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Low Energy Antiprotons for Atomic, Nuclear, Gravitational, and Applied Physics

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ABSTRACT

During the last 10 years of successful operation of the Low Energy Antiproton Ring (LEAR) at CERN numerous small scale experiments did yield a wealth of interesting physics results, despite running parasitically to the main physics program. Unfortunately, while many more important experiments should be performed and new ideas on the usage of low energy antiprotons in atomic, nuclear and gravitational physics, as well as for applied science are forthcoming, with the shut-down of LEAR the source for these experiments would vanish.

We therefore propose to include a general purpose area in the lay-out of the Antiproton Decelerator (AD) facility, now being discussed at CERN, to accomodate such experiments. We propose to form a users community to share and operate such a facility. This users community will report to the AD users committee and to the SPSLC, which will have the final authority on approving individual experiments. This document is a short description of the scope of such a facility and the techniques to be used to provide antiprotons at the different energy regimes. Attached are several letters of intent for physics experiments possible at such a facility. Many more of those are in preparation and will be appended to this document at a later stage.

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1 Motivation

Ultra-low energy antiparticles are a very unique probe in physics. In the area of collisional physics it has been shown that by merely changing the sign of the projectiles charge while keeping all other important variables (such as the projectiles mas, velocity, and the numeric value of the magnetic moment and charge) unchanged, one can learn about the important aspects of the dynamics of many-body effects, using very "clean" cases. Measurements of sngle and multiple ionization of hydrogen and helium by impact of protons and antiprotons have nicely complemented the earlier work wit electrons and positrons, and have revealed interesting charge related effect at the lowest energy reached so far. Using the output of the proposed Antiproton Decelerator (AD) at CERN., these studies can be continued in the current mode. If a Penning type trap similar to the one used in LEAR experiment PPS200 is employed as a decelerator/debuncher for the AD beam, these measurements can be extended to much lower energies. Recent measurements at LEAR have indicated that cross sections can be expected to be vastly different for protons and antiprotons below 10 keV, revealing the importance of "multiple processes" at tese low energies. Experimental results are desperately needed to guide theorists in their challenging work in this field of atomic colision theory.

During the last few years a large program of nuclear physis research was performed within experiments PS203, PS208, and PS209, using both stopped antiprotons and the direct (more energetic) beam from the accelerator. The "heating" of the nuclei by stopped and energetic antiprotons was studied using a variety of ttols, ranging from simpe inclusive radiochemical methods to very sophisticated set-ups, where the detectors covered almost the full solid angle. Taking advantage of the very peripheral character of the antiproton annihilation process in antiprotonic atoms, the composition and extent of the nuclear periphery were investigated for many isotopes, using both radiochemcal methods and the observation of shifts and widths of antiprotonic X-rays.

Proposals related to these studies, but which are of a more applied character, include the production and delivery of radioisotopes for Positron Emission Tomography (PET), the validation of a new concept called Positron Assisted Antiproton Tomography (PEAT), and a feasibility study on using antiprotons to deposit energy into gaseous hydrogen or xenon with a high efficiency.

These, and many more, experiments could be performed with a rather modest investment at the AD by installing a general purpose beam line delivering direct beam in the momentum range from 3.5 GeV/c down to 105 MeV/c, which can them be further decelerated using a system similar to the PS200 catching trap. We propose to form a users community and operate such a facility under the auspice of the AD Users Comittee and the SPSLC.

2 Facility aspects

2.1 Direct beam at 105 MeV/c to 3.5 GeV/c

All of the experiments in atomic and nuclear physics performed to date at the Low Energy Antiproton Ring (LEAR) at CERN were using the direct out-put beam, typically at its lowest momentum of 105 MeV/c. The antiprotons were either ranged out in a target, or energy degrading in material with subsequent time- of-flight (TOF) tagging was used to achieve low kinetic energies [1,2]. Under normal circumstances, these experiments were run in parallel to a main-user, taking beam in a continuous spill mode with intensities ranging from a few tens of thousands to roughly one million particles per second. Recently, some measurements were also done in a fast extraction mode, were a short pulse at high intensity was send to a single user [3].

We envision this program to be continued using a similar technique. For this purpose we propose to use the existing transfer channel currently being used to transport antiprotons from the AC to the AA and modify it into a beam line capable of handling momenta from 3.5 GeV/c down to 105 MeV/c. To match the operation of the LEAR set-up we suggest to also study the possibility of augmenting the fast extraction of $\approx 10^7$ particles every 1 minute by a semi-slow extraction mode, spreading the 10^7 antiprotons over a time period of 60 seconds, providing an average intensity of 1.5×10^5 antiprotons/second.

The lay-out of the general purpose area is shown in figure 1. The set-up is planned in such a way, that different experiments could be placed at the end of the beam line to accept direct beam from the AD. Alternatively, the existing PS200 catching trap can be inserted at this point to act as a debuncher/decelerator to modify the phase space of the AD output to accomodate a variety experiments . This latter system is described in more detail in the next section.

2.2 Ultra-low energy antiprotons from a Penning trap

At the experiment PS200 at LEAR , approximately one million antiprotons have been captured from a single pulse [4] from the accelerator containing $\approx 4 \times 10^8$ antiprotons in a 200 ns time window.. Using the technique of electron cooling [5], the energy of these antiprotons has been reduced to the sub-eV range, and a substantial fraction of the captured antiprotons ($\geq 65\%$) were collected into the central, harmonic region of the PS200 catching trap. From here they can be delivered to subsequent experiments.

Several extraction schemes are possible, and we anticipate to deliver antiprotons

- as a bunch with temporal length between 100 μsec to 1 second, and kinetic energies ranging from 100 eV to about 2 keV, or
- as a continuous beam of 10^4 to 2×10^5 antiprotons/second and spill durations between 1 and 60 minutes, at energies below 2 keV, or

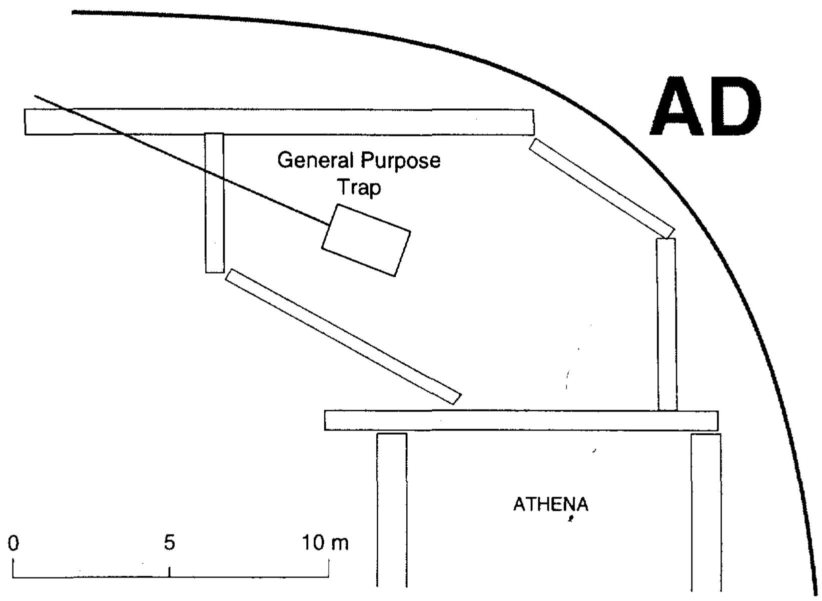

Figure 1: *General lay-out of the general purpose extraction line in the AD hall*

- as a sequence of micro-bunches with a well defined time structure and energies up to 30 keV.

2.2.1 Antiproton capture

The technical details of the PS200 catching trap are described elsewhere [6], and only a short summary is given here. The actual trap structure consists of an open end-cap Penning trap [7] of 50 cm total length and 3.8 cm diameter, situated in the cryogenic bore of a super conducting magnet. The end-electrodes of this trap can be floated at a 30 kV potential, and the entrance electrode can be switched from ground to the maximum voltage in less than 100 ns. Figure 2 shows the general layout of the system.

For the purpose of the initial antiproton capture the well is defined by the potential at the entrance foil and at the cylindrical electrode at the far end of the trap. The five electrodes in the central section can be biased to form a harmonic well at the center of the trap [8]. This well is used to store electrons for electron cooling and to collect antiprotons in a well defined region of space once they have been cooled by collisions with the electrons. The entire trap structure can be floated up to about 2 keV to allow extraction of antiprotons at such energies.

A particle pulse from LEAR is transported to the front end of the experiment and focussed onto the entrance foil of the trap. In this 135 μm thick, gold coated aluminum foil the antiprotons lose energy by collisions with the atoms of the foil material and, assuming proper adjustment of the additional degrader material up-

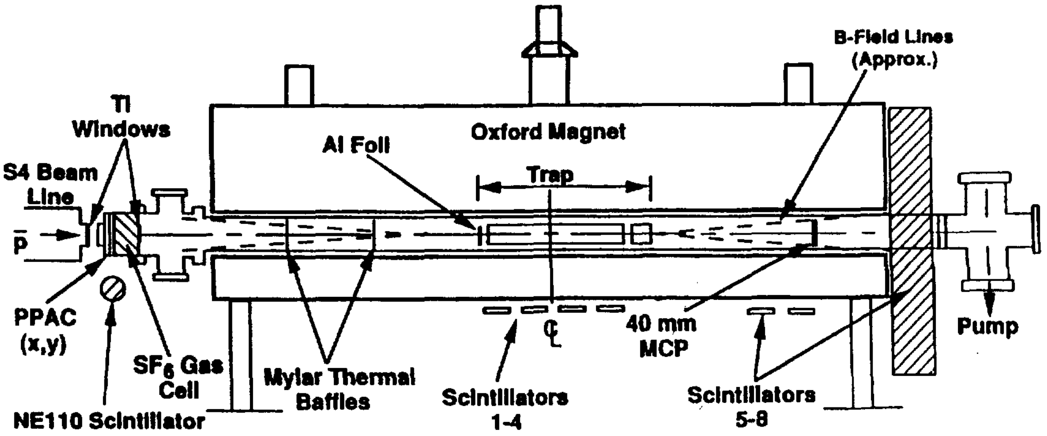

Figure 2: *Schematic of PS200 catching trap set-up as currently being used at LEAR.*

stream, a maximum number of low energy particles ($E_{kin} \leq 30$ keV) exits from the downstream face of the foil.

These particles are reflected by the electrical potential at the far end of the trap and travel back towards the entrance electrode. This electrode is ramped up to potential before the particles can escape ($\tau \leq 100$ ns), capturing them within the volume of the trap. In test experiments at PS200 an overall efficiency (including losses in the beam transport from LEAR to the entrance of our system) of approximately 0.5 %, using a 10 keV energy bite, was achieved. This efficiency rises linearily with the well-depth, and we anticipate being able to capture ≥ 1.5 % of the AD beam. This will give more than 10^5 antiprotons in the trap per pulse. Stacking of several pulses has been demonstrated at LEAR [9] and can be used to increase the number of antiprotons available for experiments to about 10^7 antiprotons.

2.2.2 Electron cooling of antiprotons

In order to reduce the mean energy of the antiprotons in the trap after capture the central well is preloaded with approximately 10^9 electrons. These electrons rapidly cool to thermal equilibrium with the surrounding wals (≈ 4 K)due to synchrotron radiation in the 3.25 Tesla magnetic field. Antiprotons oscillating in the large catching trap interact via Coulomb interaction with these electrons and dissipate energy into the electron cloud, which in turn is continuously cooled by synchrotron radiation, until both electron and antiproton clouds arrive at thermal equilibrium with the ambient temperature of the apparatus. At this moment, antiprotons and electrons will reside together in a small volume in the central portion of the trap. If necessary, electrons can be ejected by resonantly exciting their axial motion and simultaneously lowering the confining potential for a time period longer than the electron axial oscillation time, but short compared to the axial oscillation period of the antiprotons.

2.2.3 Extraction of antiprotons from the trap

Most ultra-low energy experiments will require a "semi-continuous" beam, possibly with time information on the release of the individual antiprotons. A number of possible schemes can be envisioned to extract the cloud of antiprotons from the PS200 catching trap in such a way:

(a) One can eject the antiprotons through an evaporative process, by weakly exciting the axial or cyclotron resonance frequency of the stored antiprotons. This will lead to a continuous heating and a slow 'boil-off' of particles from the well. The rate of boil-off can be controlled by the amplitude of the radio-frequency applied. Test experiments using a smaller Penning trap filled with protons have generated continuous spills of protons for approximately 30 minutes at a time [10]. This evaporative slow spill can be used for experiments where a low intensity of antiprotons and no timing information is needed. By floating the trap structure relative to ground the antiprotons can be accearated to aproximately 2 keV (with the current set-up).

(b) Additionally, one may impose a time structure onto the extracted beam: A sequence of rectangular pulses with a width slightly larger than the oscillation period of the trapped particles and an amplitude of 1 - 2 Volts is superimposed onto the constant trapping voltage. Additionally, a weak RF drive is applied at the axial resonance (or the cyclotron resonance) to continuously heat the particle cloud. The amplitude of this RF drive is established in such a way that continuous boil-off is not quite taking place yet. This heating assures a nearly constant supply of particles near the top of the electrostatic well, which then can escape whenever this well depth is reduced by the applied pulse. This method has been used during test experiments at Los Alamos to produce a timed proton beam from a small Penning trap [10].

(c) Using the above mentioned method of timed release will allow us to post-accelerate the antiprotons to an arbitrary energy within the high voltage operating range of the end cap electrode of the catching trap (currently 30 kV). When a release pulse is applied to the central section of the trap, particles in the right energy range will leave the inner trap with an energy and time uncertainty given by the release pulse. While the particle bunch is inside the 20 cm long, cylindrical end-electrode, the voltage on this electrode can be pulsed up to a maximum voltage of ≤ 30 keV and the particle bunch emerging from this electrode will therefore be accelerated to this potential. The main advantage of this method consists of the fact that the energy of the particles is referenced to ground potential and none of the subsequent equipment needs to be floated at high voltage.

2.2.4 Extraction optics

In the current configuration the radial extent of the cloud is defined by the spot size of the antiproton beam hitting the final degrader foil and, in principle, is only limited by the 5 mm active diameter of the trap entrance. Particles being ejected from the trap will follow the magnetic field lines and a 5 mm diameter beam spot will expand to 20 mm diameter by the time the particles reach the 0.2 T plane in the fringe magnetic field. Using a fluorescing ceramic disc [11] viewed with a microchannelplate intensified CCD camera, extraction of pulses was observed and this spot-size was confirmed. We plan to implement magnetron centering [12] into the PS200 catching trap system to radially compress the cloud and therefore minimizing the beam spot at the exit of the magnetic field. An einzel lens which will allow focussing of the beam onto a smaller target or into an aperture used for vaccum isolation has been designed and constructed. Calculations indicate that sufficient focusing can be achieved with this system mounted in the fringe magnetic field, if the initial spot size is less than 2 mm in diameter.

3 Summary

The set-up described in this proposal would allow a number of important experiments with low energy antiprotons to be performed, while putting a minimum of constraints on the main experiments proposed for the AD. The following is a short list of experimental programs possible at this general purpose extraction line. For some of these programs we have attached letters-of-intent. Once the facility has been approved, many more groups will be forthcoming with individual proposals. These will be coordinated by the users community and appropriate rules for joining will be established. The users community will set up an organisational structure reporting directly to the ADUC, and through this comittee to the SPSLC, which will have final authority to approve or reject individual proposals, based on the standard procedure of scientific peer reviews.

Following experiments are anticipated to become part of this proposal:

- Measurements of ionization in collisions between slow antiprotons and atoms

- Nuclear physics with low energy antiprotons from the AD

- Stored antiprotons for radio-isotope production and applications

- Antiprotons for plasma heating

- Formation of exotic atoms in pbar-H collisions

- Capture of antiprotons into metastable states in helium

- Gravity studies with ultra-cold antiprotons

In addition, this general purpose extraction line can be useful in testing ideas and instruments (i.e. alternative deceleration methods like an RFQ-decelerator, beam monitoring systems, etc.) which then could be implemented into the extraction lines serving the main-users at a later stage.

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Appendix

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CERN SPSLC "AD" PROJECT
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Measurements of ionization in collisions between slow antiprotons and atoms

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Summary

Since 1986, the PS194 collaboration at LEAR has performed comprehensive studies of ionization and energy loss for fast antiproton impact on atoms, i.e. for collisions where the projectile velocity is greater than that of the target electrons. Important new information on dynamic many-body systems emerged from these measurements.

The combination of the planned CERN Antiproton Decelerator (AD) and a large "catcher" Penning trap makes it possible to produce a mono energetic beam of slow antiprotons extracted from the Penning trap.

This means that a whole new area of research in the field of atomic collisions can be investigated, namely that where heavy, slow, negative particles collide with atoms (or molecules). In such collisions, the projectile velocity is much smaller than that of the target electrons, and the ionization proceeds via quasi adiabatic channels. The interaction with the projectile is strong, and the presence of an antiproton inside the atom has a devastating effect on it's stability. A number of new, exciting and until now unobserved phenomena, such as "Fermi-Teller ionization", are expected to be important.

Considerable theoretical effort is presently being put into the development of new models that can describe these phenomena. However, there are large discrepancies between the various calculations of cross sections, even for such a basically simple system as the collision between an antiproton and atomic hydrogen.

We propose to investigate the ionization of light atoms and molecules (with special emphasis on atomic hydrogen and helium) by impact of antiprotons having energies of a few keV.

Such an investigation would cover the interesting gap between our "fast collision" investigations during the LEAR epoch, and the past (Simons et al) and future (PS205) investigations of the cases where the antiprotons have lost so much energy that they are captured by the target atoms, forming antiprotonic atoms.

Introduction

In the field of atomic collisions, the forces between the participating particles (electrons, nuclei) are precisely known, and it is a very good approximation to assume that the particles are structure less. By measuring the cross sections and spectra associated with few - particle atomic collisions, it is possible to learn about the importance of dynamic many-body effects in very "clean" cases. This is a great help to the advancement of many-body theory in general.

During the last decade it has been shown that comparisons between impact of particles and their antiparticles are very fruitful in this respect. This is due to the fact that if we change the projectile from, say, a proton to an antiproton, we only reverse the sign of the coupling constant, while all other important variables (such as projectile mass, velocity and the numeric magnitude of the charge) are unaltered.

In this appendix to proposal P 303 we first briefly recapitulate the progress made within the field of antiproton - atomic collisions until now, and then we suggest new investigations of the ionization of atoms by impact of slow antiprotons, a subject that until now has not been investigated.

PS194 experiments until now.

Since 1986, the PS194 collaboration at LEAR has performed thorough investigations of antiproton impact single and multiple ionization of atoms and molecules, of antiproton impact fragmentation of molecules and of the energy loss of antiprotons passing through matter.

(The list of almost 50 publications stemming from the PS194 collaboration is attached to this appendix. References to those papers are denoted by "R..." in the following text.)

The energy of the antiprotons in these investigations ranged from 20 MeV and down. The lowest impact energies (13 keV for some of the ionization measurements [R41] and 20 keV for the most recent energy loss measurements [R47]) were reached by slowing down the antiprotons in beryllium degraders.

At high velocity impact, where the parameter

$$q/v << 1 \tag{1}$$

(here q and v are the projectile charge and velocity, respectively, measured in atomic units), perturbation theory is valid, and the cross sections (for ionization, molecular fragmentation and energy loss) can be written as a Born series:

$$\sigma = a_1(v)\, q^2 + a_2(v)\, q^3 + a_3(v)\, q^4 + \dots \tag{2}$$

where the leading term

$$a_1(v)\, q^2 \propto |<\Psi_f|V|\Psi_i>|^2 \tag{3}$$

and V is the interaction between the projectile and a single target electron.

The higher-order terms contain contributions from "multiple" processes where, for example, the projectile interacts with each of two target electrons, with one target electron twice, or where an electron, after having interacted with the projectile, interacts with another target electron. These terms are very difficult to calculate, because it is necessary to take into account detailed many-body phenomena (such as electron-electron correlation) in a dynamical system. Their calculation constitute a great challenge to the atomic collision theory.

If we measure σ for equivelocity proton and antiproton impact, we can extract the first higher order Born term $a_2(v)\, q^3$ with high accuracy, and hence supply the theorists with benchmark data for tests of the various models. This has been the underlying strategy for much of the work of the PS194 collaboration:

A. Single ionization cross section for atomic and molecular targets.

We have measured the single ionization cross sections for antiproton impact on H_2, He [R41], Ne, Ar, Kr, Xe [R48], N_2 , O_2 , CO, CO_2 ,and CH_4 [R45, R49]. At high energy impact, the cross sections for single ionization are the same for antiproton and proton impact, in accordance with expectations. At lower velocities, polarization of the target electrons in the first part of the collision leads to a lowering of the antiproton cross section relative to the proton cross section. At projectile velocities between 10 and 100 keV, this trend is reversed, so that the antiproton cross section is the larger. This is due mostly to the reduced/increased binding of the target electrons when antiprotons/protons pass by the target nucleus inside the electron orbits. As an example of these data, we show the case of the helium target in figure 1. Note the great discrepancy between the two theoretical curves at low velocity.

B. Multiple ionization of atoms.

We have measured the cross sections for double and multiple ionization of He [R41], and of Ne, Ar, Kr, and Xe [R48]. In the case of the helium target, it was found that even at as high impact energies as 10 MeV, the double ionization cross section for antiproton impact is twice as large as the cross section for proton impact. At first sight, this seems to be in disagreement with eq(1), but it has been established by subsequent theoretical efforts, that this difference is due to an interference between double ionization mechanisms which are initiated by one and two interactions between the projectile and the target electrons, respectively, leading to a very large second term in eq(2) [2,3]. For the other targets, similar differences were observed.

C. Fragmentation of molecules.

We have measured the fragmentation pattern of N_2, O_2, CO_2 and CH_4 for proton and antiproton impact in the energy range 50-6000 keV [R45, R49]. It was shown that the same antiproton/proton difference as found for double ionization cross sections also exists between the cross sections for creation of the various charged molecular fragments. This is due to the fact that charged fragments are most often created as a result of simultaneous excitation and ionization - a phenomenon very similar to double ionization.

D. Energy loss.

We have measured the stopping power of 20 - 2000 keV antiprotons in Si, Al, Ti, Cu, Ag, Ta, Pt and Au targets. An example of our results [R22,R47] is shown in figure 2, where it can be seen that an effect similar to that found for the single ionization cross section is present: Protons loose more energy than equivelocity antiprotons due to the polarization of the medium. However, unlike the single ionization case, this trend exist also at low energies. The reason is unknown. Measurements of the antiproton stopping power in H_2 and He showing the same behaviour have been performed by the OBELIX collaboration [4].

Proposed investigations in the AD era.

With the development of techniques for the catching and cooling of substantial numbers of antiprotons in large Penning traps [5], it has become possible to create monoenergetic beams of low energy antiprotons i.e. antiprotons with velocities that are substantially smaller than those of the electrons in light target atoms. This means that for the first time, we are able to probe atomic collisions where

$$q/v \gg 1 \tag{4}$$

with heavy, negative projectiles. As an example, we may consider the impact of a slow antiproton on atomic hydrogen: During the passage of the hydrogen nucleus, the field from the antiproton will partly neutralize the attractive proton field, see figure 3. In the case of extremely slow collisions, the electron cannot be bound if the proton - antiproton distance is less than 0.639 a.u.,where the electronic binding energy curve crosses zero [6]. This is the so-called Fermi - Teller distance [7], which defines the minimum value of the ionization cross section. However, since the collisions that we shall study are not infinitely slow, and since the approach to zero of the electronic binding energy is exponential, ionization will take place at a greater distance of approach, the so-called "effective Fermi - Teller distance". In figure 4 is shown theoretical calculations based on the "Fermi - Teller" model, as well as on other models. These results are compared with our experimental data for antiproton impact single ionization of atomic deuterium [R44]. As can be seen, experimental information is greatly needed for impact energies below 30 keV: Some of the theoretical calculations predict that the cross section increases with decreasing projectile energy, others predict a decrease, and the result is that at a few kev projectile energy, there is an order of magnitude difference.

Atomic hydrogen is not the only target which is interesting to study: Recently [R41], we observed that the ratio between the double ionization cross section and the single ionization cross section of helium increases dramatically with decreasing energy when the antiproton impact energy approaches 10 keV. This is shown in figure 5. It is conceivable that the double ionization cross section becomes larger than the single ionization cross section, a situation which is quite unknown in the "normal" case of positive ion impact, but which illustrates very well how devastating negative, slow projectiles are to the atoms they might hit.

Recently, several theorists have addressed the question of double ionization in slow (adiabatic) antiproton - atom collisions. Janev, Solov'ev and Jakimovski [8] finds that double ionization takes place in two, consequtive steps: First the "outer" electron is ejected in a "Fermi - Teller" ionization, then, later, the next is ejected, so that these two steps are almost independent, and so that electron correllation is unimportant in the double ionization process. Kimura, Shimamura and Inokuti [9] suggest that the polarization of the electrons in the initial stage of the collision leads to a decreased binding, and therefore to a relatively increased electron - electron interaction, so that double ionization is almost completely governed by electron correllation. Clearly both of these theories cannot by true, and it is important to produce benchmark data for the future theoretical work.

Here we propose to measure the single ionization cross sections for 1 - 10 keV antiproton impact on atomic deuterium, helium and heavier atoms, as well as the multiple ionization cross sections of helium and heavier atoms.

Experimental technique

We plan to use the Antiproton Decelerator AD [10] in connection with a large "catcher" Penning trap such as the one presently used by the PS200 collaboration. It has already been established that this trap is able to catch and cool large numbers of antiprotons extracted from LEAR, with an efficiency of 0.2% or higher [5].

From the AD, which is expected to produce one bunch of 2 10^7 antiprotons per minute of the same 105 MeV/c as delivered by LEAR, we can therefore expect that the PS200 trap can capture and cool 4 10^4 antiprotons. If it is possible to extract around half of these antiprotons, we should obtain 300 per sec of monoenergetic antiprotons of an energy that can be varied between say 1 keV and 10 keV.

These antiprotons would be transported to our target setup through a differentially pumped beamline such as the one presently installed at the PS200 trap by Y. Yamazaki.

We plan to use essentially the same target arrangement as the one used in our recent measurements of the single ionization cross section of atomic deuterium [R44], see figure 6, but in this case we shall of course not have to degrade the antiproton energy, and it is not necessary to measure the energy of the individual antiproton.

To estimate the beam time needed for a cross section measurement, we may compare with the lowest energy data point reported in [R44]: Here we obtained a cross section with an accuracy of 20% by passing 5 10^6 antiprotons of energy around 30 keV through the target region. In the new scheme, this would last 5 10^6/300 = 1.7 10^4 sec or 5 hours. A cross section of 10% accuracy would be obtained in less than 24 hours of beam time.

In this estimate we have assumed that the low energy ionization cross sections are of the same size as their magnitude at 30 keV which is likely to be a good guess. We expect that a considerably higher catching efficiency can be obtained as more experience is gained with the Penning trap, but have used the pessimistic value already obtained.

For other targets, the measurements will be much faster to perform, because of the much higher target densities that can be obtained with "normal" gases that do not have to be dissociated before emission into the target region. We should be able, for example, to get a 10% measurement of the single ionization cross section of helium in a few minutes. The ratio between the double and the single ionization cross sections can most likely be obtained with reasonable statistics within 2 hours of beam time.

It would be helpful if the 105 MeV/c beam from the AD could be extracted directly (or only slightly degraded) into our target region. This would make possible a direct normalization of the measurements at low antiproton energy to our data obtained at higher projectile energies. Such a direct extraction could be obtained either if the Penning trap could be moved out of the beam, or if the trap was simply inactive, with the "catching" degrader removed.

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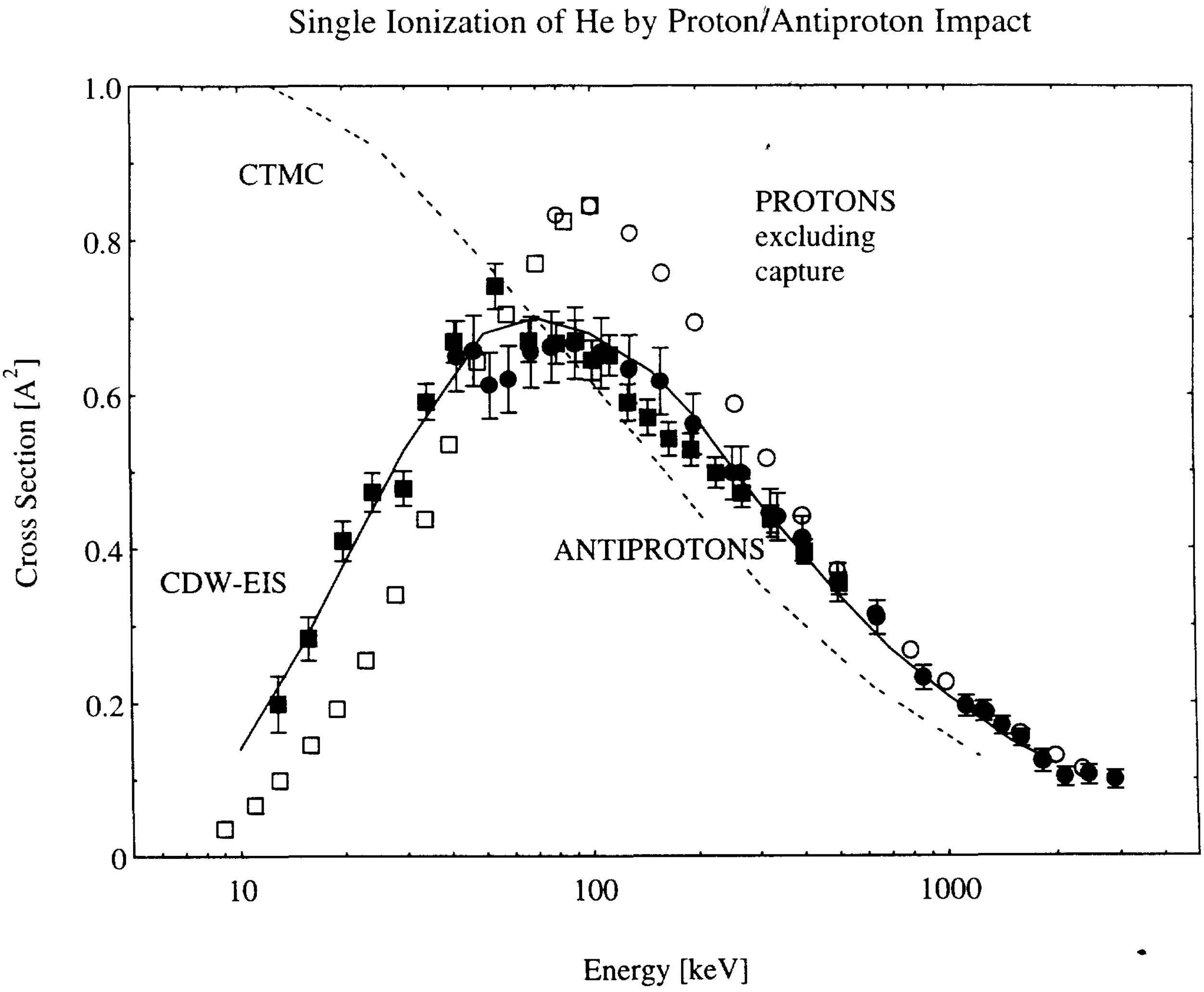
Figure captions

Figure 1.	Our data for the antiproton impact single ionization cross section of helium are compared with proton data as well as with theoretical calculations [R41].
Figure 2.	Our measurements of the stopping power of antiprotons passing through Si [R22,R47] are compared with recommended values for protons.
Figure 3.	The proton - antiproton combined electric field for collisions between antiprotons and atomic hydrogen.
Figure 4.	Our experimental data for the single ionization of atomic deuterium by antiproton impact are compared with various theoretical results. For references, see [R44].
Figure 5.	The ratio between the double- and the single ionization cross sections of helium for impact of antiprotons and protons is shown here as a function of the projectile energy [R41].
Figure 6.	Here is shown a slightly modified version of the target arrangement used in most of our measurements of ionization cross sections for high energy antiproton impact. (1) and (7) indicates the interaction region, (2) shows the extraction and focussing elements, and (3) the detector for the created slow ions. (4) is the antiproton detector intended for normalization. (5) and (6) shows the atomic hydrogen source with its RF cavity.

Figure 1. Our data for the antiproton impact single ionization cross section of helium are compared with proton data as well as with theoretical calculations [R41].



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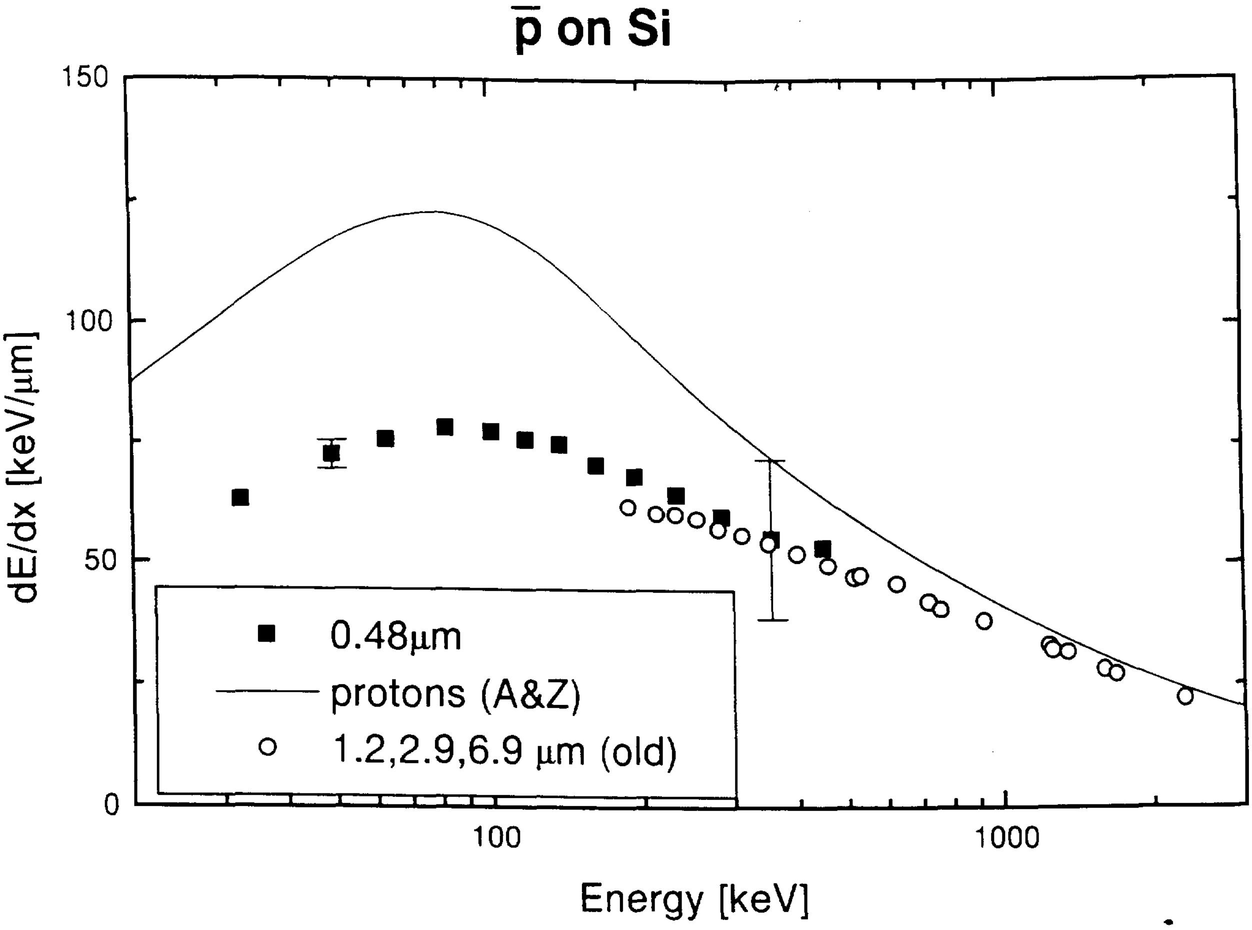

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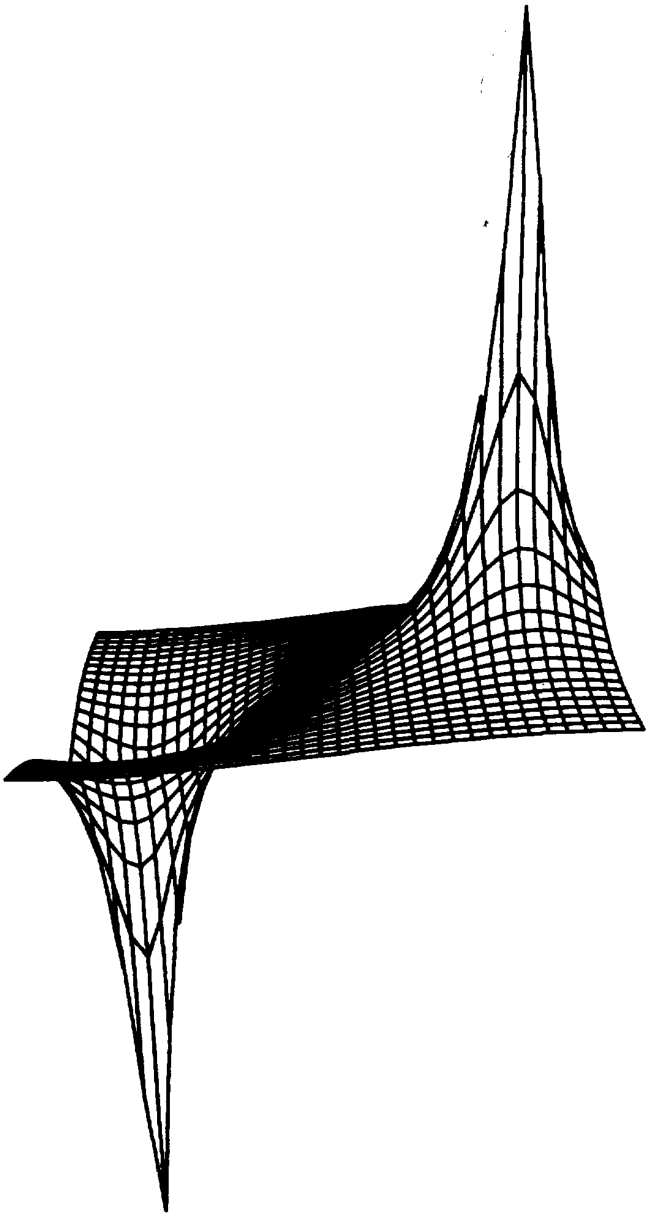

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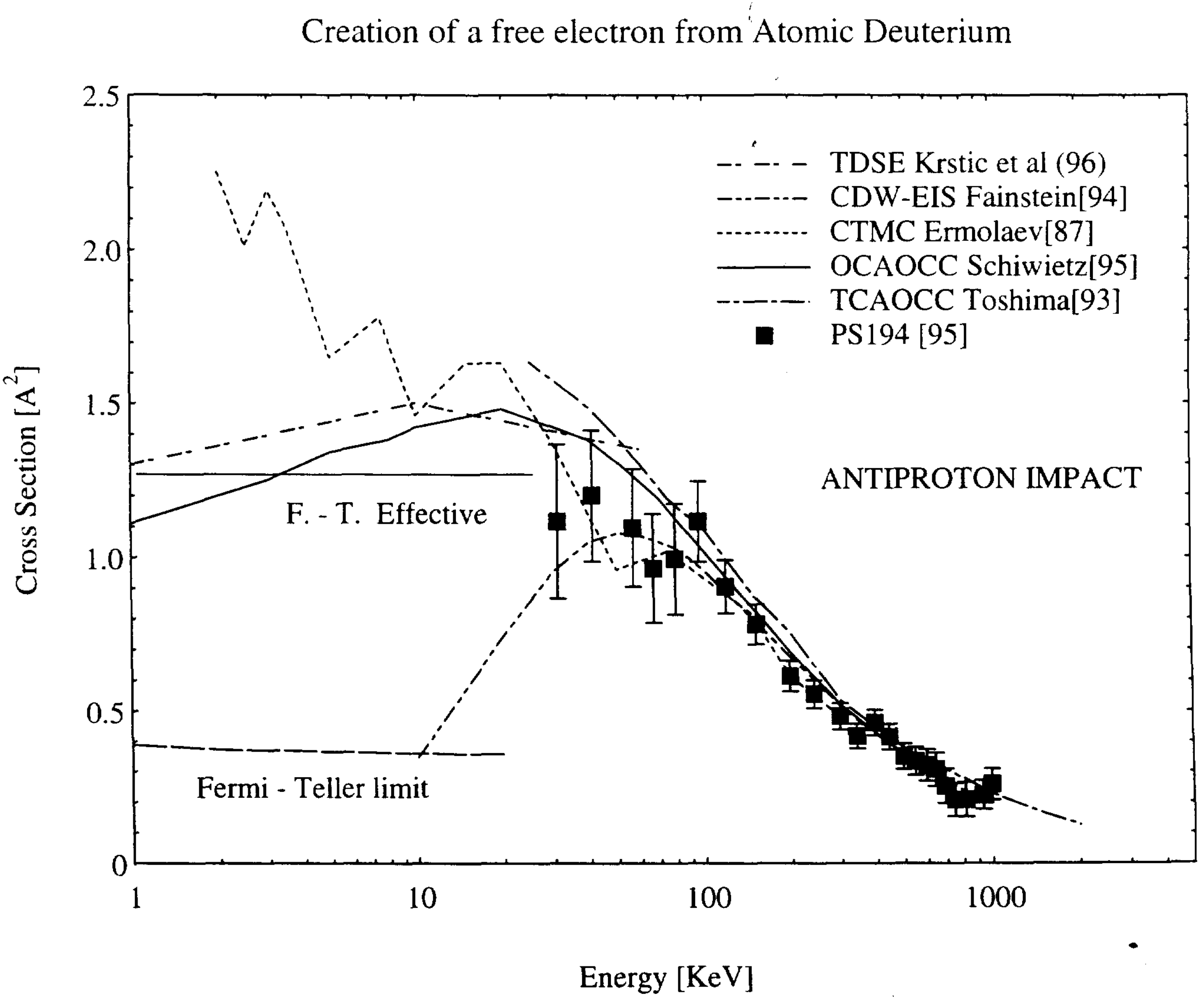

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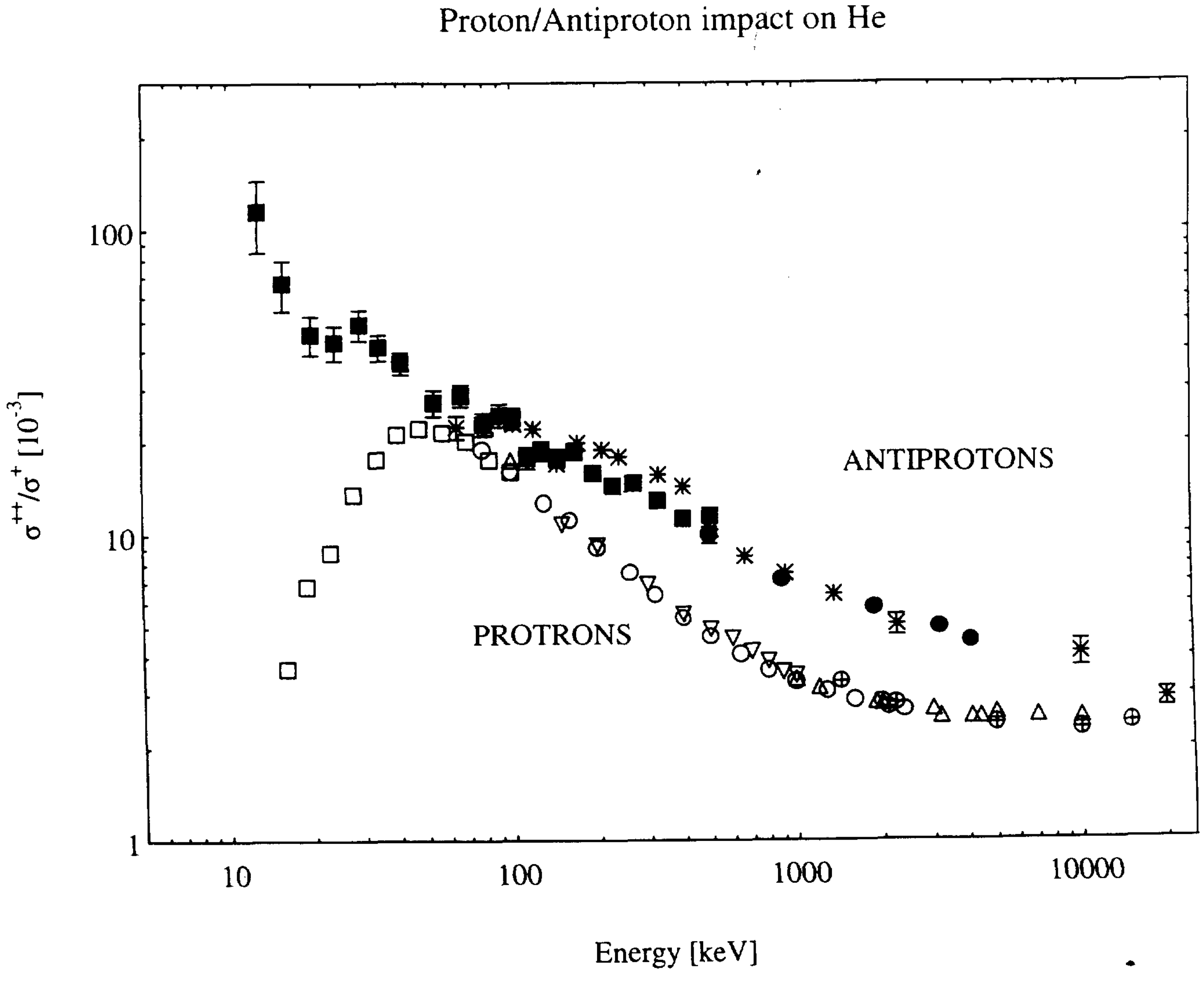

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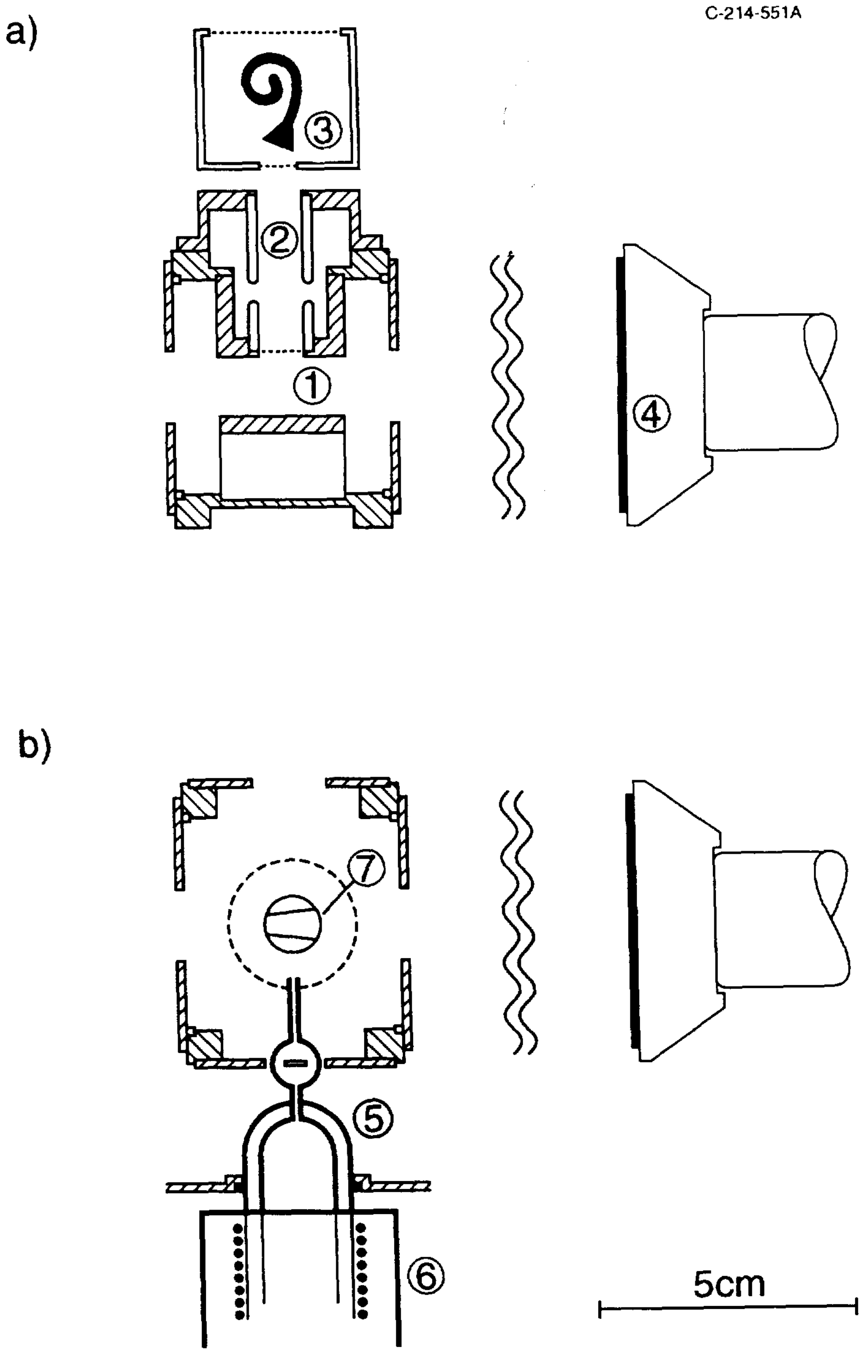

Appendix

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Nuclear Physics with Low Energy Antiprotons From the Antiproton Decelerator

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1. INTRODUCTION

During the last few years a large program of the nuclear physics research using the stopped and energetic antiproton beam from the LEAR facility was performed within PS203, PS208 and PS209 experiments. The experimental as well as the theoretical effort was mainly concentrated on two subjects. First, the investigation of the energy transfer, "heating" of nuclei by stopped and energetic antiprotons was undertaken. A variety of the experimental tools were used, ranging from the simple inclusive radiochemical experiments [MOS89, JAS93a] up to the very sophisticated ones in which detectors covering almost the full solid angle were successfully used [GOL96]. Second subject was devoted to the nuclear structure rather than to the nuclear reaction problems. Using the stopped antiprotons and taking advantage of the very peripheral character of the antiproton annihilation process in antiprotonic atoms, the composition and extent of the nuclear periphery were investigated. The new, radiochemical method [JAS93b, LUB94] testing the peripheral neutron to proton density ratio was supplemented by the investigation of the shifts and widths in the antiprotonic X-rays of many isotopes.

A number of new and exciting information was gathered for both subjects, with only a small part of the experimental data evaluated as yet. In spite of this fact it is already clear that a number of questions will be worth of continuation with the new AD facility. Some examples with a short motivation are presented below. A more detailed program of the "Nuclear Physics with AD" will be given later.

2. HEATING OF NUCLEI WITH ENERGETIC ANTIPROTONS

The investigations of the energy transfer have demonstrated that for the highest antiproton energy available in LEAR, the nuclear temperatures reached using antiprotons were not too different than for "normal" projectiles (proton, light or heavy ions) of energy comparable to the kinetic plus annihilation energy of antiprotons (i.e. 1.2 + 2.0 GeV). However, around 3 GeV bombarding energy the average energy transfer for e.g. proton induced reactions saturates: the increase of the projectile energy no more leads to the substantial change in the reaction characteristics such as the slope of the mass yield distribution of heavy reaction residues. It is not clear if a similar saturation would be observed with antimatter projectiles when their kinetic energy increases. A deeper penetration inside the nucleus of the more energetic antiprotons together with more effective kinematical focusing of the produced pions can lead to nuclear temperatures substantially higher than for protons or heavy ions. These temperatures would be obtained in a much more "clean" way than using heavier projectiles, which besides heating involve a number of other collective phenomena as rotation, compression or deformation.

The AD facility will offer the $\bar{p}$ pulses with momenta from 3.6 GeV/c down to 100 MeV/c. We propose for the beginning to investigate the $\bar{p}$ + ^{197}Au reactions, using the radiochemical method (other targets are considered as well). The observables will be the mass distributions of the reaction residues. In particular we will investigate the yield ratio of light and heavy products and the production of a few intermediate mass fragments accessible using radiochemical method (as ^{7}Be, ^{22}Na, ^{24}Na).

Previously we have investigated the $\bar{p}$ + ^{197}Au reaction for stopped and 1.9 GeV/c antiprotons. The 1.9 GeV/c data, shown in Fig. 1, were obtained using a thick Au target (500 mg/cm^2) irradiated with about 6 10^{10} $\bar{p}$ (assuming 4$\cdot 10^7$ $\bar{p}$ per pulse and pulses every minute similar statistics would be obtained using AD during 24 h).

We expect, when using the highest AD energies available, to answer the question if more than two-fold increase in the antiproton energy in comparison with LEAR possibilities allows to rise substantially the amount of energy which can be stored in the nuclear systems.

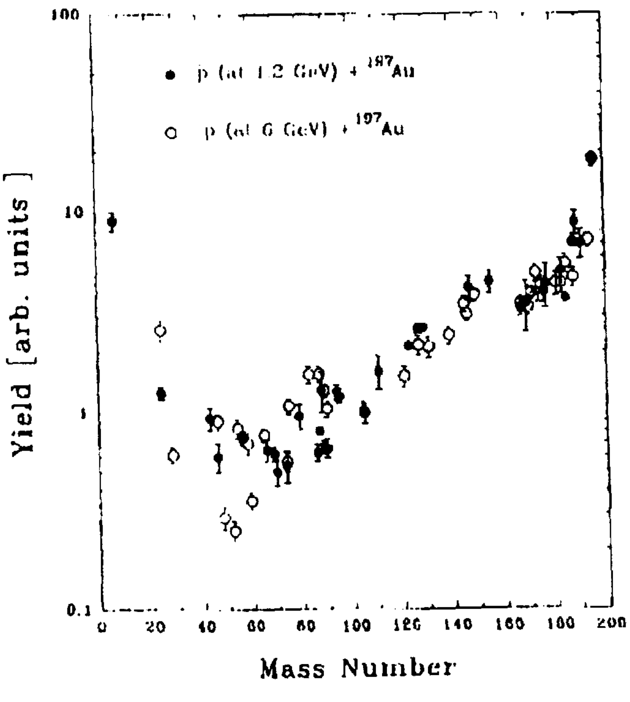

Fig. 1. Mass yield for the production of heavy residues in 1.2 GeV $\bar{p}$ + ^{197}Au (solid circles) and 6 GeV p + ^{197}Au (open circles) induced reactions. The antiproton data are from the PS208 experiment and proton data from [KAU80]. The antiproton yields (as yet available only in arbitrary units) were roughly normalised to the proton cross sections in the mass range 170 ≤ A ≤ 190.

3. INVESTIGATION OF THE NUCLEAR PERIPHERY

Although the previously indicated radiochemical method as well as the determination of level widths of the antiprotonic atoms were extensively used [JAS97] for the study of the nuclear periphery a number of interesting cases is still worth to be investigated.

As example we propose the measurements of the width of the n=5 and n=4 levels in Ca isotopes. The yield of 5→4 transition is very weak (≈ 2%) and it was impossible to single out the corresponding line from the background during the last PS209 experiment when calcium carbonate targets were used. The estimate of the gain which would be obtained using metallic targets indicates, that such a measurement is perfectly possible.

We expect to perform it behind the "general purpose" Penning trap. We hope to have these about 30 min "spills" of $1000\bar{p}$ps. The necessary antiproton X-ray coincidence would be obtained mounting targets inside a 4π pion counter. Very thin (therefore inexpensive), targets will be used. About 24 hours of $1000\bar{p}$ps per target will be necessary.

As we have already determined the width of the n=6 level in ^{40}Ca, ^{42}Ca and ^{48}Ca the proposed measurement can furnish the information on the three level widths in all these isotopes. This would be quite unique in exotic atom physic and allow the peripheral matter density analysis in Ca nuclei with high precision. (The physics case here is presented e.g. in [GJB92]).

4. CONCLUSIONS

In this short Letter of Intent we have only indicate some examples of the possible use of AD in the field of nuclear physics. A more elaborate research program is in preparation.

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Letter-of-Intent

STORED ANTIPROTONS FOR RADIOISOTOPE PRODUCTION AND APPLICATIONS

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ABSTRACT

We intend to propose a program of studies of the production of short-lived light radioisotopes by stopped antiprotons using techniques of the PS209 collaboration. The interest in these measurements lies in furthering understanding of the neutron halo surrounding nuclei, as well as development of alternate methods of producing and delivering radioisotopes for Positron Emission Tomography (PET). We also intend to propose irradiation of targets by low energy antiprotons (<100 MeV), the purpose of which is to validate a new concept called Positron Assisted Antiproton Tomography (PEAT). These efforts will require modest numbers of antiprotons in a dedicated AD beam.

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I. Introduction

The short-lived radioisotopes C^{11}, N^{13}, O^{15}, and F^{18} are used in Positron Emission Tomography (PET) as an important diagnostic of human function and disorders. Their current use is limited to treatment centers which are close to a cyclotron production facility. Antiprotons delivered in a portable Penning trap can offer greater accessibility to these isotopes by patients in more remote areas.

These isotopes also are of interest to the neutron halo problem, as they result from distant annihilation of antiprotons on a neutron at the surface of the parent nucleus. Recent measurements at LEAR of yields in compounds suggest surprisingly, large yields.

It has been demonstrated that C^{11} production can be used to measure density profiles and hence assist proton radiotherapy. Modest numbers of antiprotons offer considerable improvements over this technique in the so-called Positron Assisted Antiproton Tomography (PEAT) concept.

We intend to propose to measure the production of these isotopes by stopped antiprotons, confined first in a Penning trap in a dedicated Antiproton Decelerator (AD) beamline, and then transfered to a portable Penning trap. Separately, we will irradiate phantom targets with antiprotons at energies up to 100 MeV to verify the PEAT concept.

This program of fundamental and applied physics requires a dedicated area at the AD, and can be carried out with modest amounts of AD beamtime.

II. Portable Trap Development

In a detailed proposal that will be forthcoming, we (Penn State) intend to argue that it will be possible to store and transport modest numbers of antiprotons ($<10^9$) in a portable antiproton Penning trap. Filling of this trap will require an area at the AD with a permanent Penning trap, e.g. the current PS200 Catcher Trap, used as a transfer vehicle to the portable trap. A portable trap is presently under development at Penn State[1]. We are currently at the point of having stored electrons for periods of minutes, and anticipate that we will demonstrate extended H^+ storage in the next few months. We fully expect to be able to store antiprotons by the startup of the AD in 1999.

III. Radioisotope Production

We (Munich, Warsaw) would be prepared to measure primary yields of light positron-emitting nuclei used in Positron Emission Tomography[2]. Simulations (Penn State) indicate that it may be possible to produce up to one radioisotope atom per antiproton, including production by primary antiproton annihilation as well as secondary production by charged annihilation pions trapped in a magnetic bottle. The long-term interest of this program would be to produce in situ C^{11}, N^{13}, O^{15}, and F^{18} , with lifetimes of 20, 10, 2 and 110 minutes respectively, in widely-distributed PET treatment centers, in contrast to the present method of producing them with cyclotrons in a limited number of regional centers[1] and transporting them to treatment centers with significant decay losses.

We note that these predicted yields, if confirmed, lead to production of these radioisotopes with activities not in excess of 200 μCi per 10^9 antiprotons. These are rates that are readily measurable, yet do not pose a safety problem. Long term scale-up, such as with antiprotons produced at Fermilab @ $10^{\wedge 12}$per hour in the future, would provide hundreds of mCi per hour, sufficient to provide many treatments @ 10 mCi[1].

IV.Neutron Halo in Light Nuclei

Recent preliminary measurements by the PS209 collaboration (Munich, Warsaw) on the yield of C^{11} and F^{18} produced in thin teflon and plexiglass targets, corrected appropriately using modifed Fermi-Teller theory for compounds[3], indicate a higher than anticipated production yield by stopped antiprotons. The yields are typically in the range of 10-15% per antiproton, roughly a factor of 2-3 larger than yields of single-neutron depleted nuclei with larger atomic number[4]. We would like to confirm these measurements with better statistics and do measurements in pure C^{12}, N^{14}, O^{16}, and F^{19} targets, in order to extend neutron halo investigations into this potentially very interesting low atomic number regime.

V. Positron Assisted Antiproton Tomography (PEAT)

We (Penn State) have recently noted that C^{11} production by a low energy antiproton beam in human patients could serve as an excellent determiner of tissue density along the path of the antiproton, including its stopping point. Tissue density profiles are essential to accurate placement of intense proton radiotherapy beams into tumors. Similar techniques are currently under investigation with proton beams[5] at TRIUMF (and PSI) and heavy ion beams at GSI Darmstadt.

The advantage of antiprotons is that they produce C^{11}in greater amounts along the trajectory of the antiproton due to the additional annihilation cross section (not available to protons) and resultant secondary annihilation pions, and in addition provide a unique C^{11}image at the stopping point. We intend to propose to irradiate phantom targets, e.g. lucite, with antiprotons below 100 MeV, and with the assistance of a PET camera, demonstrate this concept. In principle, one AD shot is capable of producing a quality image.

VI. References

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Letter-of-Intent

Antiprotons for Plasma Heating

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ABSTRACT

An experiment is proposed to measure the energy deposit of proton-antiproton-annihilation product in gasous hydrogen or xenon and compare it with numerical simulation that have been conducted with respect to propulsion applications. For that purpose, a reaction chamber filled with the test gas is put into the beamline of the AD or behind a penning trap used as an accumulator. The AD is best suited for that purpose as all the antiprotons are needed in one shot. The antiprotons are degraded with a tantalum foil and annihilate in the center of the chamber. A pulsed magnetic bottle is used to trap the annihilation products within the gas where their energy is transferred to the gas. The energy deposit in the gas will cause a slight change in density which is measured with an interferometric set-up. The resulting patterns can then be used to calculate the energy deposit in the gas.

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Experiment set-up

A cylindrical gas chamber of 70 cm length and 70 cm diameter filled with hydrogen or xenon at a pressure of 0.1 bar is put into the beam line of th AD or behind a penning trap. Xenon is used for its better change of refractive index when the density changes are measured whereas hydrogen would be the ideal gas for propulsion applications The antiprotons enter the chamber through a tantalum window that acts as a degrader. The thickness (70-80 µm) of the window is chosen in such a way that most of the antiprotons will stop in the center of the chamber where annihilation occurs. The pressure of 0.1 bar in the chamber is a trade-off between better stopping at higher values and higher density changes at lower values.

To prevent the annihilation products from escaping the chamber a pulsed magnetic bottle is used. However, it is not possible to trap all the particles created from the annihilation. The highest energy particles will either touch the chamber wall of escape through the ends of the bottle. A Monte-Carlo simulation showed, that with a field of 20 Tesla at the ends and 5 Tesla in the center, 7.5% of the initial energy remains trapped. The magnetic bottle will constist of two pulsed pinch coils with a field of 18 T each operated from a precharged capacitor bank and a possible permanent magnet with 1.5 T.

The annihilation remnants will deposit parts of their energy in the gas which is heated up slightly. However, with the current amount of antiprotons, a direct measurement of the temperature rise is not possible. Thus an indirect measurement using an interferometric set-up will be used: The temperature rise in the gas will cause a change in density. When a laser beam is sent through the chamber along the axis of the cylinder, all the density changes will be added up and will cause a phase shift of the incident beam. To incease the sensitivity of the set-up, a multipath approach will be used. After leaving the chamber, the laser beam is brougth to interference with a reference beam that was bypassing the chamber. The resulting light pattern will be detected with a CCD camera. The laser beam will run through the chamber as a light sheet using cylindrical optics and will allow for a measurement of the radial distribution of the energy deposit.

The calculations in [2] have been conducted with all the particles generated in the center of the chamber. This is not true for the real experiment as the particles emerge from the degrader foil with an energy spread. This will cause the heated area to have more the shape of a spindle. However the calculated results will remain the same, as one is integrating the phase shifting effects of the density changes along the optical path.

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