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PHYSICS WITH ULTRA LOW ENERGY ANTIPROTONS – THE ANTICYCLOTRON

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1. INTRODUCTION

A growing interest is evident in physics with very low energy antiprotons. Experiments to compare the antiproton gravitational and inertial masses with those of the proton already feature in the LEAR approved experimental program [1] [2] [3] and require beams of keV or thermal energies. Further experiments to study antihydrogen formation and its CPT and gravitational properties are under discussion. Several schemes have been proposed for efficient deceleration of LEAR beams [4] to keV energies. In spite of their merits, none of these ideas has yet been followed up. Following an earlier suggestion [5], we summarise here a method based on modification of the existing KfK 'cyclotron trap' [6]. This method requires almost no capital investment, and appears capable of delivering at least 20% of the 2 MeV LEAR beam at energies below 10 keV with phase-space characteristics suitable for further cooling and deceleration [7].

2. MODIFICATION OF THE KfK CYCLOTRON TRAP-THE 'ANTICYCLOTRON'

The KfK 'cyclotron trap' is a high field-index cyclotron operating in inverse mode, and has been successfully used for investigations of antiprotonic X-rays for several years [5]. Deceleration is done by degradation in a gas filling the space between the poles. If the pressure is low enough, multiple scattering and energy straggling are 'contained' by the normal focussing properties of the cyclotron field. For antiprotonic X-ray studies, a continuous beam is injected into the field. The antiprotons spiral into the magnet centre and are captured there by gas molecules when their energy has reached 10-50 eV. Thus, in normal use the gas serves the double purpose of degrader and X-ray target. Very few antiprotons are lost by in flight annihilation or scattering during deceleration, so that the number of captures is nearly the same as the number successfully injected into stable orbits. The space distribution of captured antiprotons has been determined by measuring the X-ray intensity distribution, and consists of a cylinder of about 15 mm radius and 40 mm length. Typical pressures for X-ray experiments are 10-30 mbar for hydrogen, giving an injection to capture delay time $\sim 1\ \mu s$.

The new feature we propose is the addition of an electrostatic extraction field in the 12 cm diameter axial borehole of the magnet. This field would be switched on just before capture and would transport the antiprotons to a UHV electromagnetic trap situated 50-100 cm along the axis from the magnet centre. With a lifetime in the trap of hours or days, further stochastic, resistive or electron cooling could be carried out to reach thermal energies. Since the trapping is done outside the cyclotron in this new mode, we replace the term 'cyclotron trap' by the more appropriate term 'anticyclotron'. To keep the extraction field within reasonable limits, a gas pressure one or two orders of magnitude lower than the above is needed. This makes the injection less efficient and the deceleration time longer. The delicate balance between the E, H and dE/dx forces which determines these effects as well as the extraction characteristics has been investigated by a computer simulation of all phases of the new operation. The equations of motion of a sample of about 90 antiprotons were integrated numerically from injection to extraction from initial angles and momenta chosen by the Monte Carlo technique. The beam momentum was assumed to be 2 MeV, with $\Delta p/p = 0.1\ \%$ and emittances 10π mm mrad (H) and 20π mm mrad (V). Some of the results are summarised in figures 1-2 [8] and are valid for extraction of a single injected burst as well as for repeated extraction in the case that the central region is continually refilled by a 'dc' beam. By careful optimisation of the initial beam position and angle, betatron oscillations can be excited such that an injection efficiency of 20% - 30% is achieved. The figures refer to a pressure of 0.3 mbar hydrogen gas, and resulting in a deceleration time of 20 μs to reach an energy of about 10 keV. Figure 1 shows the axial energy distribution of the extracted sample at a distance of 32 cm along the axis of the anticyclotron. This point is reached about 500 ns after the field is switched on at $t = 20\ \mu s$. Figure 2 shows the distribution of times of arrival at this point. All the antiprotons arrive in a peak with $\sigma = 80$ ns. For figures 1-2, the extraction field was 500 V/cm. If the field is decreased to 300 V/cm, figure 1 is essentially unchanged, while a broader component containing about 25% of the sample appears under the 80 ns peak of figure 2.

The validity and accuracy of this type of computer model has been well established in the antiprotonic X-ray experiments.

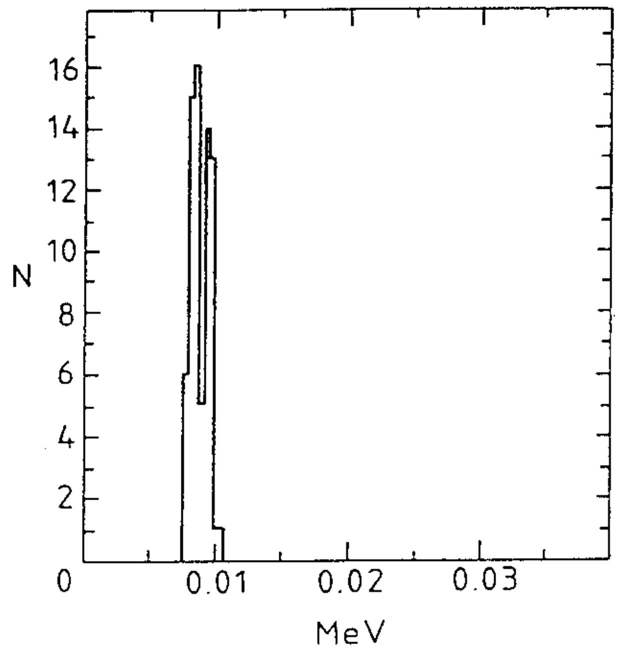

Fig.1 Axial K.E. distribution at z = 32 cm

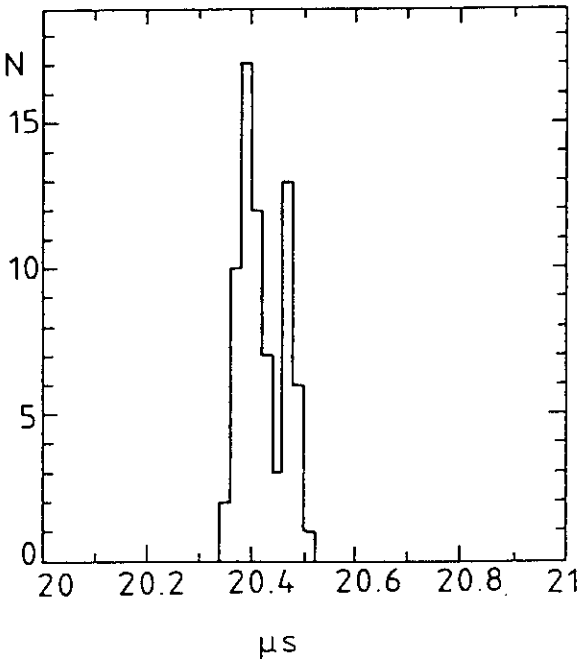

Fig.2 Distribution of arrival times at z = 32 cm

3. PHYSICS WITH THE ANTICYCLOTRON

A primary motivation for the present studies is the production of a $\bar{p}$ sample at T < 300 K for the antiproton gravitation experiment (PS200). However, traversal of nine orders of magnitude of energy clearly opens up in itself a considerable new field of research. Only a brief sketch of this is possible here:

a. Detailed analysis of the extraction process as a function of the extraction field strength and delay, the gas Z and the pressure would yield valuable information concerning the underlying ionisation and dE/dx processes in the tens of keV region where almost no such data exists. This information is of fundamental importance to many LEAR users.

b. All antiprotons in figures 1-2 could be collected in a high vacuum Penning type trap of 10-15 cm length and 4 cm radius and cooled from keV to eV energies by one of several methods [9], [10]. If the $\bar{p}$ are allowed to be captured in such a trap at controlled, very low residual gas pressures, exotic atom formation and X-ray cascade studies can be made under highly idealised conditions (negligible Stark effect, improved detector geometry and acceptance etc.) which have previously been unobtainable. Measurements with Auger electrons would in addition open up an entirely new field in exotic atom Physics. Improved studies of strong interaction shifts and widths may also be possible in this idealised environment. Finally QED tests on highly ionised atoms are conceivable following the discovery [5] that antiprotons ionise gas atoms with Z < 60 almost completely during the cascade.

c. The $\bar{p}$ can be transferred to a further trap before capture which can be dimensioned to allow rapid cooling to extremely low (< 1 meV) energies. Apart from its function as the 'launching' trap for PS200, this small trap could form the first step towards antihydrogen formation for CPT tests and studies of the gravitational properties of neutral antimatter.

d. Controlled release and reacceleration from the cold $\bar{p}$ sources of b) or c) is possible and would provide $\bar{p}$ beams of energies in the range 10-200 keV for a variety of further studies. This possibility may be of interest for the high precision comparison of the $p-\bar{p}$ inertial masses.

4. CONCLUSIONS

We are investigating the conversion of the KfK 'cyclotron trap' into a low energy antiproton facility. Much of the development will take place within the PS200 program. We hope to do definitive tests soon.

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