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PHYSICS WITH THERMAL ANTIPROTONS

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ABSTRACT

The same beam cooling techniques that have allowed for high luminosity antiproton experiments at high energy also provide the opportunity for experiments at ultra low energy. Through a series of deceleration stages, antiprotons collected and cooled at the peak momentum for production can be made available at thermal or sub-thermal energies. In particular, the CERN, PS 200 collaboration is developing an RFQ-pulsed ion trap beam line for the antiproton gravitational mass experiment at LEAR that will provide beams of antiprotons in the energy range 0.001–1000.0 eV. Antiprotons at these energies 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.

THE ANTIPROTON GRAVITY EXPERIMENT AT LEAR

Theoretical approaches to gravitation abound whereas experiments in gravity, until just recently, could be counted on one hand. A fundamental measurement in experimental gravity that has not yet been done is the measurement of the gravitational force on antimatter. In certain extended supergravity models, specific particles have different gravitational masses from their associated antiparticles.[1] However, as yet there has been no direct test of this prediction. The gravity experiment at LEAR (PS200)[2] will test directly the equality of particles and antiparticle gravitational masses in the baryon sector with protons and antiprotons.

Experimentally we plan to use the time-of-flight (TOF) technique pioneered by Witteborn and Fairbank in their measurement of the gravitational force on the electron.[3] In this approach the particles are launched vertically up a drift tube. The TOF of the particle up the tube together with the initial velocity gives a measure of the gravitational force acting on the particle. For such a vertical launch and a fixed drift length, ℓ, where the detector is mounted, there will exist a critical initial velocity such that the particle arrives at the detector with zero velocity. For all initial velocities lower than the critical one, the particle simply does not have enough initial kinetic energy to reach the detector. Thus, there will exist a cutoff time in the TOF spectrum ($t_c = \sqrt{2\ell/g}$). In our experiment we will be dealing with a one dimensional Maxwell-Boltzmann distribution of velocities. To measure the gravitational effect on antiprotons, the initial velocity and hence the kinetic energy distribution has to be low enough in average value so that the resulting TOF spectrum has sufficient particles near the cutoff time for a significant measurement. The energy required is more conveniently measured in degrees Kelvin rather than the more familiar MeV or keV. 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

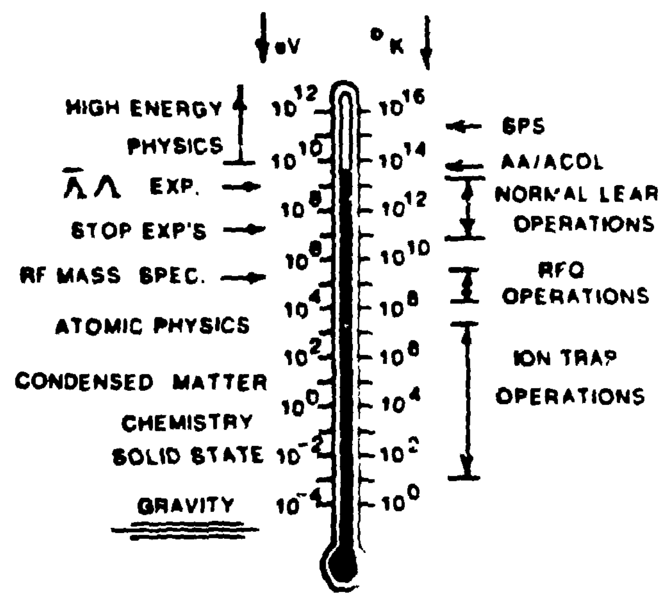

Figure 1: The antiproton thermometer shown is calibrated in electron volts down the left hand side and in degrees Kelvin down the right hand side.

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 $\approx 2.7 \times 10^{15}$ K (2.5×10^{11} eV). Normal LEAR operations span the temperatures between $1.5 \times 10^{13} - 5.8 \times 10^{10}$ K (1.2 GeV – 5 MeV). On the upper end of this range the $\bar{\Lambda}\Lambda$ 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 designing an RFQ decelerator and ion trap system. We are also considering using a foil degrader and plan tests of this concept soon. 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.

The overall system we are planning is displayed schematically in Fig. 2. The experimental sequence starts with the extraction of a 2 MeV bunched beam from LEAR. At present, beam at LEAR is available at 5 MeV with poor emittance. However during the ACOL shutdown, LEAR will be upgraded to provided the 2 MeV fast extracted beam with good emittance that is required by our experiment. The bunched beam in LEAR has a macrotime structure set by the 8th harmonic buncher already in the LEAR ring. A single phase bucket of this bunched beam is fast extracted from LEAR and delivered to the entrance of our experimental beam line. A microtime structure matched to the operating frequency of the RFQ decelerator will also be imposed on the macroburst. This microstructure can be imposed either in, or external to the LEAR ring. Bunching in LEAR makes the most efficient use of antiprotons, whereas bunching

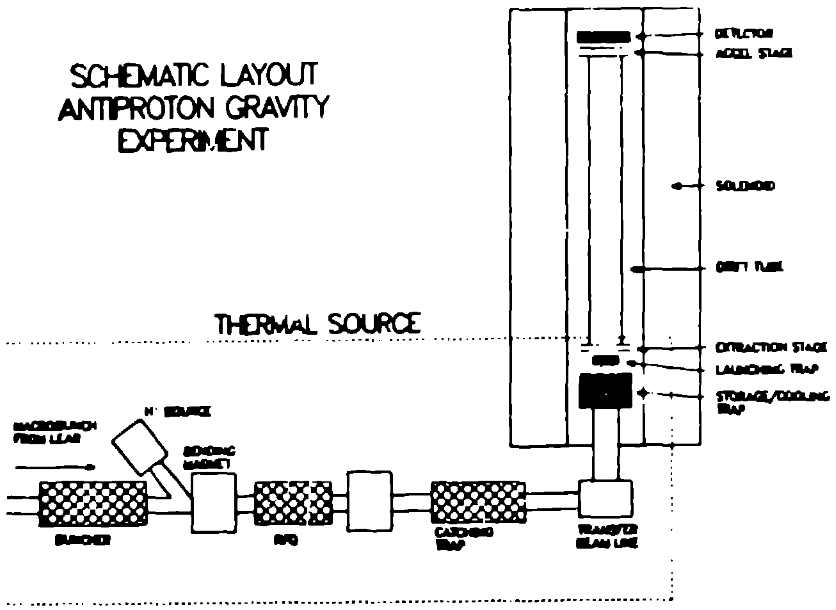

Figure 2: Overall system for the low energy beam line required by the antiproton gravity experiment.

externally will have higher loss rates. In the figure an external bunching section is shown. In any event, this bunched beam at 2 MeV is decelerated in an RFQ currently under design at Los Alamos[1] to 20 keV. With a suitable bending magnet in the beam line the 20 keV beam can be made available to our experiment or to others. Immediately following the RFQ is the first stage of pulsed ion traps that will be used to capture, store, and cool the antiprotons. The first stage catching trap is shown in schematic cross section in Fig. 3. This device is cylindrically symmetric about the horizontal axis and is designed along the lines of a Penning trap.[5] The multiring configuration provides a harmonic potential along the horizontal axis centered at the electrode with the circular cross section when the electrodes symmetric about this one are at specially

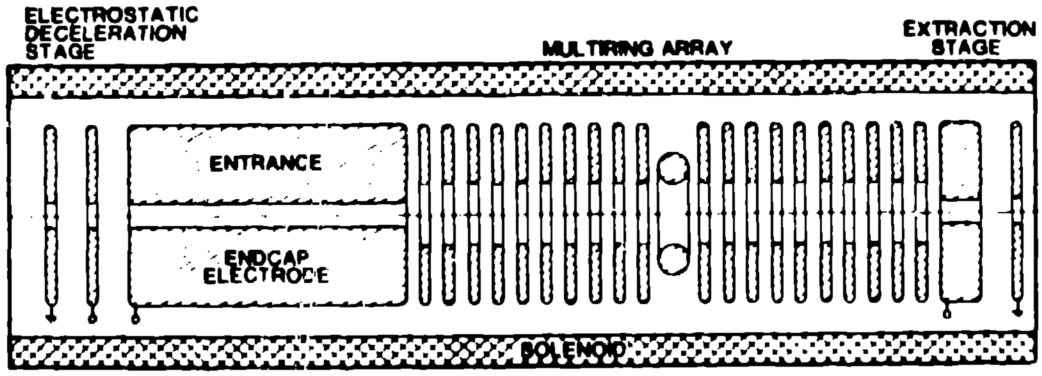

Figure 3: Schematic cross section of the first stage catching trap. The device is azimuthally symmetric about the horizontal axis.

matched potentials. The endcap electrodes at the far ends of the multiring array have small (~ 0.6 cm diameter) apertures in them to allow the beam burst to enter or exit. A magnetic field along the horizontal axis generated by the solenoid shown in the figure provides the radial confinement of the burst. Initially the beam burst emerging from the RFQ is 50 cm in length and enters the catching trap from the left in the figure. At this time the entrance endcap electrode is at 15 kV so that the burst is decelerated to 5 kV as it enters this elongated electrode. This results in a 25 cm burst length at 5 keV propagating inside this long electrode. When the entire burst is inside, the potential on this electrode is quickly (< 25 ns) brought to ground before the burst starts to propagate inside the multiring array. The down stream endcap electrode is maintained at ~ 8 kV so that the burst decelerates inside the trap and eventually turns around. Before the burst can propagate more than half way back, the potential on the entrance endcap electrode is brought up to ~ 8 kV. Thus the burst cannot leave the way it entered and is therefore caught. Initial testing of a half scale version of the multiring trap has demonstrated the promise of this approach.[6] While in this trap the antiprotons will be cooled to 10-100 eV using resistive, stochastic, or electron cooling. The success of the Genoa and Pisa groups with stochastic cooling in traps suggests that this option will be used.[7] When this is accomplished, the particles will transferred to a highly compensated harmonic trap located near the base of the vertical drift tube for further resistive cooling. In this intermediate trap the particles will be cooled to ~ 5-10 K and stored in preparation for transfer, 100 at a time, into the final launching trap. Once the launching trap is loaded, the potential will be suddenly dropped, thus releasing half of the particles upward in the drift tube. The TOF is measured using a microchannel plate at the top of the drift tube. The vertical ion trap drift tube system must operate at extremely low pressures (< 10^{-14} Torr) to avoid loss of antiprotons through annihilation with residual gas atoms. Consequently this system will be cryogenic, operating at liquid Helium temperatures (~ 4 K).

The calibration standard for our measurement of the gravitational acceleration of the antiproton will be the H^- ion. This stable ion has the same charge, magnetic moment, and almost the same inertial mass (within 0.1%) as the antiproton. H^- ions will be injected into our beam line at 20 keV using an ion source upstream of the RFQ (Fig. 2). The RFQ will not be energized during H^- injection. This configuration allows us to exercise the system independent of LEAR beam operations. To measure the gravitational acceleration of antiprotons relative to the H^- ion will require the launching of a total of 10^6 to 10^7 particles for a 1% measurement. There will be ~ 10^7 particles in each 8th harmonic macrobunch from LEAR. This is sufficient for one TOF spectrum with some safety margin. Many TOF spectra will be required to assure reproducibility. Each antiproton run will be followed by a run with H^- ions.

The measurement of the gravitational mass of the antiproton is a fundamental measurement that has not yet been performed. No convincing theoretical argument has been made to anticipate the result. This important measurement will test the Equivalence Principle for matter and antimatter and provide a powerful constraint on modern attempts to unify gravity with the other forces of nature.

ANTIPROTONS IN ATOMIC AND CONDENSED MATTER PHYSICS

Originally our interest in antiprotons was solely directed at executing the gravity experiment. However, to accomplish this we will develop in essence a thermal source of antiprotons making these particles available at energies of interest to atomic and condensed matter physics for the first time. This is illustrated in Fig. 1 where the energy regime and applicable physics are listed along with the experimental equipment required. Charged particle probes have provided important information on matter in the condensed state. The arsenal of probes employed up to now includes charged ions, electrons, positrons, and muons. Antiprotons offer a unique new probe of matter in the condensed state.

Antiprotons are, in essence, intrinsically stable, negatively charged particles with a hadronic mass. Unlike electrons, their dynamics in normal matter is not driven by the Pauli exclusion principle. For this and other reasons the photon emissions associated with the downward cascade of thermal antiprotons from high Rydberg states contain new information about the electronic environment of the nucleus, compared to analogous Rydberg transitions involving a leptonic mass.

The intrinsic stability of the antiproton makes it ideal for the study of new stability mechanisms in condensed matter. Dynamic stability, wherein particles are held in a steady state (an excited state) for long times by virtue of compensating instabilities, is particularly interesting. The principle of dynamic stability is illustrated by the familiar alternating gradient synchrotron, but it is not limited to such macroscopic application. The existence of localized states of dynamic stability for antiprotons is currently an open question. Simple arguments based on electrostatics and variational principles that imply the absence of stable antiproton ground states in condensed matter are not valid when excited states are involved. A possible example of nonlocalized dynamic stability is channeling, whereby an antiproton in a certain energy range travels along a particular crystallographic axis without annihilation.

Unlike potential applications of antiprotons in the fields of atomic and nuclear physics, the perspectives in condensed matter physics are still quite open. This is due to the novelty of conceivable applications: an extensive previous literature from which to draw is not available. Nevertheless, four specific condensed matter environments can be identified as possessing unique features that might lead to significant payoffs.

The superfluid state of liquid ^{4}He is remarkable in its display of a coherent quantum state over macroscopic distances. When disturbed by boundaries and impurities this quantum state recovers over a very short distance, approximately the size of the interatomic spacing. Much is known about the behavior of a variety of impurity ions in superfluid helium. Examination of the behavior of $\bar{p}$ impurities offers the possibility of new insights. Unlike free electrons, which create small bubbles in the liquid due to their zero point motion and the Pauli exclusion principle, $\bar{p}$'s should act more like free protons and create high density clusters of ^{4}He atoms around themselves by electrostrictive attraction. The subsequent annihilation of the $\bar{p}$ should be preceded by photon emission containing information about its immediate neighborhood. Superfluid helium is essentially transparent to a very wide spectrum of radiation and can be cooled to a temperature where its own excitations are effectively absent. In fact, approximately 11% of the superfluid helium atoms are in a Bose condensed state of zero momentum. These features ensure the greatest possible advantage in observing, with high precision, the $\bar{p}$ transition and decay products in condensed matter because of an extremely small energy spread in these products due to center of mass doppler broadening. It is also possible that the $\bar{p}$ would never see the condensed state of ^{4}He, especially if the electrostrictive cluster formation time is rapid in comparison to $\bar{p}$ annihilation time. In any case, the thermal center of mass motion would probably be the smallest achievable in any context.

It is tempting to speculate that the macroscopic quantum coherence of the superfluid state, including the delocalization of the fraction of the ^{4}He in the Bose condensed state, may give rise to truly dramatic effects in the behavior of the $\bar{p}$, such as coordinated annihilation, stable states, etc. Whether such effects exist is not known, but they seem unlikely in view of the large discrepancies in the size of the antiproton impurity compared with the coherence length of the superfluid state and in view of the coulomb energy available in the $\bar{p}$ ^{4}He atom compared to the energy associated with the loss of superfluidity over a comparable volume. Nevertheless, prudence would recommend an open mind — surprises have occurred before in condensed matter physics.

The liquid surface of superfluid ^{4}He also offers a unique environment for $\bar{p}$ studies because it is microscopically smooth, in equilibrium with a vapor of effectively zero density (at low temperatures), and can be charged with ions either above or below the surface. In particular, electrons on the vapor side can be held against the helium surface by applying an electric field; they do not penetrate the surface because of the relatively high energy required to make the bubble state mentioned earlier. Because this electronic surface charge density can be substantial and can be excited in various plasma modes, the possibility exists of finding electron $\bar{p}$ states that are bound to the surface but have negligible $\bar{p}$ density at the surface. In effect, the $\bar{p}$ would be trapped between the external electric field and the electronic surface charge, which in turn is repelled from the surface by the Pauli principle. As mentioned in the general remarks above, such trapping would have to occur in an excited state.

Many of the features of quantum coherence apply to both superconductors and superfluids; a superconductor is essentially a charged superfluid in a solid, neutralizing background. Electric and magnetic fields are shielded quite effectively in superconductors over distances comparable to the penetration depth; a length scale present only in charged superfluids and typically having a magnitude of many lattice spacings. Thus, one cannot expect known superconductors to shield and stabilize a $\bar{p}$ in any obvious way on an atomic scale, but what *will* happen is not clear either. The origin of the effective electron attraction, which gives rise to superconductivity, is a subtle and delicate interplay between electronic and lattice properties, both of which are disturbed by a $\bar{p}$. A best guess now is that the influence of a $\bar{p}$ impurity may be too localized to probe superconductivity, although it could give information on other electronic structure.

A $\bar{p}$ is attracted to positive charge. In the presence of an effective source of positive charge, other than protons, one could expect $\bar{p}$ trapping. In many respects, especially involving dynamics and transport, the absence of electrons in a bulk medium is equivalent to positive charge. This "positive" charge can be either delocalized as holes in a conduction band or localized as ionic lattice vacancies and certain crystal imperfections. Of course, such pseudo positive charge cannot violate the laws of electrostatics, and the earlier remarks on the absence of ground state stability still hold. Nevertheless, the existence of localized excited states of the $\bar{p}$ hole system are possible in principle, and the model could serve as a fruitful paradigm.

A charged particle at an interstitial position or a vacancy position in an ionic crystal can be localized at a point where the local electric fields cancel, i.e. a position that is force free but nevertheless unstable. The possibility of stabilizing this position by imposing a time varying external electric field which effectively creates an attractive local potential well, relative to the unstable directions, then exists. The strength and frequency of this field may be tunable to favor particular sites and to avoid combinations that would unduly disrupt the underlying crystal structure. A wide variety of crystal types and laser sources are available to explore this possibility.

Finally, the possibility of forming localized, stable orbits which encompass one or more lattice sites should not be overlooked. This could be envisioned as a microscopic, quantum analog of a storage ring. Again, extensive knowledge from the science of crystal structure is available to aid in the search for the optimum environment.

SUMMARY

A thermal source of antiprotons is currently being developed for the antiproton gravity experiment at LEAR. This source will make antiprotons available at energies of interest to atomic and condensed matter physics. Charged particles have been used as a probe in these fields for many years. Antiprotons offer many unique properties as a probe of normal matter. Moreover, there may exist dynamically stable states of antiprotons in a matrix of normal matter under special conditions. Physics with bottled antiprotons, whether in the bottle or out has many new avenues of research that are as yet unexplored.

REFERENCES

1. J. Scherk in "Unification of the Fundamental Particle Interactions," S. Ferrara, J. Ellis, and P. van Nieuwenhuizen, eds., Plenum, New York, 1981.

2. N. Beverini, J. H. Billen, B. E. Bonner, L. Bracci, R. E. Brown, L. J. Campbell, et al., PS200 proposal, Los Alamos National Laboratory report, LAUR 86-260.

3. F. C. Witteborn and W. M. Fairbank, Rev. Sci. Inst. 48, 1(1977); Nature 220, 436(1968); Phys. Rev. Lett. 19, 1049(1967).

4. J. H. Billen, K. R. Crandall, and T. P. Wangler, Proceedings of the third LEAR Workshop, Tignes Savoie France, January 19-26, 1985, "Physics with Antiprotons at LEAR in the ACOL Era," U. Gastaldi, R. Klapisch, J. M. Richard, and J. Tran Thanh Van, eds., Editions Frontieres, Gif sur Yvette, France, 1985.

5. D. J. Wineland, W. M. Itano, and R. S. van Dyck, jr., Adv. At. Mol. Phys. 19, 135(1983).

6. M. H. Holzscheiter, B. S. Birmingham, R. E. Brown, M. V. Hynes, N. Jarmie, S. Graessle, Bull. Am. Phys. Soc., 33, 932 (1988).

7. N. Beverini, V. Lagomarsino, G. Manuzio, F. Scuri, G. Testera, and G. Torelli, "Proceedings of the Workshop and Symposium on the Physics of Low Energy Stored and Trapped Particles," June 14-18, 1987, Stockholm, Sweden, Physica Scripta, to be published.