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Future Plans of PS 194

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Introduction

Since 1986, PS194 has conducted a number of experiments at LEAR. The aim was to use "slow" antiprotons as projectiles in atomic collisions, and thereby to obtain new knowledge on the mechanisms that govern processes such as ionization and energy loss.

Basically, the fundamental idea behind this programme is that if we use protons *and* antiprotons at the same velocity, we can measure what happens to the various reaction amplitudes when the sign of the coupling constant is reversed. This gives a powerful tool for disclosing higher order effects and effects due to electron-electron correlation.

Our investigations until now fall in two categories: (a) measurements of the single- and multiple ionization of atoms (including atomic hydrogen(!)) and molecules, and (b) measurements of the energy loss of antiprotons as they traverse solid matter.

The PS194 papers published until now are given in the attached list. References to this list are marked "RL..".

In the following, we present our plans for the autumn 1995 LEAR run and our plans for future work at LEAR.

Immediate Plans (autumn 1995 run)

1. Stopping Power of Antiprotons in Solid Matter

For swift, charged, pointlike, non-relativistic particles the energy loss in matter is given to a high degree of accuracy by the socalled Bethe formula:

$$dE/dx = - (4\pi e^2 N Z_2 / mV^2)\, Z_1^{\,2}\, L_0$$

where N and Z_2 are the target density and atomic number, respectively, m is the electron mass, and V and Z_1e are the projectile speed and charge. The $Z_1^{\,2}$ dependence is valid only at projectile energies well above 1 MeV/amu. Below such energies, higher order terms play a decisive role for the stopping power, and L_0 has to be replaced by

$$L = L_0 + Z_1\, L_1 + Z_1^{\,2}\, L_2 + ...$$

The first correction term (called the Barkas term) can be deduced via a comparison of dE/dx measured for proton (Z_1 = 1) and antiproton (Z_1 = -1) impact.

We have measured the Barkas term for Si and Au targets for projectile energies between 3 MeV and 200 keV (RL22 and RL23). In figure 1 is shown an example of these data. It should be noted how large the Barkas effect is even at rather high projectile energies.

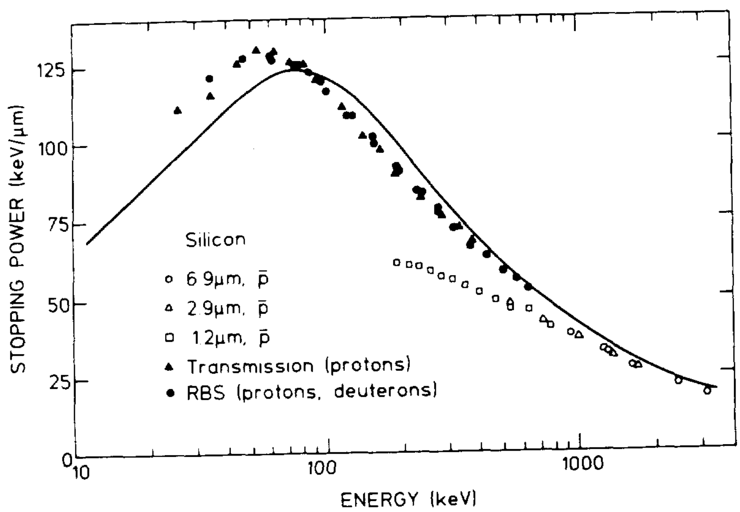

Figure 1

During the autumn 1995 run we plan to perform a comprehensive investigation of dE/dx for a number of target materials (Al, Cu, Ag, Au, ...) so that the target dependence of L_1 can be established.

There exist another investigation of the stopping power of antiprotons in matter (1). Rizzini and the Obelix group used H_2 and e as targets and were able to measure (in an indirect way) down to projectile energies as low as a few keV. However, at high projectile energies, where the Barkas term can be established (since even higher terms are negligible there), their data are not accurate enough to permit a quantitative deduction of L_1.

2. Channeling with MeV Antiprotons

For many years, channelling effects for positive particles in the MeV region have been investigated both theoretically and experimentally. Today, the understanding is so profound that it is possible to describe nearly all aspects of channeling in good agreement with experimental results. Consequently, channeling is now used as a tool in many applications in the energy region from keV to multihundred GeV. Around the CERN SPS, several crystals are today installed for: (i) beam splitting, (ii) beam extraction, (iii) strong-field effects, etc. (For a review, see Ref. 2)

Investigations of channeling for negative particles are much more scarce. MeV electrons were

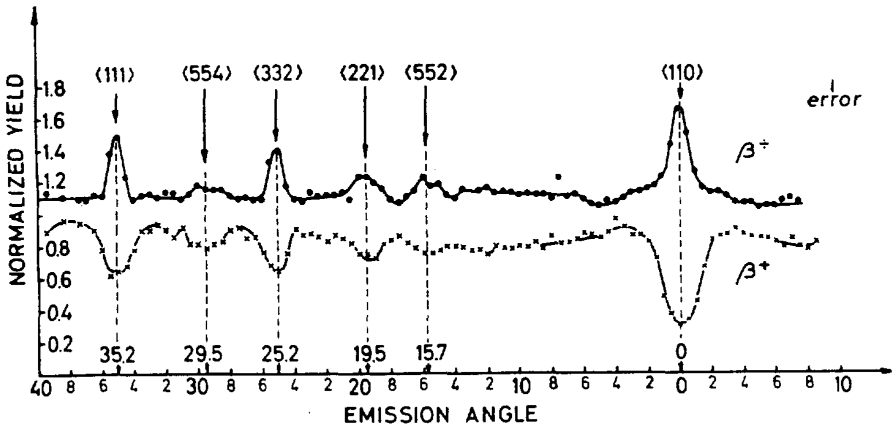

Figure 2 Angular dependence of emission yields of e^- (150-250 keV) and e^+ (200-300 keV) embedded in a Cu crystal (Ref. 3).

used for such channeling experiments, which gave a qualitative picture of the effect. Many experimental problems arise using electron beams because of the strong multiple scattering which requires very thin crystals. The influence of channeling of the energy loss and x-ray excitation was not measured due to experimental difficulties. Moreover, the small electron mass leads to the well known diffraction effects associated with coherent scattering from many lattice atoms. In fact, these problems were one of the motivations for GeV channeling at CERN. For GeV negative particles, strong channeling effects have been found for many processes, but the influence of channeling on close-encounter processes for MeV heavy negative particles has not been investigated.

Measurements with antiproton beams of energies in the MeV range will offer a very important extension of the knowledge and include for the first time non-relativistic, heavy, strongly interacting negative projectiles. The observation of antiproton and proton channeling can serve to elucidate the discriminatory manner in which the crystal interacts with negative and positive particles, as shown in the figure. The investigations can be performed in a collimated MeV $\bar{p}$ beam by measuring the variations of close-encounter (annihilation, K x rays) yields around a crystal direction. Calculations predict enhancement of such processes by a factor of ~6 (2).

Future Plans

Our plans for future work at LEAR in 1996 (and hopefully thereafter as well) are centered on an investigation of the basic mechanisms of the ionization of atoms and molecules for impact of low velocity antiprotons. It will be clear from the following discussion that almost nothing is known about what happens when a heavy, negative particle collides with an atom (or molecule) at a speed that is lower than a typical speed of the target electrons.

We plan to investigate this regime and thereby to create data that will be able to guide the theorists (and perhaps us) to an understanding of this phenomenon - and hence to a better understanding of atomic collisions in general.

1. Single Ionization

In our previous LEAR work we have measured the cross section for single ionization by 13 keV - 3 MeV antiproton impact on H_2 and He (RL18, RL20, RL41) and for 30 keV - 1 MeV antiprotons on atomic hydrogen (RL42).

Our recent results on atomic hydrogen are shown in figure 3. There exist for this target, because of the simplicity of the system p^- + H, a number of presumably very accurate calculations of the ionization cross section. For example, the Classical Trajectory Monte Carlo method has been used (4), as well as One Center - and Two Center Atomic Orbital Close Coupling (5,6) calculations. Furthermore, a more approximative method, the Continuum Distorted Wave - Eikonal Initial State method was applied (7).

From figure 3 it can be seen that all these calculations do well for impact energies above 50 to 100 keV. However, it is sad to see how the theoretical curves take off in all directions when we approach lower projectile energies. We conclude that the theorist as such do not know how to calculate this very basic cross section for projectile velocities lower than that of the target electron (13.6 eV electrons have the same velocity as 25 keV antiprotons).

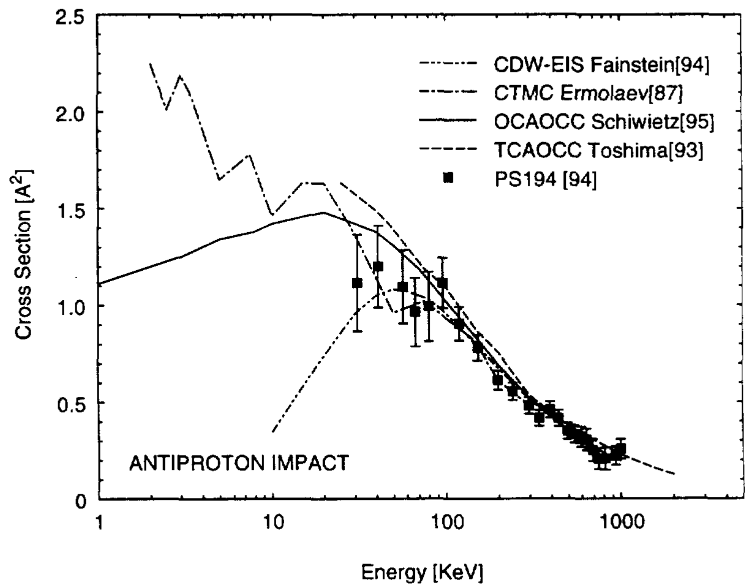

Figure 3 The ionization cross section for antiproton impact on atomic hydrogen.

A clue as to which theoretical cross section is correct is obtained from our measurements on He, where we also have CTMC (8) and CDW-EIS (7) calculations. As can be seen in figure 4, for that target, the CDW-EIS approximation works fine down to an impact energy of 10 keV.

When an antiproton approaches atomic hydrogen (or helium) slowly, the atomic electron will become unbound if the antiproton reaches a certain critical distance. This mechanism therefore suggests that at projectile energies below 10 keV, the ionization cross section should increase with decreasing projectile energy. This remains to be seen.

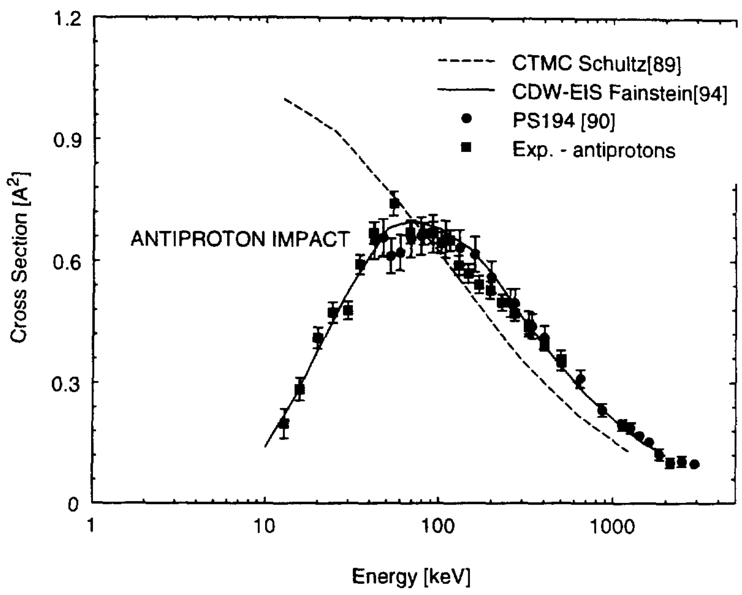

Figure 4 The single ionization cross section for antiproton impact on Helium.

2. Double Ionization

It is strange, but true, that the cross section for the removal of two electrons from helium by antiproton impact is considerably larger than the same cross section for proton impact *irrespective of the projectile velocity*. We have shown this to be true for projectile energies between 13 keV and 20 MeV (RL41). Some of these data are shown in figure 5.

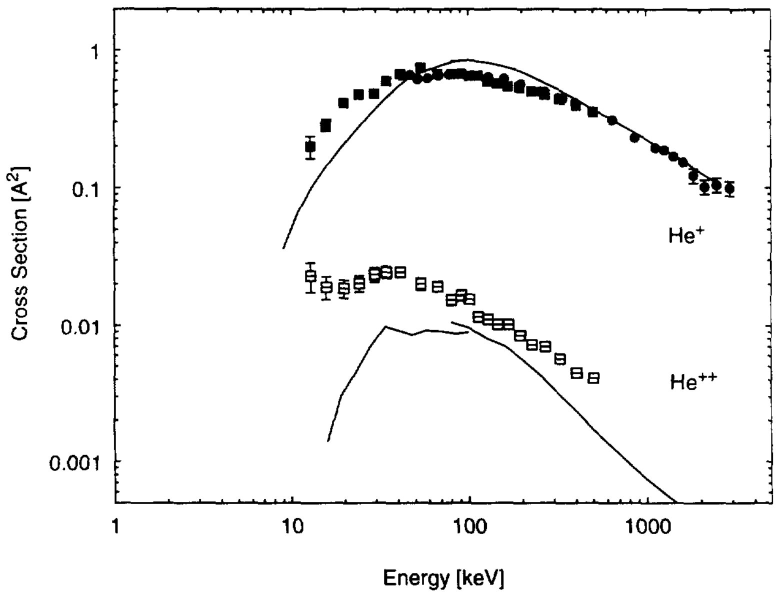

Figure 5 The cross sections for single and double removal of electrons from Helium by proton impact (curves) and antiproton impact (■)

It is known by now (RL39) that at high projectile velocities this difference is due to an interference between two mechanisms that both leads to double ionization, and that this interference is very closely connected to the electron - electron correlation both in the static wavefunction and during the collision.

For low projectile energies we have no theoretical explanation of the behavior of the double ionization cross section. It can be seen that at the lowest energies reached in our work so far, for antiprotons it increases with decreasing energy. A slight extrapolation (to perhaps 5 keV) makes the double ionization cross section *larger* than the single ionization cross section.... a very strange phenomenon, if it exists. It is known that if an antiproton is capture to an atom, it will "peel" off all of the atomic electrons. But here we regard collisions where the antiproton is far from being captured.

3. Ionization plus Excitation

We have shown recently (RL43) that it is possible to study not only double ionization but also ionization + excitation processes for antiproton impact at LEAR. It is not possible to use atomic targets because the additional excitation has to be established by the (inefficient) detection of photons. However, molecules that are ionized *and* excited will dissociate, so the detection of e.g. a O^+ ion created from a CO target is a sign of ionization + excitation. We are therefore planning to study these processes at low impact velocity, too.

4. Technique

It is our plan to use the beam of antiprotons that can be extracted from the large Penning trap of the collaboration PS200 (9) and the apparatus that we have used until now to measure the cross sections for antiproton impact single ionization, ionization + excitation and double ionization of small atoms and molecules. According to Holzscheiter et al (9) we should be able to reach antiproton energies as low as 1 keV.

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