

On the double ionization of helium by very slow antiproton impact

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ABSTRACT

Here we present experimental information on the cross section for double ionization of helium atoms by slow antiproton impact. It is used to discern between many advanced theoretical calculations. Earlier measurements of the ratio R between the double and single ionization cross sections for antiproton impact on helium show a persistent increase for the projectile energy decreasing from 10 MeV to 10 keV. The present data show that below 10 keV this increase stops and we give an upper limit to R .

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1. Introduction

In 1986 [1] it was found experimentally, that the double ionization cross section for impact of 1–10 MeV antiprotons on helium was roughly twice as large as the corresponding equivelocity cross section for proton impact. This was a great surprise at the time, since it was assumed that at such projectile velocities (~ 6.3 – 20 a.u.) the first Born approximation would give a fairly good description of most ionization and excitation cross sections. In this approximation, the cross sections are proportional to the square of the projectile charge and independent of the projectile mass. Therefore this model could not even approximately explain the factor of two between the R values for protons and antiprotons.

Later it was understood that the difference is mostly due to the correlation between the two helium electrons during the collision,

i.e. due to *dynamic correlation*, and the first theory to include this effect in a systematic way was published by Reading and Ford in 1987 [2]. It gave a satisfactory account for the above mentioned factor of two. Since then a large number of theoretical calculations which take into account dynamic correlation have been published on this subject. For the single and double ionization cross sections a fair mutual agreement between the various calculations as well as with experimental results were obtained for “fast” collisions, where the projectile velocity is much larger than 1 a.u. However, for “slow” collisions, the mutual agreement was poor – often with differences in the order of a factor of two. This was the case also for antiproton projectiles, even though for this kind of projectile no electron capture is possible, a fact that greatly facilitates the calculations. Recently, experimental data for the single ionization cross section for antiproton impact on helium in very slow collisions became available [3]. This has made possible a discrimination between the various theoretical models for single ionization.

For double ionization of helium by slow antiproton impact, the mutual disagreement between various published theoretical calculations is even worse – amounting to as much as a factor

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of 20 at 1 keV. In this paper we shall present experimental data for the double ionization cross section of helium for 3–25 keV antiproton impact and we shall compare these data with the various calculations as well as with previously published experimental information.

2. Experimental

The antiproton projectiles used in this work were obtained from the CERN antiproton decelerator, AD, as a pulsed beam of ~ 5 MeV energy. They entered the beam line of our ASACUSA collaboration and were decelerated to 115 keV in a radio frequency quadrupole decelerator (RFQD). The efficiency of the RFQD assures us an antiproton intensity around this energy which is two orders of magnitude higher than if a simple foil were used for the deceleration. After the RFQD, the antiprotons are captured, cooled, accumulated and compressed in MUSASHI, a multiring Penning trap situated inside a 2.5 T superconducting solenoid [4,5]. Here a timed application of high voltage to the end-cap electrodes assures the capture of the antiprotons. They are then cooled via interaction with a pre-loaded electron cloud, the temperature of which is kept low due to synchrotron radiation. Several antiproton pulses are captured and cooled before a rotating wall compresses the entire antiproton plasma to a sub-millimetre diameter. It is then extracted as a 250 eV DC beam lasting approximately 15 s. The beam is transported from the UHV conditions of the trap to the vacuum of 10^{-7} mbar in AIA, the Aarhus ionization apparatus, in a transport beam line equipped with several apertures separating three differential pumping stages.

In AIA, the antiprotons are focussed and then pass an acceleration gap in which they achieve their final collision energy of 3–25 keV. They enter the collision chamber which, together with its pumps and electronics is kept at the proper high-tension. The antiprotons pass through an aperture which defines the target volume and then pass a target gas jet which is perpendicular to the antiproton beam. The antiprotons are then detected by a 4 cm diameter MCP detector which gives both a timing and a position signal. The ions created in the interaction volume are extracted by a 400 V cm^{-1} electric field into a flight tube where they are spatially and temporally focussed onto another MCP detector. The time difference between the two signals from the MCP detectors gives the difference between the ion and the antiproton flight time from the collision site to the detectors. Hence a TOF spectrum of the ions is achieved, in which it is simple to identify the signal from He^+ , He^{++} and other ions. After each antiproton measurement we inserted an electron gun into the beam line and a Faraday cup instead of the projectile MCP detector. This made possible a measurement of TOF spectra for 3 keV electron impact with identical target conditions. Using well-known cross sections for ionization by 3 keV electrons we obtained the integrated target density and the ion – MCP detector's efficiency for the various ions. A more thorough description of AIA as well as of the experimental technique is given in Knudsen et al. [3].

Fig. 1 shows a typical TOF spectrum for a target gas which is 90% helium and 10% argon. In this case the antiproton energy was 7 keV. From such spectra we can easily deduce the cross section for single ionization of helium (as well as the single- and double ionization cross sections for argon). However only for a few antiproton energies do we have enough statistics to extract the cross section for double ionization of helium. We do know, however, the shape and the position of the He^{++} peak from the shape and position of the other three, so we can give an upper limit to the double ionization cross section in those cases. Since a He^{++} signal S would be obtained as a total T minus a background B , and if the sig-

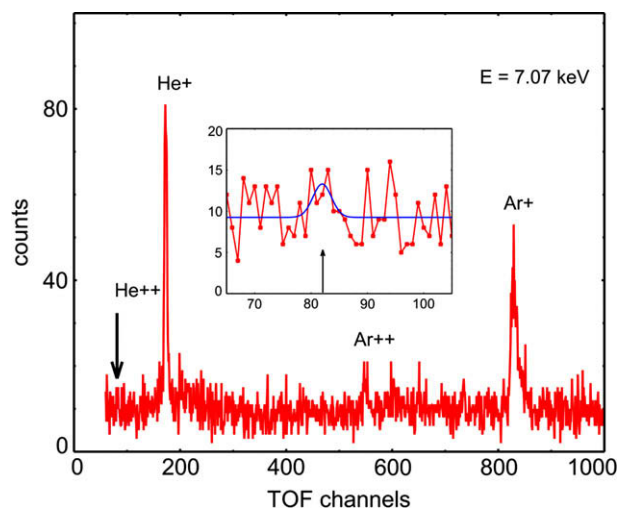


Fig. 1. A TOF spectrum for ions created in collisions between 7.07 keV antiprotons and a gas jet consisting of helium and argon atoms. The He^+ , Ar^+ and Ar^{++} peaks are indicated, as well as the position where He^{++} ions are expected. The insert shows the He^{++} signal, fitted with a Gaussian at the expected position and of the expected width.

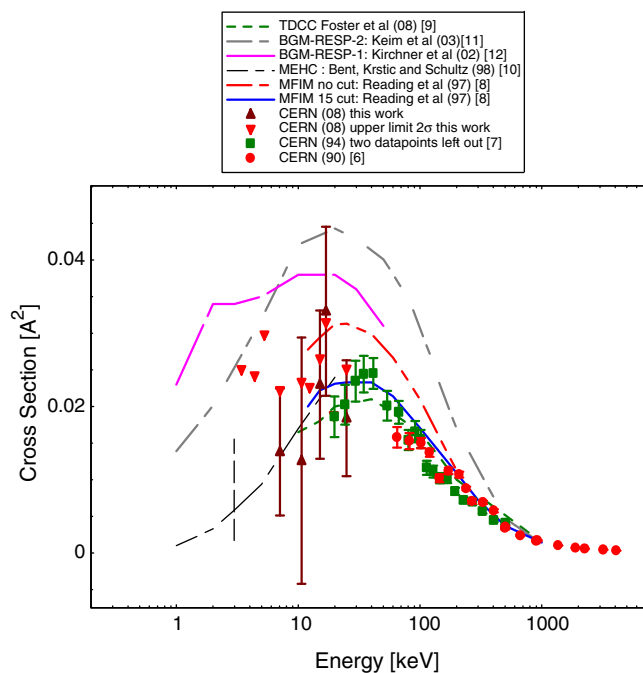


Fig. 2. The cross section for double ionization of helium by antiproton impact. The vertical dashed line indicates the lowest impact energy for which our apparatus accepts more than 90% of the ions and the scattered antiprotons. (Please note that the fact that one of the present data points lies above the “upper limit” is not an inconsistency. The data points scatter statistically around the true cross section value with a statistical spread corresponding to \sqrt{S} , while the upper limit is based on the (smaller) spread of $\sqrt{2B}$ around zero.)

nal is much smaller than the background, we get an upper limit of S as $2\sqrt{(2B)}$ at a 2σ confidence level.

3. Results and discussion

The results are shown in Fig. 2, compared with our previous results obtained at the CERN LEAR facility [6,7],² as well as with the-

² According to the discussion in [3], we have left out two of the data points published in [7].

oretical calculations. For five antiproton energies we were able to extract the double ionization cross section (albeit with large uncertainties). These data agree nicely with the previous data near 15 keV, where they overlap, even though they were obtained with quite different experimental techniques. They also show a decrease with decreasing energy. For all the antiproton measurements of this work we present the upper limit of the experimental cross section (2σ confidence level) in Fig. 2. This upper limit scatters around a value of $0.025 \times 10^{-16} \text{ cm}^2$.

From the comparison in Fig. 2 between the experimental data and the theoretical calculations, we conclude that the Multi-cut Forced Impulse method (MFIM) of Reading et al. [8] fits all experimental data rather well when 15 cuts are used, but (not surprisingly) much less if no cuts are used. The recent time dependent close coupling (TDCC) calculations of Foster et al. [9] fit our data even better. The multi electron hidden crossing (MEHC) calculations by Bent et al. [10] agree well with our low energy data. This is surprising, since the same model gives a much too low single ionization cross section, as shown in [3]. The reverse is the case for the basis generator method with response (BGM-RESP) of Keim et al. [11] and Kirschner et al. [12]. Their calculated single ionization cross sections agree well with our measured results [3], but as can be seen in Fig. 2, their double ionization cross sections are much too large.

The ratio R between the double and the single ionization cross section of helium has been a benchmark since the first discussions of the influence of dynamic electron correlation [1,13] in such processes. In Fig. 3 we show the existing experimental data for impact of protons [13–17] and antiprotons [7,17,18,this work]. As can be seen, R increases steadily when the projectile energy goes from multi-MeV towards 10 keV. Until the present work, this increase showed no signs of stopping, and especially the two lowest data

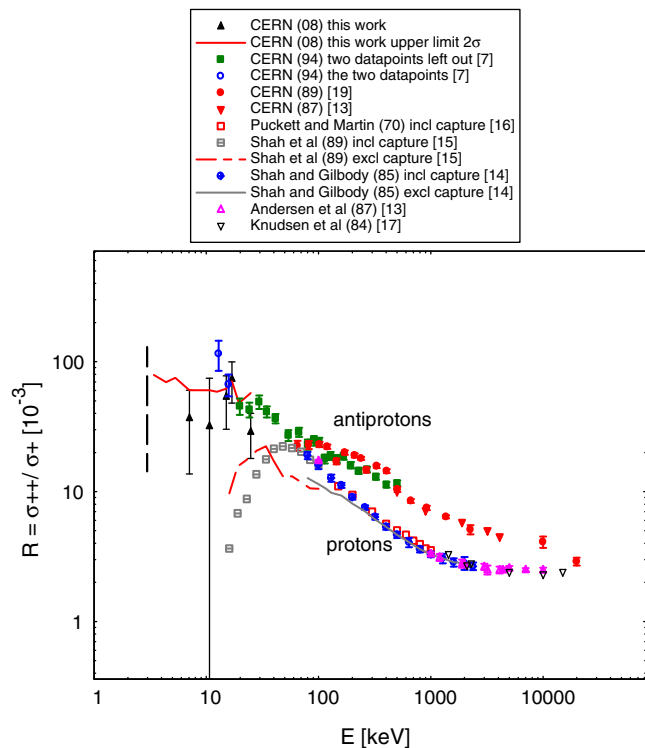


Fig. 3. The measured ratio R between the double and the single ionization cross section for proton and antiproton impact on helium. The curves show R excluding electron capture. The vertical dashed line indicates the lowest impact energy for which our apparatus accepts more than 90% of the ions and the scattered antiprotons.

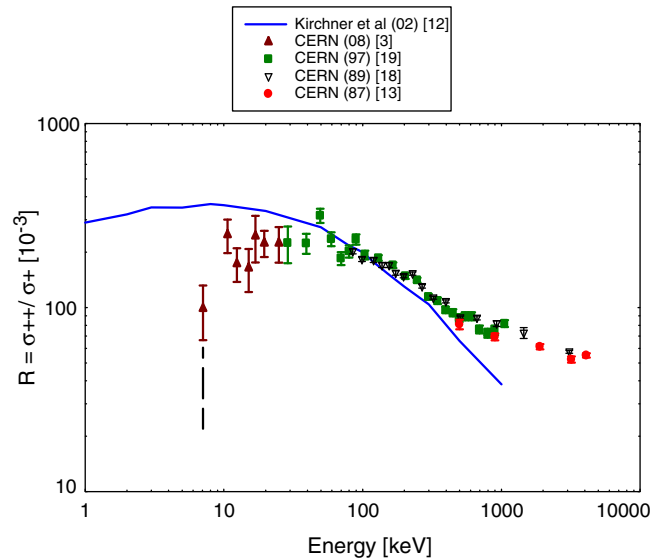


Fig. 4. The ratio between the double- and the single ionization cross section of antiprotons colliding with argon atoms. The vertical dashed line indicates the lowest impact energy for which our apparatus accepts more than 90% [18] of the ions and the scattered antiprotons.

points of [7] indicated such a continued rise. However, with the correction of these data points [3] and with the present measurements and upper limit it is clear that R has a maximum near 10 keV with a value around 0.045.

We may compare the above results for the helium target with the (from a theorist's point of view) much more complicated argon target. Fig. 4 shows the experimental data for R for antiprotons [3,13,18,19]. As can be seen, for decreasing energy, at 100 keV R reaches an almost constant value of 0.25. The BGM-RESP calculations of Kirschner et al. [12] do not agree very well with these data.

4. Conclusion

We have used the data published here – as well as those published earlier by our group – to discern between a number of advanced theories for the double ionization of helium atoms by antiproton impact. We also found upper limits to the low energy double ionization cross section and to the ratio between double and single ionization cross sections.

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