On the measurement of ionization cross sections for antiproton impact on atoms and molecules

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Abstract. During the last two decades, we have obtained experimental data for a broad impact energy range (3 keV – 20 MeV) of the total cross sections for single and multiple ionization in collisions between antiprotons and a number of atoms and molecules, as well as cross sections for fragmentation of those molecules. In this paper we discuss the experimental progress which was necessary for this achievement and present and discuss some of the data obtained.

1. Introduction

It is a surprising fact that the accuracy with which we are presently able to calculate the outcome of seemingly simple dynamic atomic processes such as single and multiple ionization of few electron atoms and molecules by charged particle impact is often not better than 10%, and in several cases are even uncertain to a factor of two or more. The reason is not that the participating particles are not well known, nor that the forces between them are in any doubt, but that the many-body nature and especially the electron-electron interaction hinders an accurate calculation for such systems. It is therefore important that the experimentalists supply accurate benchmark data for cases which are as simple as possible to treat theoretically, so that the theoretical models can be tested and those that are promising may be fine-tuned.

In 1986 our group realized that very good candidates for supplying such data are the collision systems where antiprotons ionize few electron atoms, such as atomic hydrogen and helium. This is due to the fact that antiprotons do not allow bound states of electrons around them, and so the electron transfer channel is closed. This gives a great theoretical simplification. Furthermore antiprotons are heavy, and therefore follow approximately linear paths with constant velocity, and in addition, they can ionize even though their velocity is much smaller than that of the target electrons, opening the possibility of studying ionization in slow, almost adiabatic collisions.

Some of our first results (on the antiproton ionization of helium) were taken with a beam energy of 20 MeV [1], and recently we published data down to impact energies as low as 3 keV [2,3] thereby achieving a data set covering a factor of 7000 in projectile energy. In this paper we present the experimental progress leading to this achievement. A thorough comparison with theory is given in [2,3].
2. Experimental technique at the CERN LEAR

The Low Energy Antiproton Ring LEAR at CERN was designed to supply intense and almost DC beams of antiprotons. For some time, the lowest energy was 20 MeV, but eventually, a useful beam of 5 MeV was attainable. Figure 1 shows our experimental setup with which we measured cross sections from 20 MeV down to 13 keV. Antiprotons extracted from LEAR with energies higher than 5 MeV passed directly into the interaction zone, where they collided with a thin gas of the target species. They were subsequently detected with unit efficiency by a scintillator detector to give the number of antiprotons $N_{\text{antiproton}}$. The ions created in the target gas were extracted by a fairly strong electric field of 800 V/cm into a spatially and temporally focusing flight tube and detected by a channeltron detector, giving the detected number of ions $N_{\text{det}}$. The cross sections were normalized to the single ionization cross section for proton impact on the same target at the highest energies, as measured by Shah and Gilbody [4], assuming the antiproton and proton cross sections in this case to be identical. From this we could calculate the product of the ion detection efficiency $\epsilon_{\text{ion}}$ and the integral over target density $n$ times the pathlength $l$ through the target and therefore obtain $\sigma$ from:

$$N_{\text{ion}} = \sigma N_{\text{antiproton}} \epsilon_{\text{ion}} \int n(l) \, dl$$

(1)
To achieve lower impact energies we had to slow down the antiprotons, and at that time the only option was to use the energy loss in a suitably thick foil. Therefore it was necessary to measure the velocity of each antiproton after passage of such a foil. This was achieved by passing the antiprotons through a thin scintillator situated just after the degrader foil and being a part of the slowing-down solid matter, which also consisted of a beryllium and a plastic vacuum window. With the signals from this start detector combined with the signals from the stop detector, we obtained the individual antiproton speed. This method of achieving slow antiprotons was very inefficient, especially in achieving antiprotons below ~ 20 keV, as is illustrated in Figure 2. The method has been refined during the years by collaborations working at the CERN Antiproton Decelerator AD, but they are still not able to get more than in the order of a percent in the range of energies below 20 keV [5].

Figure 3 A typical ion TOF spectrum obtained with the experimental setup shown in Figure 1. In this case the target was neon, and the various charge-states and isotopes of neon can be identified, as well as ions created by the ionization of rest gas water vapour. There is also a “prompt” peak stemming from, for example, antiprotons annihilating near or in the start detector and triggering the ion detector with a pion.

Figure 4. The experimental cross section for single ionization of neon for impact of antiprotons [6] and protons [7] (solid curve: Including electron capture, dashed curves: Excluding electron capture).

Figure 3 shows a typical ion TOF spectrum, where it can be seen that the discrimination between ions of various m/q values is excellent. There are tails attached to some of the TOF peaks. They stem from
double collisions: mostly from ions which charge-exchanged in the target or in the flight tube, and hence arrived later than normal. Extrapolation of the content of these TOF peaks to zero target pressure remedied this problem.

An example of the results obtained at LEAR is given in figure 4. Here is shown the single ionization cross section measured on neon for impact of antiprotons [6]. These data are compared with experimental proton data [7]. At the highest energies it is expected that the cross section for single ionization is proportional to the projectile charge squared, due to the fact that the projectile acts as a small, short-lasting perturbation. This is not true at lower velocities, where the so-called Barkas effect shows up [8]. It is due in part to the polarization of the target atom in the first part of the collision which leads to a larger cross section for positive projectiles. Another contribution comes from the fact that the acceleration/deceleration of the projectile during the collision is different from that belonging to a Coulomb collision [9] because of the screening of the target electrons.

These effects are common to one- and many-electron targets, but this is not the case always. An example of an effect which is due entirely to electron-electron interaction can be seen in figure 5. Here, the ratio between the double- and the single ionization cross sections of helium for antiproton and proton impact is given. As can be seen, the antiproton double ionization cross section is a stunning factor of two larger than the proton cross section, even at these high projectile velocities where perturbation models usually work quite well. This difference is now well understood, see e.g. [12] as being due to an interference between several different channels each leading to double ionization: In one, the so-called ”Two Step One (TS1)" the projectile interacts only once, namely with one target electron, which then interacts with another, causing both to be ejected. Or the second electron is promoted to the continuum after the removal of the first in a “Shake Off (SO)” process. The probability amplitudes for these processes are proportional to the projectile charge, $q$. In the so-called “Two Step Two (TS2)" process the projectile interacts with both electrons consecutively which gives a probability amplitude proportional to the projectile charge squared. The resulting cross section is therefore given as:

$$
\sigma^{++} \sim |a_{TS1+SO} q + a_{TS2} q^2|^2
$$

(2)
which clearly contains a term proportional to $q^3$ and hence gives a proton/antiproton difference. This term can be calculated accurately only if the TS1, SO and TS2 processes, which are strongly influenced by (or results entirely from) electron-electron interaction, can be accurately modeled.

3. Experimental technique at the CERN AD

Following the improved understanding of high-velocity phenomena such as those discussed above, an increasing demand for benchmark data taken at low antiproton energies arose, such that collisions involving projectiles moving with speeds lower than that of the target electrons could be investigated. In such cases, perturbation models are inadequate, and the electron-electron interaction is very important for many-electron targets.

We have used the beam line of the CERN ASACUSA collaboration to achieve measurements of ionization cross sections down to an energy of 3 keV corresponding to a speed $\sim 25\%$ of that of the electrons in helium. This breakthrough is due mainly to two ingenious apparatuses: The RFQD and the MUSASHI trap. The beam line is sketched in Figure 6.

![Figure 6](image)

Figure 6 The ASACUSA beam line with the RFQD, MUSASHI, extraction beam line and AIA. The development of the antiproton energy through the beam line is illustrated. Not to scale! The beam line is some 20 m long.

At the CERN Antiproton Decelerator the lowest extractable antiproton energy is 5 MeV, just as was the case for LEAR. Entering the ASACUSA beam line as a short pulse, the antiprotons extracted from the AD are pre-bunched to fit the acceptance of the so-called RFQD, which is an inverted radio frequency accelerator, and hence acts as a further decelerator, which brings the antiproton energy down to $\sim 100$ keV with an efficiency of $\sim 50\%$ [13]. These antiprotons are then passed to the entrance of MUSASHI, a multi-ring Penning trap with a high magnetic field created by a superconducting coil [14,15]. After traversal of a thin foil in which they are decelerated to less than 20 keV the antiprotons are stopped at the other end of the trap by a negative potential, and are reflected upstream. In the meantime a similar negative potential has been pulsed on at the entrance, and so the antiprotons are trapped. They now make multiple passes through a cloud of preloaded cold electrons in which they lose energy until they are “at rest” having the ambient temperature of the superconducting coils. The so-called “rotating wall” technique is now applied to compress the antiproton cloud in the axial direction, and then it is extracted from MUSASHI as a 10 sec long pulse containing some $2 \times 10^5$ antiprotons in total. The cycle length of the AD is $\sim 80$ seconds, but sometimes it is advantageous to stack several bunches of antiprotons in the MUSASHI before extraction. In order to get the (few) antiprotons to collide with our target gas and produce a sufficient number of ions we need a fairly high target pressure, which means a fairly high base pressure in the collision chamber of around $10^{-6}$ mbar. However, the vacuum in MUSASHI is better then $10^{-12}$ mbar, and should remain
like that. Therefore, an extraction beam line has been constructed [16] in which several differential pumping stages allow the direct connection between our apparatus and MUSASHI.

Figure 7 The AIA apparatus with its central collision region. Note the electron gun and the Faraday cup which are used for the normalization procedure.

The extracted beam – of energy in the order of 250 eV - enters the Aarhus Ionization Apparatus (AIA) and is focused onto the entrance of an acceleration gap in which it attains the final collision energy. This is achieved by raising the entire collision chamber with its pumps, electronics, etc., to a positive high voltage, which can raise the collision energy to up approximately 20 keV.

The central collision region is much like the setup used at LEAR. We do not need to register the energy of the antiprotons, since it is known from the high voltage applied to the collision chamber. We start a TOF measurement using the signal for the arrival of each antiproton on the end-detector which is a 4 cm diameter micro channelplate (MCP) detector. The stop signal is given by the arrival of an ion at the ion detector – also a MCP. Figure 8 shows a typical TOF spectrum - in this case of helium containing 10% argon. The $\text{He}^+$ and $\text{Ar}^+$ peaks can be clearly seen.

Figure 8. A typical ion TOF spectrum. The target gas consisted of 90% helium and 10% argon.
In these experiments, we normalized the measurements by putting a 3 keV pulsed electron beam through the collision region and measuring the number of created ions (of each kind) and the electron current. From the well-known electron impact ionization cross sections [17] we then obtain a calibration of the antiproton cross sections. An example of the data achieved is shown in Figure 9.

![Figure 9](image_url)

**Figure 9.** The cross section for single ionization of helium by antiproton impact. The antiproton data are from [2,10,18], while the proton data are from [4], and shown as curves.

The vertical line in figure 9 shows the lower limit for full acceptance of ions and projectiles of the apparatus. At lower energies, either the projectiles are deflected outside the end detector, or the ions are not collected by the extraction field.

4. The experiment in the near future

It seems difficult to reach much lower collision energies with the technique discussed above, due to the limitations given by the deflection of the projectiles in the ionizing collisions themselves and the recoil of the target ions, but also due to deflections of the projectile in the extraction field. However there is another way to produce new benchmark data, namely to stay with projectiles of some keV, but measure differential cross sections. This is not possible with the present average number of antiprotons per hour, but if we “recycle” those antiprotons which did not collide with a target atom in one pass, to allow a second passage of the target, this situation improves greatly.

![Figure 10](image_url)

**Figure 10.** The “recycler ring” equipped with a so-called reaction microscope. Those antiprotons which create an ionization will be deflected, and give a signal in the MCP detector. The rest will go through a central hole in this detector and return to the target for another go.

This is possible by using a “recycler” ring, in which the “unused” antiprotons return to the target for another try at ionizing a target atom. If we can make the unused antiprotons recycle 1000 times, we have in effect the equivalent of a single pass experiment with 1000 times higher antiproton fluence. For this to come true, we are designing [19] a small electrostatic ring, which is shown in Figure 10.
Since it is not supposed to store the antiprotons for more than 10 μsec or so it does not need a high vacuum. In the figure is indicated a so-called “reaction microscope” [20] with which we can measure the triple differential ionization cross section of antiprotons colliding with the target atoms, of which helium will surely be the first candidate.

5. Conclusion
The development of the LEAR and AD accelerators at CERN was of course the sine qua non of this field, but great advance in experimental apparatus has happened too, and has made possible the use of these machines to extract useful benchmark data for the development of atomic collision theory. There seems to be a promising future, too.

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