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AUTHOR(S): Michael V. Hynes, P-15

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PHYSICS WITH LOW TEMPERATURE ANTIPROTONS

Michael V. Hynes
Los Alamos National Laboratory
Los Alamos, NM 87545

ABSTRACT

The advent of the new beam cooling techniques and their application to antiproton production has already made possible major advances in high energy physics. These same techniques offer uniquely exciting possibilities for ultralow energy physics. Through a combination of deceleration stages, antiprotons produced at several GeV (where the production cross section is at a maximum) can be made available for experiments at thermal velocities. High precision measurements of the antiproton mass and magnetic moment can be performed. Comparison of these measurements with those for the proton will test the CPT invariance of internal baryon dynamics at an unprecedented level. In addition the gravitational constant for antimatter can be measured for the first time, and to high accuracy. Each of these measurements will provide very important information on the dynamical symmetry between matter and antimatter in our universe. Antiprotons at thermal velocities will also make these fundamental particles available for experiments in condensed matter and atomic physics. The recent speculation that antiprotons may form metastable states in some forms of normal matter could open many new avenues of basic and applied research.

I. Introduction

In collaboration with groups from Texas A & M, Rice University, and UCLA, several of us at Los Alamos have been studying the experimental aspects of implementing the gravitational mass measurement of the antiproton originally discussed by Goldman and Nieto.1) The basic approach in this experiment involves a time of flight (TOF) measurement where the antiproton is launched either up or down in a gravitational field. Such an approach is in analogy to that used by Witteborn and Fairbank2) for the electron measurement. In order to bring the TOF distance and timing into an experimentally tractable range, very low antiproton energies (velocities) are required. Indeed these energies are better described in terms of degrees Kelvin rather than in electron volts. The scale for these energies and how they relate to the physics and experimental equipment used at other energies is displayed in Fig. 1. The thermometer shown in the figure is calibrated in electron volts down the left hand side with the corresponding temperature in degrees Kelvin on the right. The physics of interest is schematically indicated on the right hand side whereas on the left, the experimental equipment used is listed. The realm of high energy physics is somewhat arbitrarily indicated to start at 10^{14} °K (10^{10} eV) and extend upward without limit thru 10^{16} °K (10^{12} eV). The SPS for instance operates at $\sim 2.7 \times 10^{15}$ °K (2.5×10^{11} eV). Normal LEAR operations span the temperatures between $1.5 \times 10^{13} - 5.8 \times 10^{10}$ °K (1.3 GeV – 5 MeV) with some luck. On the upper end of this range the $\overline{\Lambda}\Lambda$ experiment runs with all the stop experiments at the lower end. As shown in the figure, antiproton temperatures in the range of 1 – 10 °K are required for the gravity experiment. In order to achieve this antiproton temperature we are proposing to build an RFQ decelerator and ion trap system. Such a system will extend the normal LEAR operating temperatures by ten orders of magnitude. Such an extension of antiproton temperatures opens very exciting possibilities in atomic physics, condensed matter, chemistry and solid state.

II. The Low Temperature Beam Line

The overall system we are planning is displayed schematically in Fig. 2. A bunched beam of antiprotons is extracted from LEAR at 5 MeV or lower. The bunching cavity required in the LEAR ring would be matched to the operating frequency of the RFQ. The insertion of such a cavity and the techniques for both slow and fast extraction have been discussed recently by Lefevre and Mohl.3) The details of our design study for the RFQ decelerator and associated beam line elements were presented at this conference by Jim Billen. Briefly, a matching cavity is used to rotate the beam bunch in phase space to best match the acceptance of the RFQ. In our design study a 2-MeV bunched $\bar{p}$ beam was

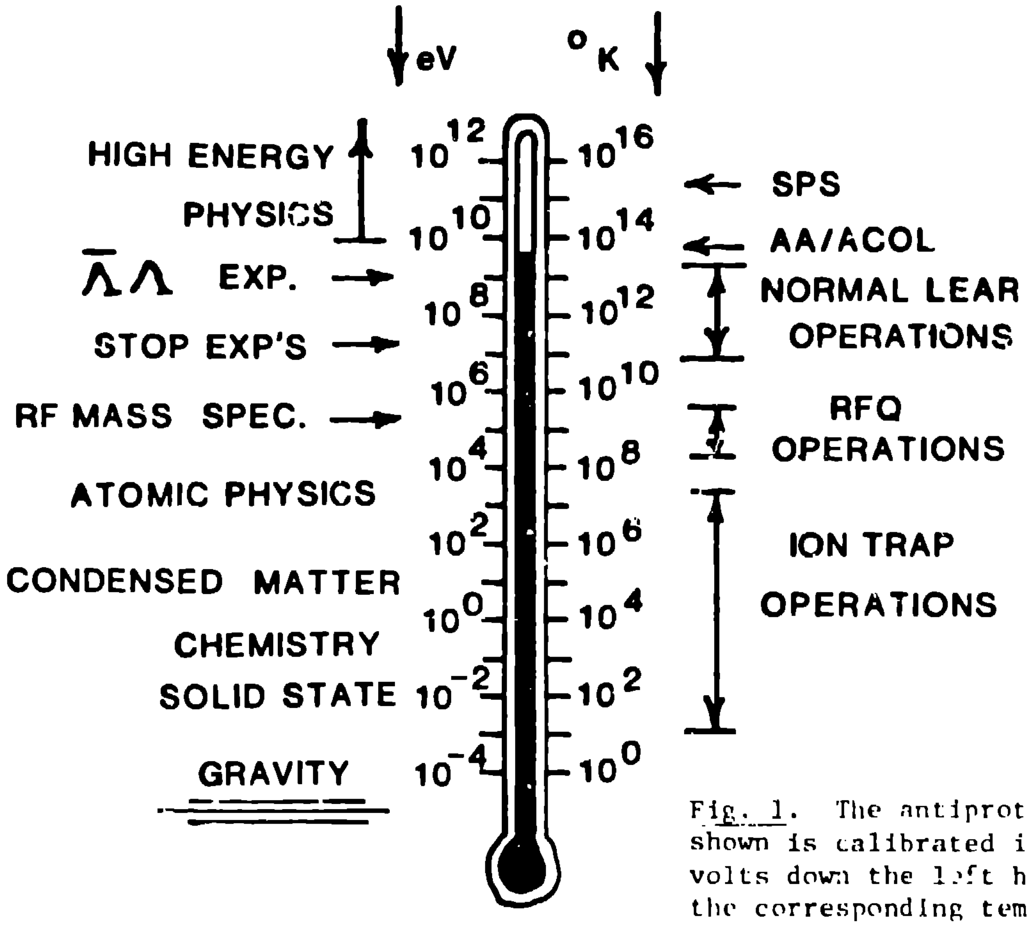

Fig. 1. The antiproton thermometer shown is calibrated in electron volts down the left hand side, with the corresponding temperature in degrees Kelvin down the right hand side. The physics of interest along with the equipment used in each energy regime is also shown.

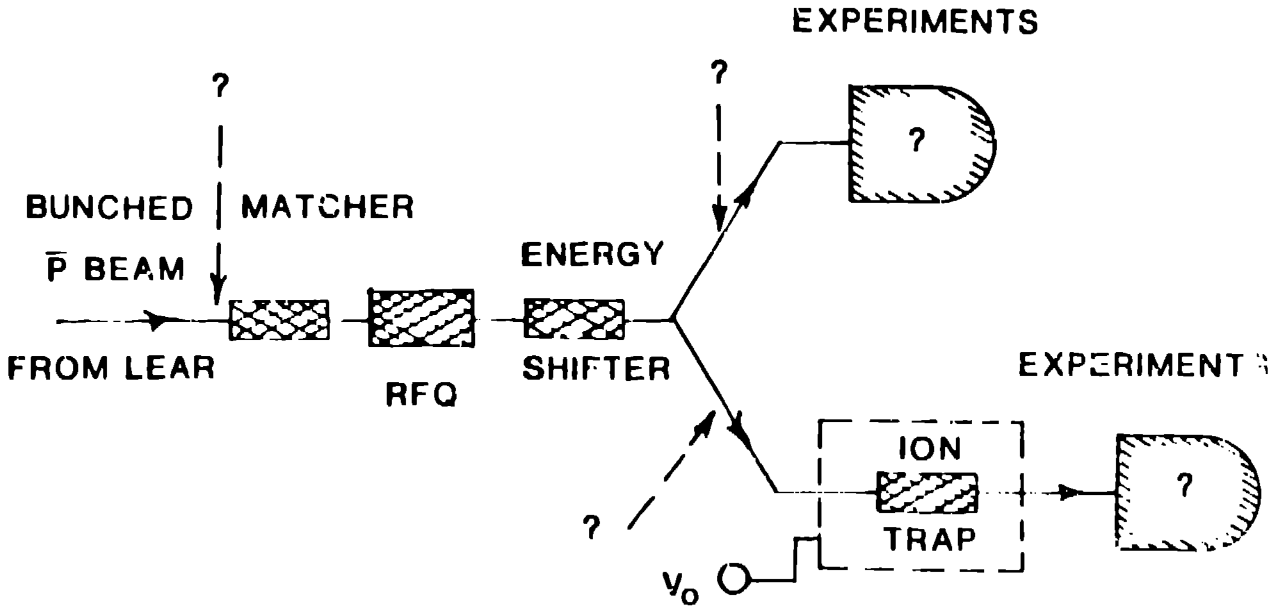

Fig. 2. Overall system for low energy/low temperature operation (see text also).

presumed to be available from LEAR. For energies substantially more than this (> 5 MeV), a small drift tube linac may be required. The RFQ will decelerate the antiprotons to approximately 100 keV with very little (< 10%) emittance growth. The lowest energy available from the RFQ is still being studied. The 100 keV output energy was chosen to illustrate the use of an energy shifting cavity located after the RFQ. This device allows for a continuous adjustment of the beam energy by as much as ± 80 keV. Thus beams between 20 - 180 keV can be made available. A debunching cavity follows the energy shifter at a suitable drift length to once again rotate the output phase ellipse to achieve the best energy resolution. For example, at 20 keV the beam energy spread would be ± 0.5 keV. As shown in the figure, the beam now can be used directly for experiments. The RF mass spectrometer experiment which will measure the $\bar{p}$ inertial mass to 1×10^{-9} could use this beam. Many of the stop experiments could eliminate their degrader foils using this new beam as well. On the other hand, the beam can be transported to our planned ion trap for further energy reduction. Using an ion trap in such a capacity (and indeed for the gravity measurement) has been discussed by the groups from Pisa and Genoa.$^{4)}$

In our ion trap scheme, we envision using a large, possibly cylindrical, ion trap$^{5)}$ for catching and cooling the beam from the RFQ to electron volt energies. Such a trap is shown schematically in cross section in Fig. 3. The entire trap system will most likely be operated at an elevated voltage to take advantage of some amount of D. C. deceleration (V_0 in Figs. 2 and 3). As the beam burst approaches the trap, the front endcap electrode (see Fig. 3) is run at the elevated ground potential (V_0), while the rear endcap electrode is operated at a total voltage greater than the beam energy. As the beam burst enters the trap it will turn around at the rear endcap electrode, at which point the voltage on the front endcap electrode is quickly brought to the same

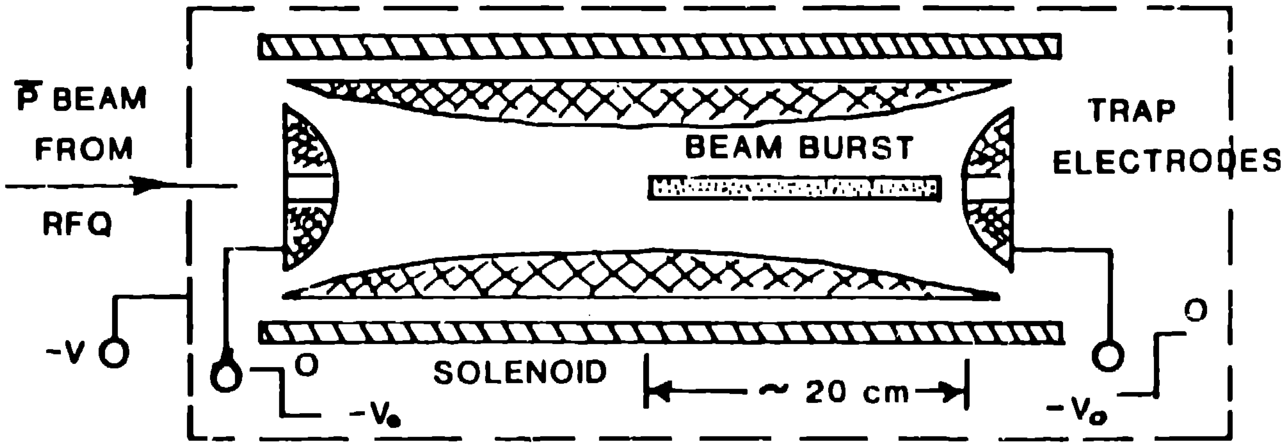

Fig. 3. High energy (20 keV) bulk catching and cooling trap shown in schematic cross section (see text also).

voltage as the rear electrode. The beam burst will now also turn around at the front electrode and is thus trapped. Fast rise time, high voltage pulsers have been built at Los Alamos for other applications.[6] Which designs can be readily adapted to an ion trap application. The trap assembly can now be lowered in voltage adiabatically to normal ground potential. Additional cooling using resistive damping of image currents[7] and electron cooling[8] can be used to further reduce the antiproton temperature. Subsequently, the antiprotons will be moved to an "harmonic trap" at cryogenic temperatures for further cooling. This whole process may take several tens of minutes after which another burst can be caught, cooled and added to the previous cooled burst(s) in the trap. In a fast extraction mode 10^7 to 10^8 $\bar{p}$'s could be in each burst. Thus in a day 10^{10} $\bar{p}$'s could be stored in the trap at low temperatures, ready for experiments. The cold antiprotons can be launched, one or several at a time and be transported to the experiment at hand or experiments using the antiprotons in the trap as a target can be performed.

Two ion trap limitations need to be considered in designing experiments for such a system. Firstly, the number density of antiprotons is limited by a space-charge-like effect which leads to radial deconfinement in the trap and subsequent $\bar{p}$ loss.[9] Because the magnetic field is the source of radial confinement in the traps we envision, the limit to the number density is a function only of this field as shown in Fig. 4. The fields we plan using in our traps will be between 5 and 6 Tesla where 10^{10} $\bar{p}$'s/cm^3 can be safely stored. Secondly, collisions with residual gas molecules in the trap will lead to a fixed loss rate. The experimental execution time combined with this loss rate sets the vacuum required in trap. To estimate this loss rate, the cross sections from Ref. (10) for $\bar{p}$ + H annihilation can be used. The results of this estimate are shown in Fig. 5, where contours of constant annihilation rate

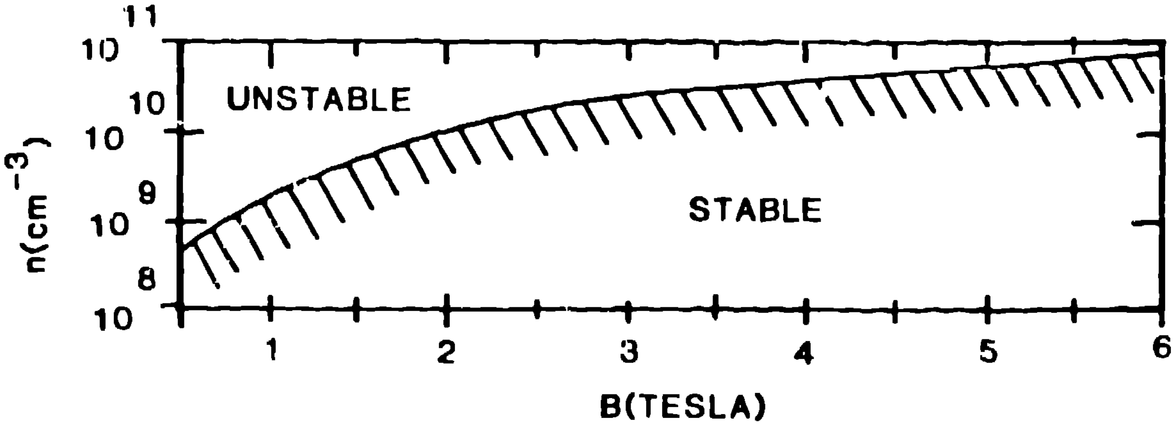

Fig. 4. Stability limit for antiproton density in a Penning trap as a function of the applied magnetic field.

are plotted as a function of antiproton temperature and residual gas pressure. Pressures better than 10^{-15} Torr and temperatures of about 10^{o}K are required to keep the loss rate below 10^{-6} sec^{-1}. This vacuum requirement may seem extreme but the storage trap we envision will be at liquid helium temperatures or better (4^{o}K). At such cryogenic temperatures residual gas molecules are simply frozen out on the walls of the cooler container. The only thing left is helium vapor which can be readily pumped using a super cooled adsorption surface. Vacuums considerably better than 10^{-15} Torr can be obtained using cryogenic techniques. Loss rates can thus be enormously reduced.

III. Experimental Possibilities

Originally our interest in low temperature antiprotons arose from our plans for a gravitational mass experiment. In designing a system to achieve an antiproton temperature appropriate for this measurement it became obvious that many other experimental possibilities could be opened in atomic physics, chemical physics, condensed matter and solid state.

In atomic physics for example, many of the experiments planned for ELENA could be carried out using the ion trap as a source or a target of thermal antiprotons. One can envision ejecting the thermal antiprotons down a long vacuum isolation line into a gas cell or polarized gas jet at very low pressure. To have one interaction length of gas will require approximately 0.3 Torr pressures (assuming $\sigma = 10^{-16}$ cm^2). Such low pressures are completely free of Stark mixing effects and one can imagine now using the Stark mixing effects as a possible probe of chemical and molecular dynamics as one increases the pressures involved. There are also some very exciting possibilities for obtaining a polarized beam of antiprotons using the ion trap as a source.

In condensed matter physics, ions have been used as a probe of superfluid dynamics.[11)] Antiprotons are a unique charged ion with very different dynamics than normal matter ions. Their interactions in a superfluid may reveal some interesting surprises. This last speculation is driven by the fact that atomic scale barriers of ~ 1.0 eV and ~ 1 Å lead to very small barrier penetration coefficients. The results for a barrier penetration calculation for antiprotons are shown in Fig. 6. In the figure the transmission coefficient (T) is plotted versus the barrier width (a) in Angstroms for several barrier heights (V_o). The antiproton energies are also indicated. With such small transmission probabilities on an atomic scale there may exist meta-stable states of antiprotons in normal matter. The principle reason for the small transmission coefficients for antiprotons is due to their mass. Thus negative muons or other negatively charged particles (not electrons) or lower mass will not exhibit the meta-stable state behavior.

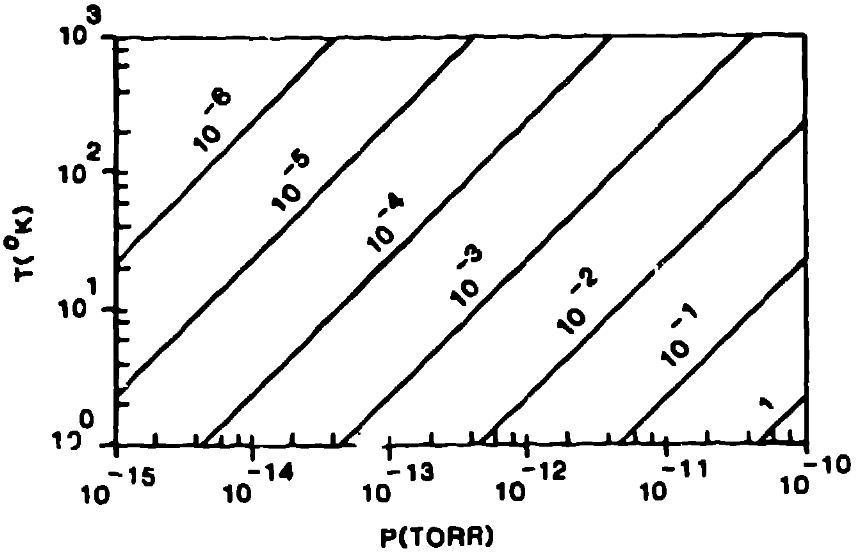

Fig. 5. Contours of constant annihilation rate as a function of antiproton temperature and residual gas pressure. The cross sections are taken from Ref. (10).

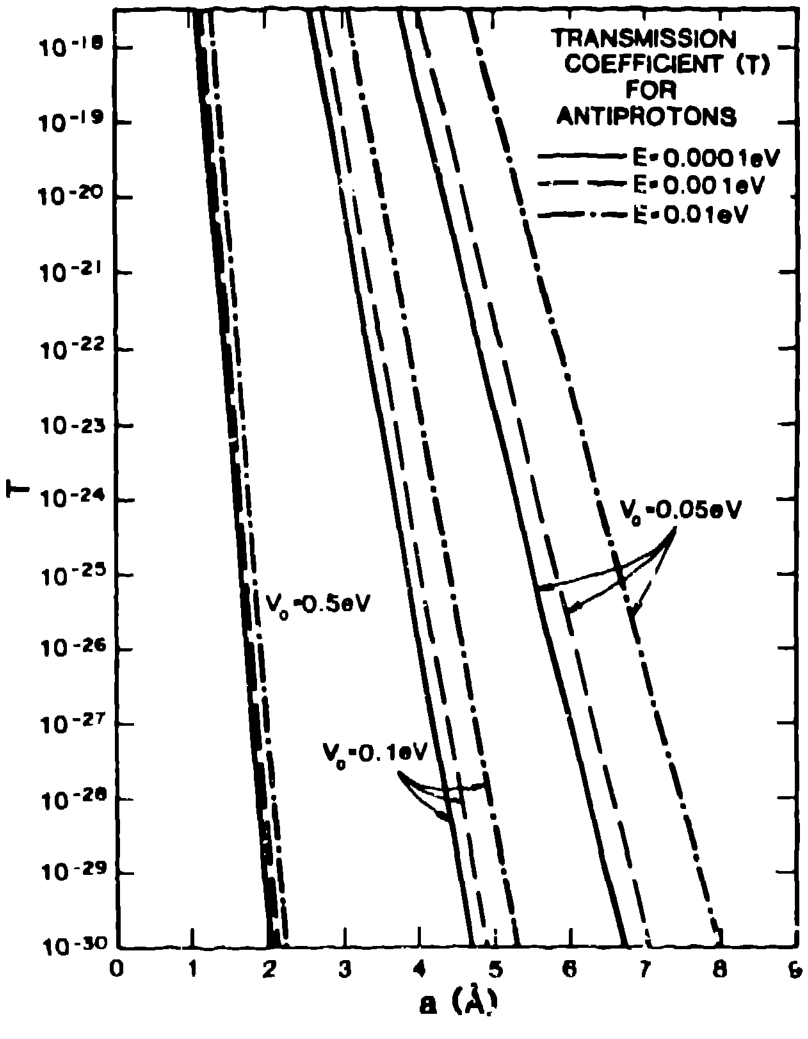

Fig. 6. Antiproton barrier penetration coefficient plotted versus barrier width. The barrier height (V_0) and antiproton energy are as indicated.

IV. Conclusion and Summary

In order to execute the gravitational mass experiment for the antiproton very low temperature $\bar{p}$'s will be required. The beam line system we envision for achieving these temperatures can make antiprotons available at a wide variety of low energies. Extending the operating band of energies available at LEAR to very low energies opens many new experimental possibilities in addition to the gravity measurement.

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