targets could indicate that also for antiprotons inner-shell ionization becomes less important at energies below ~ 1 MeV.

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