

## Ionization of Helium and Argon by Very Slow Antiproton Impact

H. Knudsen,<sup>1</sup> H.-P. E. Kristiansen,<sup>1</sup> H. D. Thomsen,<sup>1</sup> U. I. Uggerhøj,<sup>1</sup> T. Ichioka,<sup>1,\*</sup> S. P. Møller,<sup>2</sup> C. A. Hunniford,<sup>3</sup>  
R. W. McCullough,<sup>3</sup> M. Charlton,<sup>4</sup> N. Kuroda,<sup>5</sup> Y. Nagata,<sup>5</sup> H. A. Torii,<sup>5</sup> Y. Yamazaki,<sup>5,6</sup> H. Imao,<sup>6</sup>  
H. H. Andersen,<sup>7</sup> and K. Tökési<sup>8</sup>

<sup>1</sup>*Department of Physics and Astronomy, University of Aarhus, Denmark*

<sup>2</sup>*Institute for Storage Ring Facilities, University of Aarhus, Denmark*

<sup>3</sup>*Department of Physics, Queens University Belfast, United Kingdom*

<sup>4</sup>*Department of Physics, University of Swansea, United Kingdom*

<sup>5</sup>*Institute of Physics, Komaba, University of Tokyo, Japan*

<sup>6</sup>*Atomic Physics Laboratory, RIKEN, (Saitama) Japan*

<sup>7</sup>*Niels Bohr Institute, University of Copenhagen, Denmark*

<sup>8</sup>*ATOMKI, Debrecen, Hungary*

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The total cross sections for single ionization of helium and single and double ionization of argon by antiproton impact have been measured in the kinetic energy range from 3 to 25 keV using a new technique for the creation of intense slow antiproton beams. The new data provide benchmark results for the development of advanced descriptions of atomic collisions and we show that they can be used to judge, for the first time, the validity of the many recent theories.

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In the beginning of the last century, with the invention of quantum mechanics, it became possible to describe the structure of the simplest atoms hydrogen and helium. It was, however, difficult to calculate accurate results for the states of helium because of the electron-electron correlation in that atom. Since then, it has become possible to perform calculations on many atoms to a high degree of accuracy.

It has proven to be a much more difficult task to perform similar calculations on atomic systems which are not static but dynamic, such as atomic collisions. Again one of the difficulties lies in the electron correlation inherent to many of these collisions. At an early stage it was clear that benchmark experimental data for the simplest atomic collisions were needed to compare with calculations. We realized that one of the simplest and basic of such systems is the ionization of helium by antiprotons, since there is no complication from charge transfer due to the negative charge of the antiproton and also because the projectile is heavy, allowing a semi-classical theoretical approach. The large mass of this projectile also allows the investigation of “slow” ionizing collisions, a feat which is not possible with electron impact.

At the LEAR facility at CERN single and double ionization cross sections for antiprotons colliding with helium were measured from MeV energies down to 13 keV [1,2]. These data led to much theoretical activity that resulted in the development of advanced models which will be discussed below. However, almost all of these calculations coalesce at projectile energies above 100 keV, where the projectile acts as a perturbation. To discriminate between these theories, it is necessary to measure at considerably lower energies.

Using the AD facility at CERN together with a much more advanced technique for the creation of an intense beam of very slow antiprotons, we have succeeded in measuring the single ionization cross section of helium down to an impact energy of 3 keV—a factor of 4 improvement. We also obtained similar data on single and double ionization of argon. With these new data it is possible to judge for the first time the validity of the models for atomic collisions.

In our experiment, the antiprotons slowed down to 5.3 MeV by the CERN AD were further decelerated to 115 keV by a radio frequency quadrupole decelerator and then injected into a 2.5 T superconducting solenoid via a thin degrader foil to reduce their kinetic energy to around 10 keV. The antiprotons were accumulated in a multiring trap (MRT) housed in the solenoid [3]. The MRT consists of 14 ring electrodes with one of them near the center azimuthally segmented into four parts so that a rotating electric field can be applied. Charged particles stored in the MRT can be compressed or expanded with the rotating field [4]. In the first step, a cloud of preloaded electrons was expanded radially to let the cloud size be comparable to that of the incoming antiprotons. The antiprotons were then injected, captured, and cooled to sub-eV energies through collisions with the electrons. After cooling, the electrons were ejected, and the pure antiproton cloud was compressed [5]. The antiprotons were then extracted as a 250 eV dc beam by slowly ramping up the trapping potential and transported to a magnetic-field-free region through  $x$  and  $y$  deflectors and electrostatic lenses with three differential pumping stages separated by apertures [6]. The number of antiprotons transported to the end of the differentially pumped beam line was typically  $6\text{--}7 \times 10^5$  per AD shot.

In the apparatus sketched in Fig. 1, the antiprotons were focused and then accelerated to an energy between 3 and 25 keV. Subsequently they entered the collision chamber. The right-hand side of the apparatus was maintained at the required high voltage for the acceleration. The antiprotons were focused and steered into an interaction region where they passed through a gas jet consisting of 90% helium and 10% argon. Subsequently the antiprotons were detected by a 4 cm diameter microchannel plate detector (MCP) which supplied a timing signal and also an image of the antiproton beam shape on a phosphor screen. The ions created in the interaction region were extracted by a  $333 \text{ V cm}^{-1}$  electric field perpendicular to the antiproton beam and the gas jet and focused spatially and temporally onto another MCP detector, which gave a timing signal and information on the position of the impacting ions. The time difference between the detection of an antiproton and an ion created by it was recorded as a time-of-flight spectrum (TOF). The spectra show clear peaks at the expected positions for  $\text{He}^+$ ,  $\text{Ar}^{++}$ , and  $\text{Ar}^+$ , and show no other features except for a low and almost flat background of accidental coincidences.

The cross sections,  $\sigma$  were found from  $N_{\text{ion}} = N_{\text{antiproton}} \sigma n l \varepsilon_{\text{ion}}$ . Here  $N_{\text{ion}}$  is the registered number of ions of the species of interest,  $N_{\text{antiproton}}$  is the number of registered antiprotons (the efficiency of the antiproton detector is one),  $nl$  is the integral of the gas density along the projectile path, and  $\varepsilon_{\text{ion}}$  is the efficiency for detecting the created ions. To find the product of the last two factors, an electron gun was inserted in place of the last Einzel lens. An ion TOF spectrum was measured using a 3 keV pulsed electron beam while accumulating the electron beam charge in a Faraday cup which replaced the antiproton detector in these measurements. From the known cross sections for ionization by 3 keV electrons, we then obtain the product  $n l \varepsilon_{\text{ion}}$ . For the normalization we used the absolute electron impact single ionization cross section of helium measured by Shah *et al.* [7] and the single and double ionization cross sections of argon of McCallion *et al.* [8]. This choice of normalization cross sections is not obvious, since Laricchia *et al.* [9] recently recom-

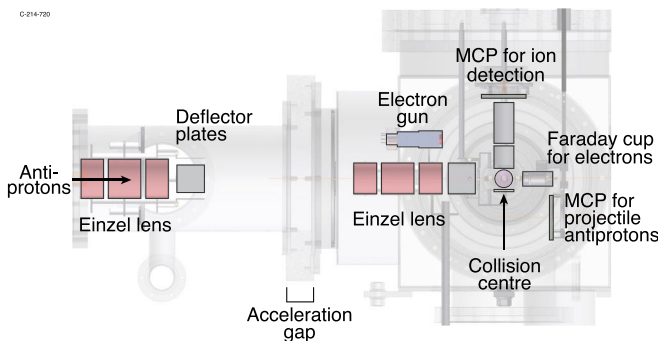


FIG. 1 (color online). Diagram of the experimental arrangement.

mended applying the electron data by Sorokin *et al.* [10]. This would lead to a renormalization of all our antiproton data by factors of 0.94 and 0.90 for helium and argon, respectively. We have chosen the data by Shah *et al.* for normalization to obtain internal consistency with the proton data by the same group, with which we compare our results below.

The electron beam was used also for an investigation of the density profile of the target gas. The beam was swept in two dimensions over the target region and two dimensional density profiles were extracted from the resulting ion TOF spectra. The result is that the gas density under the extraction aperture is constant within 20%, and in the region of  $2 \times 10^{12} \text{ cm}^{-3}$ .

The present experimental data for the single ionization cross section of antiprotons colliding with helium atoms are shown in Fig. 2. The error bars indicate the total experimental uncertainty, excluding the systematic error stemming from the normalization. The results are compared with the data obtained at LEAR [1,2] as well as with similar data for proton impact on helium obtained by Shah *et al.* [11,12], including and excluding electron transfer. The present data agree well with the earlier data where they overlap except for the two lowest energy points of Hvelplund *et al.* [2]. Clearly these two points indicate a lower cross section. This may be due to a possible underestimation of the background in the TOF spectrum from which the number of antiprotons in each energy bin was determined in that work, which would lead to lower cross sections at the lowest antiproton energies. (At higher energies, this effect would be negligible because here the “foil degradation technique” is not at its limit.) Figure 2 also shows the lower energy limit for total acceptance of the system for ions created in the interaction region. The

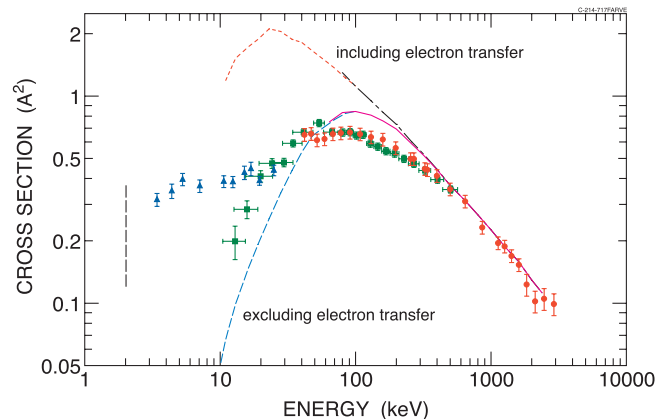


FIG. 2 (color online). The cross section for single ionization of helium is shown in this figure. The present data ( $\blacktriangle$ ) are compared with the antiproton data by ( $\bullet$ ) Andersen *et al.* [1] and ( $\blacksquare$ ) Hvelplund *et al.* [2]. Also shown are proton data by the Belfast group [11,12] as curves. The vertical line indicates the limit for total ion and projectile collection of our apparatus. The energy error bars of the present data are negligible.

acceptance is limited by the recoil energy given to the ions formed and by the corresponding angular deflection of the projectiles, both of which become more significant as the projectile energy is lowered.

In Fig. 3 we compare the present data for helium single ionization with our data obtained at LEAR and with theoretical results. Since the publication of our first data for ionization by antiprotons a large number of theoretical calculations of the process have been published. Some of these did not present data for the single ionization cross section. This is the case for the two step model by Janev *et al.* [13], the atomic orbital close coupling theory by Schiwietz [14] and the semiclassical molecular state expansion method by Kimura *et al.* [15]. Other theoretical results deviate grossly from the present results, such as the classical trajectory Monte Carlo calculations by Schultz [16], the continuum distorted wave eikonal initial state results by Fainstein *et al.* [17] and the two center plane wave born approximation calculations of Das and Malik [18], and are not shown in the figure.

A decade ago, Reading and his group developed the independent event method (IEV) and the independent particle method (IPM) based partly on ideas by Janev [13]. These two calculations [19] give results which, like the rest of the theoretical results to be discussed in this Letter agree with the experimental data above the maximum in the ionization cross section. However, the IEV and the IPM results are too large below the maximum and they decrease too slowly with decreasing projectile energy. A better theory, which in principle is able to take electron correlation fully into account, is the multicut forced impulse method which was also developed by Reading's group [20]. Here the projectile orbit is "cut" into several segments, where the collision propagates within the

independent-electron model (close coupling calculation). At each cut, the resulting wave function is collapsed onto the set of fully correlated He states. The theory includes  $e-e$  correlation, the better the more cuts. The results are in good agreement with all experimental data above 10 keV, but seem to fall too rapidly below this energy.

Following this progress, Bent *et al.* [21] developed the multielectron hidden crossing theory, which uses the adiabatic electron Hamiltonian but with the internuclear distance extended into the complex plane. The Hamiltonian is of Hartree-Fock type with configuration interaction, and sequential double ionization is assumed. The resulting single ionization cross section is some 30% too low.

A model which has been widely adapted during the last years is the multielectron close coupling atomic orbital theory in which the time-dependent two-electron wave function is expanded in terms of eigenstates of helium. Lee *et al.* [22], Igarashi *et al.* [23,24], and Sahoo *et al.* [25] have performed such calculations. The results by Lee *et al.* are in good agreement with our experimental results except between 10 and 30 keV where their cross section is too high. The results by Igarashi *et al.* and Sahoo *et al.* are too high below the cross section maximum by 20–30% and 30%, respectively.

With the arrival of ever faster computers, it has become possible to solve the time-dependent Schrödinger equation directly via a lattice calculation. This was done by Schultz and Krstic [26] who obtained agreement with our data except in the 10–30 keV interval.

Another approach was taken by Tong *et al.* [27] and by the group of Kirchner [28,29] who used time-dependent density functional theory with an optimized effective potential and self-interaction correction. The results by Tong *et al.* are in reasonable agreement with our low energy data,

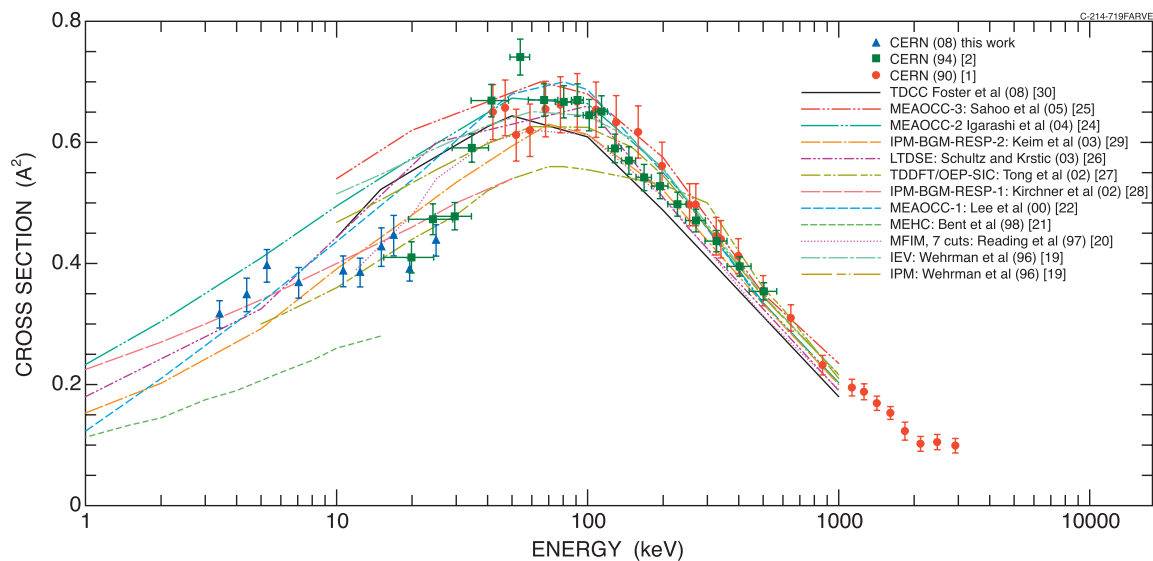


FIG. 3 (color online). The present data and those measured at LEAR [1,2] for single ionization of helium are compared with theoretical calculations. Two data points from Ref. [2] are not shown (see text).

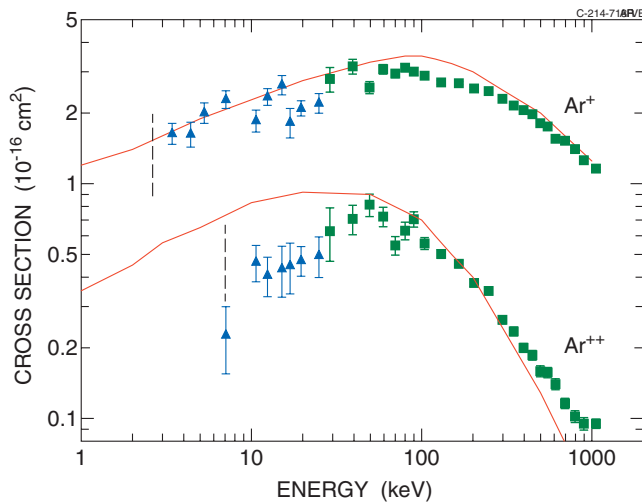


FIG. 4 (color online). The cross sections for single- and double ionization of argon are shown in this figure. Present data ( $\blacktriangle$ ) and the results of ( $\blacksquare$ ) Paludan *et al.* [31] are compared with the calculations of Kirchner *et al.* [32] which are shown as curves. The vertical lines indicate the lower limit for total collection of our apparatus.

although the maximum value is approximately 15% lower than our data. The data by Kirchner *et al.* were obtained by application of their basis generator method to solve the single electron Schrödinger equation. The group has published two sets of results of which the data by Kirchner *et al.* [28] show the best overall fit to our data below the cross section maximum but are approximately 15% too low at the maximum, as were the calculations by Tong *et al.* [27]. The results by Keim *et al.* [29] show the best overall fit to our data of all the calculations discussed above, including agreement at the cross section maximum. Quite recently, Foster *et al.* published results from their lattice time dependent close coupling method [30]. The results agree with the experimental data above 30 keV but are too high in the 10–30 keV interval.

Figure 4 shows our results for the single- and double ionization of argon by antiproton impact. The data are compared with our earlier measurements [31]. As can be seen, the old and new data agree well. We compare the data with the theoretical calculations by Kirchner *et al.* [32], which are based on the method they applied to the helium target, but developed to take into account autoionization and Auger processes. Although this theoretical framework is still under development, it already shows a fairly good agreement with all our data, even though some discrepancies are noticeable.

In conclusion, we have obtained experimental benchmark data for the development of advanced models and calculations of atomic collisions in general and for ionization, in particular. We have compared these data with the many until now mostly untested theories. Because of the increasing scattering of the projectiles and the correspond-

ing increased recoil energy of the created ions as the projectile energy is lowered, it is not possible to go to much lower energies with the present TOF setup. (A short account of some of the difficulties encountered en route to the present data is given in Ref. [33].)

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\*Permanent address: Department of Information and Communication Technologies, Universitat Pompeu Fabra, Spain.

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