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LETTER-OF-INTENT TO FERMILAB

PRECISION TESTS OF CPT AND GRAVITY USING LOW ENERGY ANTIMATTER AT FERMILAB

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I. Introduction

At the workshop entitled "Physics at Fermilab in the 1990's", held in Breckenridge, Colorado on 15–24 August 1989, approximately two dozen particle/atomic physicists met to review new physics that could be done with the Antiproton Accumulator. Several interesting topics emerged. Prominent among these were tests of invariance principles inherent in the theories of gravity and electromagnetism, specifically the weak equivalence principle and CPT. Although LEAR is capable in principle of achieving significant tests in these areas, it was felt that, considering the extreme degree of difficulty and considerable time required to perfect these experiments and the uncertainty of the future of LEAR, plans should be made to establish a capability at Fermilab to carry out this work to its deserving conclusion.

Since that time, a collaboration has been formed for the purpose of informing Fermilab of this exciting physics and to outline an experimental program as presented in this letter-of-intent. The remainder of this report reviews in brief the physics objectives and techniques which we feel are appropriate to these goals, and the accelerator developments required to carry out an experimental program.

II. Physics Objectives and Methods

The proposed experiments aim at the three principal goals:

1) Test of the CPT theorem with very high precision by comparing the mass and the magnetic moment of the antiproton with that of the proton (CPT test in an elementary system);
2) Comparison of the gravitational interaction between particles and between particles and antiparticles (weak equivalence principle);
3) First synthesis of atomic antimatter, study of its confinement, high resolution spectroscopy of antihydrogen and investigation of its gravitational interaction.

II.1 CPT Tests with Antiprotons

The techniques used to measure the mass of trapped ions are highly developed and allow us to apply them to the hadronic constituent of atomic antimatter. They provide the most sensitive test of CPT in the baryon domain. Since there exists no general theory from which a confirmation of the validity of the CPT theorem in one sector can impose bounds on other sectors, we must test the fundamental symmetry wherever we can obtain ultrahigh sensitivity in order to detect a possible violation.

The difference of the magnetic moment of the antiproton compared to that of the proton is determined only to two parts in 10^3 [1]. Similarly, the proton—antiproton mass difference is known to one part in 10^5, whereas the electron—positron mass difference is known to one part in 10^7 [2]. We will show that limits on both the magnetic moment and mass differences can be reduced by many orders of magnitude.

II.2 Test of Gravity Theory with Antiprotons

As pointed out by Holtkamp, Holzscheiter and Hughes at Breckenridge, the experimental observation that all forms of matter experience the same gravitational acceleration is embodied in the weak equivalence principle of gravitational physics. However no experiment has tested this principle for particles of antimatter such as the antiproton or the antihydrogen atom [3]. Clearly the question of whether antimatter is in compliance with weak equivalence is a fundamental experimental issue, which can best be addressed with low energy antiprotons. Some thirty years ago the notion of "antigravity", according to which antimatter would fall up, enjoyed a brief popularity. However, theoretical arguments were raised against this idea [4], and it was not until the development of supergravity theories that weak equivalence for antimatter was again questioned.

In 1979 Joel Scherk pointed out [5] that certain supergravity theories could allow the antiproton to fall down faster than ordinary matter. This idea, which is in a sense the exact opposite of "antigravity", avoids the old objections, and connects the anomalous gravity for antimatter with both "fifth—force" [6] and gravitational redshift experiments [7]. In Scherk's model, the graviton, which provided the conventional infinite range attractive force, has two partners, known as the "graviphoton" and "graviscalar", which are capable of providing additional gravitational strength forces of macroscopic range. The graviphoton is a vector field and so must be coupled to some conserved charge, which could be taken phenomenologically to be a baryon number. This field would then give a repulsive force between "like" charges, so that it would tend to repel normal matter from the earth. However, the graviscalar, which is a spin zero field, would always be attractive, and therefore tend to mask the effects of the graviphoton on normal matter.

For antiprotons, on the other hand, both the graviphoton and graviscalar would give attraction in the Earth's field, and so the antiproton would experience a larger gravitational acceleration than normal matter. The strongest constraints on Scherk's model come from gravitational redshift experiments [7], and allow a few percent larger gravitational acceleration for antiprotons and antihydrogen than for normal matter. If one prefers not to use a specific model for gravity, constraints deduced from normal matter experiments become totally meaningless for the antimatter sector. No predictions on the outcome of a measurement of the gravitational mass of antimatter is possible in this case, and only a direct experimental test can answer this fundamental question.

II.3 Synthesis of Antihydrogen and Its Precision Spectroscopy

Antihydrogen is a fundamental system that has neither been detected in nature nor produced in the laboratory. Its synthesis is of great interest for studying matter-antimatter symmetries and interactions. Its electric neutrality imposes, on one hand, the problem of its storage, but on the other hand offers the possibility of accumulating large amounts due to the absence of space-charge effects. In turn, large amounts of antihydrogen increase the sensitivity for detecting specific effects of great physics interest.

The fact that a lepton is attached to the antiproton permits atomic spectroscopy (in particular, laser and microwave spectroscopy) to be performed, and thus extend the precision on our knowledge of fundamental properties and symmetries. For example, a measurement of the hyperfine splitting (hfs) in the ground state of antihydrogen allows, in principle, a test of CPT invariance many orders of magnitude better than the antiproton mass measurement. This is based on the fact that the same measurement in hydrogen has been made with a maser to a precision of one part in 10^{13} [8]. It also follows that this measurement immediately results in a more accurate value of the antiproton magnetic moment.

The neutral antihydrogen atom is not affected by electric fields, and much less than the antiproton by magnetic fields. Therefore, the gravitational interaction can eventually be studied with much greater precision. The possibility of manipulating antihydrogen with laser light and selecting hyperfine states provides a way to polarize antiprotons [9]. Such a source of polarized antiprotons would be of great interest for both low and high energy antiproton-proton strong interaction physics. Similarly, the determination of the

1S–2S energy separation provides a high sensitivity test of CPT invariance in the compound system.

To date, three methods for the production of antihydrogen have been proposed: (1) spontaneous or induced radiative capture of a positron by an antiproton in a merged beam arrangement [10]; (2) a three–body reaction using positronium atoms and antiprotons [11]; and (3) a three–body reaction using a dense positron plasma and antiprotons at very low temperature [12]. Processes (2) and (3) exhibit much larger cross sections than the spontaneous radiative capture process (1). The dense positron plasma approach requires cooling the antiprotons and positrons to temperatures of ~ 1 K or below, but offers the advantage of producing ultra–cooled antihydrogen atoms which subsequently could be trapped in a magnetic bottle, thus permitting further investigations. The induced radiative capture process (1) could be applied to trapped antiprotons and positrons, thereby reducing the need of a dense positron gas.

High precision measurements of the mass, magnetic moment and gravitational interaction of the antiproton require very slow particles. The initial synthesis of antihydrogen can be achieved with weakly relativistic energies with a subsequent in–flight study of its spectroscopy to fair precision. For ultra–high precision spectroscopy, trapped and very cold particles are required. It is therefore necessary to reduce the kinetic energy of the antiprotons from the accumulation energy of 8 GeV to energies comparable to room temperature or below.

II.4 Experiments at LEAR

In a recent experiment [13] approximately 6×10^4 antiprotons have been captured into a small trap employing a 3 keV energy bite. In this initial trap stage (commonly referred to as the catching trap) the antiprotons can easily be cooled to room temperature by mixing the antiproton cloud with an electron cloud of sufficient density [14,15]. At this point the antiprotons can be extracted (and reaccelerated if necessary) with a very low energy spread for collision type experiments or they can be transported to a next stage trapping experiment, better suited for the specific physics case at issue. Both experiments currently under preparation at LEAR with ultra–low energy antiprotons, namely the comparison of the inertial mass of the antiproton and the proton [16] and the study of the gravitational acceleration of antiprotons in the Earth's gravitational field [17], require cooling to cryo–

genic temperatures and extreme vacua, more easily obtained in a specifically designed, small Penning trap.

The inertial mass measurement will be carried out by comparing the cyclotron frequencies of antiprotons and protons in the same magnetic field using a single particle of each species stored in a cylindrical Penning trap. The proposed accuracy of 1 part in 10^9 will constitute the most accurate CPT test for the baryon sector to date. To study the gravitational acceleration of antiprotons in the Earth's gravitational field, it is proposed to perform a "Time-of-Flight" measurement of ultra-cold antiprotons launched from a Penning trap. Such a measurement will yield a time-of-flight distribution exhibiting a "cut-off time" independent of the details of the initial energy distribution of the particles in the trap. The main difficulty of this conceptually very simple experiment [18] comes from the fact that the gravitational force is so weak in comparison to electromagnetic forces acting on the charged antiproton. Shielding of stray electric fields to the level below 10^{-7} Volts/m presents the major technological challenge in view of the electric fields produced by work function fluctuations on metal surfaces, the so called "Patch-effect". The experiment is expected to yield a statistical accuracy of a few tenths of a percent based on the total number of particles which can be launched on a reasonable time scale. An improvement of this accuracy would require a larger number of antiprotons and time to develop techniques which would be available at Fermilab.

III. Machine Developments

III.1 Decelerator Ring (DR)

As previously emphasized, it is necessary to have antiprotons decelerated to an energy of ~ 2 MeV energy with emittances appropriate for injection into a RFQ. As pointed out by Mills, Möhl, MacLachlan and Marriner at Breckenridge, antiprotons could be provided to the DR by extracting in the standard way (11, 52.8 MHz bunches) from the Accumulator, sending the 8 GeV beam backward through the Main Ring (or Main Injector) into the Booster, decelerating to 400 MeV, extracting the bunches at the bottom of the magnetic field cycle, and transporting them to the DR. Here they must be cooled and decelerated to 2 MeV. The lattice design can be patterned after several previous studies at CERN. The ring would have four bends, 16 quads, and four long straight sections. Other properties are given in Table 1. A sketch of the ring is shown in Figure 1. Injection could be in a single turn via a magnetic septum in a medium straight section and a fast kicker in a long straight section. Ejection can be done either in a single turn or slow mode.

Cooling is needed at several stages: after injection, during deceleration, and at 2 MeV. At injection (400 MeV), stochastic cooling of 1–2 GHz band width will provide a cooling time of 1–2 minutes. Electron cooling would be faster, but would require a major hardware effort at this energy. Space charge effects and instabilities limit the number of stored particles at 2 MeV. A good phase space density is, however, needed for efficient deceleration and trapping. Hence, one needs a good repetition rate with reliable beam intensity when filling the trap. This requires the fast cooling times provided by electron cooling. The DR can be operated as a normal synchrotron and is not a sophisticated stretcher ring like LEAR (ultrahigh vacuum, ultraslow extraction, instabilities, ripples, etc.).

The sketch provided in Fig. 1 of the DR will naturally need to be refined at the proposal stage. Very preliminary estimates place the cost in the $10–20M range, comparable to a major fixed target experiment at Fermilab.

III.2 Post Deceleration

There are several methods to decelerate antiprotons from MeV energies to energies appropriate for trapping experiments. These include a radio frequency quadrupole (RFQ) decelerator, which is potentially the most efficient and is our preferred option. With proper phase space matching from 2 MeV kinetic energy one can decelerate 40–50% of the incident particles to 20 KeV where they can be trapped in a Penning trap. A design study for these specific requirements was presented by P. Zhou and Fred Mills of Fermilab at Breckenridge [19].

IV. Summary

In summary, CPT invariance tests at a level below 10^{-10} would become possible if the number of trapped antiprotons could be at the level of 10^{10}. This would be possible at a low energy ring fed by the Fermilab Accumulator, which provides a much larger antiproton accumulation rate than the CERN accumulator. Such a ring would permit all the very challenging and fundamental experiments described above.

The intended experiments comprise the measurement of the inertial mass and the magnetic moment of the antiproton in order to test CPT invariance in the baryon sector and to determine the gravitational mass of the antiproton with higher precision than possible at LEAR. Further, we want to synthesize anti-hydrogen for the first time, attempt to capture it in a very shallow magnetic bottle and ultimately perform high resolution spectroscopy to further extend the limits of CPT invariance. The hfs frequency for hydrogen is known to the 10^{-13} level and a measurement for antihydrogen at even the 10^{-10} level would rival known CPT tests in the baryon sector, with ultimately the same precision as for hydrogen conceivable when using a few antihydrogen atoms only. Also it is planned to measure the gravitonal acceleration of antihydrogen in order to improve upon measurements with antiprotons and their recognized systematic errors. Such experiments require ultra-cold antihydrogen atoms (< 100 mK) and the development of suitable lasers to manipulate antihydrogen atoms once they are trapped.

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Table 1 – DR Parameters

Momentum range	.06–1.0 GeV/c
Circumference	60 m
LSS Free length	4.7m
β_{xmax}	6 m
β_{ymax}	12 m
Dispersion_{max}	3.1m
Tunes (Q_x, Q_y, γ_t)	(2.3, 2.7, 3.0)
Dipole bend radius (0.087–1.6T)	2.3 m
Dipole bend angle	45°
Dipole gap	100 mm
Quad gradients (F, D)	7.4, –9.1 T/m
Quad length, poletip radius	300, 70 mm
Revolution frequency (.06, 1 GeV/c)	0.32, 3.60 MHz
RF voltage (h = 1, $\Delta P/P = \pm 3 \cdot 10^{-3}$, 1 GeV/c)	3.7 kV
Laslett tune shift; 10^{10} pbar, .06 GeV/c, unbunched)	.02

Figure 1, DR geometry