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EXTREMELY LOW ENERGY ANTIPROTONS

A PROGRESS REPORT TO THE SPSLC BY THE TRAP COLLABORATION (PS196)

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I. OVERVIEW

Over the last few years, a series of experiments by our TRAP Collaboration has made it possible to slow, cool and store antiprotons at energies 10^{10} lower than was previously possible[1,2,3,4] We now routinely capture, slow, cool and then store antiproton at energies below 1 meV, in thermal equilibrium at 4.2 K. Antiprotons from LEAR (at 6 MeV) are slowed in matter[2], and then captured in an ion trap[1,3]. We first demonstrated such slowing and capturing several years ago in a 24 hour demonstration experiment[1]. A brief report of this experiment in Sec. II introduces the techniques which allow capturing antiprotons in an ion trap. In the last couple of years, using our dedicated beam line at LEAR, we have greatly increased the antiproton capture efficiency and the antiproton storage time. Electron cooling within an ion trap was demonstrated for the first time (Sec. IV), establishing that electron cooling was the efficient way to cool a high energy antiprotons in an ion trap as we had anticipated[5]. The extremely cold antiprotons can be held for a very long time within the small central volume ($< 1\ mm^3$) of a Penning trap[6]. In one case, antiprotons were held for two months[4]. During this time we observed no loss of antiprotons from the trap and were thus able to establish that the antiproton lifetime exceeds 3.4 months[4]. The pressure within our ion trap is thus better than 5×10^{-17} Torr.

Not surprisingly, the availability of cryogenic antiprotons stored indefinitely withi a small accessible volume opens up new experimental possibilities. Our first measurement was a 1000-fold improvement in the measured antiproton mass[4] compared to previous measurements done at CERN[7] and at Brookhaven National Laboratory[8,9,10]. Several experimental developments not only made this advance possible but have wider applicability. A new superconducting solenoid system[11,12], invented to cancel the effect of the changing magnetic field in the LEAR experimental area, will allow a significant improvement in the precise mass spectroscopy of many charged ions and particles. A new, high quality trap design utilizes stacked cylindrical rings[13], quite unlike the hyperbolic electrodes used in the past, provides access to the trapped particle for laser beams, etc. as well as for slowed antiprotons. The antiproton and the proton were shown to have the same inertial mass to a fractional accuracy of 4×10^{-8} (Sec. IV). The new measurement is the best test of CPT invariance done with a baryon system by orders of magnitude and is one of only a few highly accurate tests of CPT invariance done by comparing properties of a particle and its antiparticle.

Over the next several years we anticipate further improvements. Already we have demonstrated a linewidth resolution which is 10 times narrower than the accuracy of the measurements we have published. While this report is being presented orally, we will be doing our final measurements

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with antiprotons for this year. (Unfortunately, LEAR will be engaged with high energy antiproton experiments during the last part of this year.) We may be able to complete the systematic tests which are necessary for us to publish an additional 10-fold improvement in the measured inertial mass of the antiproton by the end of this year, but we may not have enough beam time remaining this year to make this possible. We now feel quite confident that we will reach, and likely even surpass, our original goal of comparing the inertial masses of antiproton and proton at an accuracy of 1 part in 10^9. Given the high accuracy, however, this will take some time as we tune and incrementally improve our apparatus.

Although we have not been taking many antiprotons for our experiments this year, it is and will be of crucial importance that we be able to obtain these antiprotons spread out over as much of the year as possible. The systematic tests that we must do require that we frequently eject our trapped antiprotons, load protons to make a reference measurement, and then return to study antiprotons. **We hope the committee will consider this requirement when considering requests that LEAR spend extended periods of time at energies exceeding 200 MeV/c since this precludes the operation of our experiment during these times.**

The availability of extremely cold, stored antiprotons opens up other new experimental possibilities as well. We would like to measure the antiproton magnetic moment and numerical simulations we have carried out suggests that this may be possible[14]. Others aspire to launch extremely cold antiprotons from a trap like the one we have used, timing the free fall of antiprotons in the earth's gravitational field to measure the gravitational force on antiprotons[15], though no gravity experiments or experiments with antiprotons have yet been carried out. Our experiments clearly show that the antiproton capture and cooling can be carried out, but they do not address the daunting challenges brought on by the gravitational force of the earth on an antiproton being equal to the electrical force of only one elementary charge located 12 cm away.

Perhaps the most intriguing application for extremely cold antiprotons is the possibility of making cold antihydrogen atoms. An antihydrogen atom, of course, is the bound state of an antiproton and a positron. Precise spectroscopic comparisons can be envisioned between hydrogen and antihydrogen, especially if one can store these atoms in a trap such as that provided by a magnetic field gradient[16]. Also, since antihydrogen is electrically neutral it may be possible to measure its gravitational properties without the extreme difficulties posed by much stronger electrical forces[17].

With antiprotons, we have already demonstrated that we can stack successive bursts of antiprotons into a small ion trap. That is, after one burst of antiprotons from LEAR is captured in our trap and electron cooled we can immediately capture another burst of antiprotons for cooling by the same electrons. Specifically, we already demonstrated that we can accumulate more than 10^5 cold antiproton by stacking several smaller bursts of antiprotons received from LEAR. During the next year we hope to study this process. We should be able to increase the number of trapped antiprotons to 10^6 or more by doing such experiments when LEAR and our beam line are both optimally tuned. If the physical size of our trap was increased, and if the trapping potential was increased it seems very likely that we could achieve 10^7 antiprotons or more. To do such studies will require antiprotons. The LEAR staff is interested in carefully tuning our line at the beginning of the antiproton runs next spring. We note that the focus of the extracted LEAR beam is much better when the electron cooling in LEAR is working. Electron cooling in LEAR is thus extremely useful to us, insofar as it gives us much more reliable and reproducible loading of antiprotons into our trap.

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VI. POSSIBILITY OF ANTIHYDROGEN

This section is intended as a brief introduction to experiments we are pursuing whose ultimate aim is to produce and study antihydrogen. It is not a general review of such matters. If the committee wishes we could provide more information. We hope to soon be able to report some experimental progress with antiprotons.

Experiments underway at Harvard University demonstrate that large numbers of positrons can be accumulated in vacuum and stored in Penning trap[18]. These positrons will originate in a radioactive source. At the same time, experiments are being planned at the University of Mainz[19] to use the LINAC positron source at Giessen, the hope being to establish whether more trapped positrons can be accumulated in a LINAC than with a radioactive source.

We have looked into the various schemes for producing antihydrogen. More experimental information is badly needed. The largest instantaneous rate for antihydrogen production looks to be three body recombination of two positrons and an antiproton[20]. Since the antihydrogen will most likely be produced in a high Rydberg state it will be necessary to do initial experiments with Rydberg antihydrogen (eg. precise microwave spectroscopy measurements) or to develop a way to selectively transfer the population to a desired low lying state. The high Rydberg states are extremely polarizable which may make it possible to temporarily confine these atoms by their large electric moments. Alternatively, positronium could collide with antiprotons to produce antihydrogen[21]. Although this latter process has generally been discussed in the conjunction with keV antiprotons in a racetrack trap[21], it seems to us that to get sufficient antiproton density and sufficient antihydrogen production rate may well require using extremely cold antiprotons confined in a Penning trap as described in previous sections. A new variation which has recently been mentioned is the possibility of using excited positronium to increase the recombination cross section[22].

We find the possibility of making low energy antihydrogen much more attractive than merging beams of antiprotons and positrons in a high energy storage ring[23]. The possibility to store and reuse what looks to be a rather limited supply of antihydrogen atoms is only present for antihydrogen at low temperatures. It becomes energetically possible below 4.2 K to confine the antihydrogen, because of its magnetic moment, in a minimum of a magnetic field this has been done with sodium[24] and other atoms. Since we began exploring this difficult scenario[16] spin polarized hydrogen atoms at 0.04 K have been confined in this way[25]. A deeper well may be required than has been used so far to confine atoms (a 1.5 Tesla well is needed to trap antihydrogen at 1 K, for example). The coldest atoms in the thermal distribution can of course be caught in a shallower well. In fact the trap environment is now considered to be most promising for precise laser spectroscopy of hydrogen atoms[26].

At Harvard, we are investigating the recombination of electrons and protons even though we know it will be very much harder to detect recombined hydrogen than it will be to detect antihydrogen. Antiproton and positron annihilation signals will provide a much more sensitive

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and background-free way to detect antihydrogen. It will be much harder to distinguish hydrogen produced in recombination from hydrogen atoms in the background gas or on the surfaces of the apparatus. So far, we have demonstrated that we can locate electrons and protons in adjacent and in nested Penning traps[27]. Experiments currently being prepared will include a channel plate detector and a field ionization region with which we will attempt to detect Rydberg hydrogen produced when cold electron and proton plasmas are allowed to merge. These experiments, and other experiments being contemplated, are very difficult. Antihydrogen has not yet been made and will not be made very soon. However, the appeal of making the first antimatter, and of examining its structure with a precision which could rival the procision achieved in the kaon CPT test, makes this difficult endeavor worth a serious effort.

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