TESTING THE WEAK EQUIVALENCE PRINCIPLE WITH ANTIPROTONS

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ABSTRACT

No successful experiment has ever been done on the gravitational properties of antimatter. A proposal to measure the gravitational acceleration of the antiproton was accepted in 1986 as part of the experimental program of the LEAR (Low Energy Antiproton Ring) machine at CERN. The many technical problems involved have been closely studied over the last three years. The general status of the experiment is reviewed in the light of these studies.

1. INTRODUCTION

Theories of gravitation, ancient and modern, are all based on some version of the Equivalence Principle. The form incorporated into General Relativity (or GR)-the best known and most successful theory to date-goes far beyond the version first demonstrated by Galileo and confirmed with ever-increasing accuracy [1] many times since. There are, however, few direct experimental confrontations between GR and experiment. Recent decades have been quite fruitful in devising new tests, either of the theory's axiomatic basis or of specific predictions derived from its field equations. Thus the measurement by lunar laser ranging methods of the fall of the earth and the moon towards the sun [2] extended the equivalence domain to include the fall of bodies bound by gravitational forces, while the additional propagation delay accumulated by radar signals in grazing the sun [3] provided a new test of GR's predictive power.

In 1986 an experiment to test the Weak (Galilean) form of the Equivalence Principle for antiprotons was approved at the LEAR (Low Energy Antiproton Ring) machine at CERN. In asserting that what really falls under gravity is energy and that all forms of energy fall equivalently, GR naturally implies that antimatter should fall like matter. The experiment thus constitutes a test of the extendability of the Weak Equivalence Principle to the antimatter domain, where no successful equivalence measurement has yet been done. The accuracy aimed at in this experiment is ~ 1%-approximately the precision attained by Galileo almost four centuries ago.

2. GENERAL DESCRIPTION OF THE EXPERIMENTAL METHOD

Many complex experimental problems lie behind the conceptual simplicity of the 'Galilean' (time of flight against gravity) method described in the original proposal for this experiment [4]. Some important changes of approach have resulted from three years of detailed study of these and I will therefore take the opportunity presented by this meeting to review the solutions now envisaged.

Although LEAR is a 'low energy machine, the kinetic energy (T) of its slowest beam is 2 MeV, corresponding to a velocity (v) of about 20000 km/s. This is to be compared with the m/s velocities needed to bring one-second times of flight to the laboratory scale. A distinct group of problems is therefore associated with decelerating LEAR antiprotons (about 10^8 of them in a bunch of duration 500 ns) to the energy equivalent of a few m/s (~ 10^{-7}eV, 1 mK) without incurring severe losses due to phase-space blowup. A second class of problems is connected with the upward launch of the sample in an environment adequately screened from non-gravitational forces.

We are helped along a little by nature with the first group, since the Maxwell-Boltzmann velocity distribution ensures that a sufficiently large antiproton sample at liquid helium temperature will contain enough antiprotons with m/s velocities to do a 1% measurement of g over a 1 m flight path. It is not necessary therefore to go to the trouble of producing a 1 mK sample. In what follows I make the arbitrary distinction between 'deceleration' (above ~ 10 keV) and 'cooling' (below ~ 10keV). The attainment of this temperature falls naturally into three phases :

a) Deceleration to the neighbourhood of the Bohr velocity (c/137, T ~ 25 keV) and collection of the decelerated sample in a potential well.
b) Cooling the trapped sample from v ~ c/137 to the neighbourhood of the Rydberg energy (13.6 eV).
c) Cooling from the Rydberg energy to 4.2 K.

Here again, the hand of nature is evident. Not surprisingly, as the antiprotons pass clear natural 'signposts' like the Bohr velocity and the Rydberg energy, new things start to happen and the character of the problems changes.

The second group of problems comes about because gravity is so weak compared with the other forces of nature. The 'screening' therefore has to be done to high order. It is best to assume that no screening tube will be perfect at a level of 10^{-7} Volts/m. Therefore we plan to do a comparison measurement with H^- ions to calibrate out residual electromagnetic forces. Screening from strong interaction forces reduces to a requirement on the residual gas pressure in the screening tube, and this is less stringent than it is during cooling (fig 1).

2.1 DECELERATION FROM T = 2 MeV TO v ~ c/137, TRAPPING IN A POTENTIAL WELL

Two methods are being investigated for the deceleration phase. The first involves a simple degradation foil with thickness adjusted to maximise the number of exiting antiprotons in a given energy range. The second uses a cyclotron magnet operated in inverse mode. Evidently, the design of the subsequent potential well will be determined by the characteristics of the sample produced by the deceleration process. Whichever method is used, a potential well of given width cannot be adjusted to collect an arbitrarily large energy range simply by making it deeper. The reason for this is that the oscillation period diminishes with increasing well depth and losses will occur if this falls below the duration of the LEAR bunch. In-

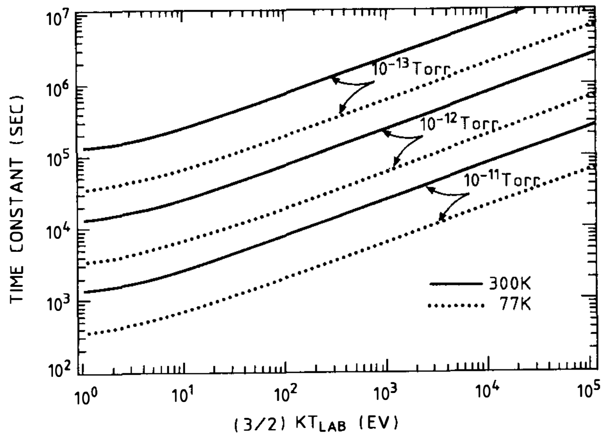


Fig. 1 Time constant against annihilation vs energy at various residual gas pressures and temperatures.

creasing well depth must therefore be compensated by an increase in the trap size. This constraint is implicit in the relation between the range of axial (beam direction) kinetic energies ΔT_z present in a burst of duration τ and the axial dimension L of the trap needed to accept that burst [5] :

$$L = k\,(2\Delta T_z/M)^{1/2}\,\tau \qquad (1)$$

Here k is a constant depending on the shape of the well, M is the antiproton mass. For a square well k=c/2, for a harmonic well k=c/π. The well depth must of course be at least equal to ΔT_z.

For the degrader foil method, the TRIM [6] program was used to simulate the energy loss mechanism. Not much dE/dx data exists for low energy antiprotons, so calculations of the yield of low Z foils of various thicknesses were initially made for protons at several beam energies. The calculations were then converted to antiproton yields by measuring some 'calibration' points in the lowest energy LEAR test beam (5 MeV) available in 1988. The results imply that a typical LEAR bunch at 2 MeV would yield a sample of about 0.4% of its particles at energies below 4 keV in a cone of half-angle 15^o. According to eq. 1 and section 2.2, a Penning trap with L=13 cm, V_0=4 kV and B=1 T would match this emittance and thus collect 4×10^5 particles from the bunch.

The statistical accuracy obtained by launching a sample of this size against gravity is almost adequate (fig 2) for a sample temperature of 1 K. However, some loss of particles during cooling from keV to meV energies must be anticipated, so that a simple Penning trap is probably ruled out. A new type of 'multiring trap' has been proposed in which the axial dimension is increased and several ring electrodes are placed along the

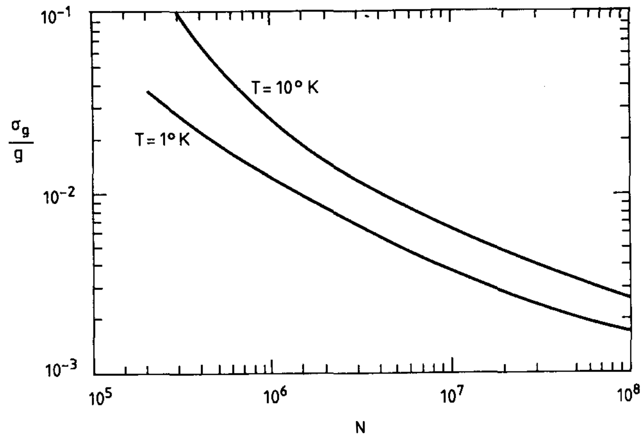


Fig. 2 Statistical error on the acceleration of gravity vs number of $\bar{p}$ launched

axis. Such devices have been studied theoretically [7]. A multiring trap which would accept 5% of the foil-degraded 2 MeV bunch would have a length of 50 cm. Several such prototypes have been constructed and the technical problems posed by this 'extended' design are being investigated at Los Alamos.

A promising alternative to the foil degrader method is the so-called 'anticyclotron'. The method proposed [8] uses low pressure gas in the space between the poles of a typical axisymmetric cyclotron magnet to decelerate a 2 MeV antiproton bunch injected near the corresponding equilibrium orbit. For sufficiently low gas pressure the degradation is adiabatic and the well known focussing properties of cyclotron fields counteract the tendency of the phase space occupied by the bunch to blow up. Very few antiprotons annihilate in flight so that after a certain delay (e.g. 50 μs for 0.1 mbar H_2) the sample forms a cylindrical swarm at the magnet centre. The swarm can then be extracted by a pulsed electrostatic field before its capture by the gas molecules, and transferred to a Penning trap via a 2000 A window placed in the axial borehole of the magnet.

The anticyclotron solution has been extensively modelled by computer. A suitable magnet is available for testing the method experimentally at LEAR in October 1989. This magnet has already been used in the mode described above to decelerate antiprotons to capture (near the Rydberg energy), and the validity of the methods used for computer simulation of the injection and deceleration process has therefore been well established. For a hydrogen gas filling at 0.1 mbar, an injection-extraction delay of 50 μs and an extraction field of 500 V/cm, the sample produced has the following (estimated) characteristics :

$$\tau = 160 \text{ ns}, \qquad \Delta T_z = 2 * 1.8 \text{ keV}, \qquad T_z = 12 \text{ keV}.$$

Note that the bunch duration obtained is actually less than that of LEAR by a factor of three. This occurs because the extraction is along the z-direction while the injection and deceleration are in the x-y plane. Eq. 1 indicates that a simple 8 cm Penning trap would be well matched to such a sample. The sample size would be about 20-30% of the injected bunch. The 60-70% losses nearly all come from the 'passive' injection system, in which axial and radial betatron oscillations are excited to maximise the number of antiprotons which miss the entrance window after their first cyclotron orbit. An active injection system is under study which would bring the overall efficiency closer to 100%.

2.2 COOLING FROM v ~ c/137 to T ~ 13.6 eV

At the energy corresponding to $v = c/137$, stochastic cooling methods are feasible in Penning traps [9)] and have been demonstrated experimentally [10)]. For extended (multiring) traps the theory of stochastic cooling has been worked out in detail theoretically [7)] although it has yet to be demonstrated in practice. This topic will therefore be discussed in a future publication. Stochastic cooling is our preferred method for reaching the Rydberg energy, at which point the capture cross-section on residual gas molecules is expected to become large and faster methods as discussed below will probably be necessary.

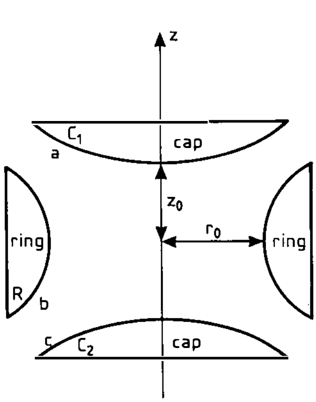
Figure 3 shows the geometry of a typical Penning trap, which consists of a 'ring' electrode and two 'cap' electrodes. All electrodes are hyperboloids of revolution about the z-axis. A uniform magnetic field (B) is superimposed along the z-axis. The Laplace equation solution for infinitely extended electrodes is an electrostatic quadrupole field :

$$V = V_o\,(z^2 - r^2/2)/\,2\,d^2, \text{ with } d^2 = (r_o^2 + 2\,z_o^2)/4 \qquad (2)$$

The motion of charged particles in a such a device is a combination of the following components :

a) Cyclotron motion around the axial (z-direction) magnetic field lines.
b) Magnetron-like precession of the cyclotron orbits in the (x-y) plane.
c) Harmonic oscillation parallel to z in the quadrupole field.

Energy could automatically be coupled out of the particles' z-motion to any dissipative circuit connected between the cap electrodes via the induced currents to these electrodes. Likewise, transverse energy could be dissipated in external circuits if the ring electrodes are split into quadrants. However, the finite lifetime of the antiprotons against annihilation on residual gas molecules places an upper limit on the time available for cool-



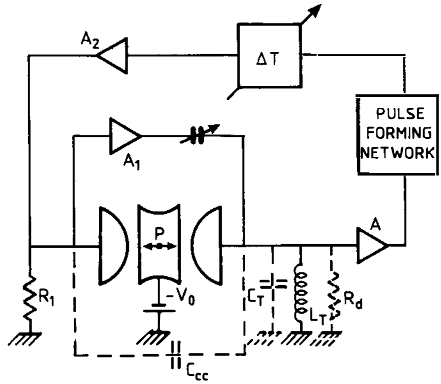


Fig. 3 Penning trap geometry.

Fig. 4 Circuit for stochastic cooling of axial motion.

ing these motions. Figure 1 shows the calculated lifetimes at various residual gas pressures, using realistic parametrisations of the capture cross-section. The time constant for these 'passive' cooling methods is much too long for all reasonable gas pressures. Nature, having provided the Second Law to force the hot antiprotons to share their energy with the rest of the universe then cheats us by working too slowly! The stochastic technique replaces the dissipative circuit by a tuned circuit in resonance with the motion being cooled. The mean centre of mass velocity of the antiproton sample can be derived from the tuned circuit signal, and the centre of mass can then be stopped by an appropriate pulse applied to the opposite electrode. After a suitable time to allow centre of mass motion to build up again, the process is repeated. Continued cycling in this way pumps energy out of the particle motion with a time constant proportional to the period of the motion being cooled and the number of antiprotons. Figure 4 shows a circuit for stochastic cooling of the axial motion. (The parallel amplifier compensates signals fed back through the trap via strays). Table 1 lists the characteristics of Penning traps with depth 3.5 keV , r_0=2,5 cm and B=1 T versus the bunch duration accepted. The anticyclotron sample corresponds to the second line.

A Penning trap to cool the anticyclotron sample to some tens of eV is being developed in Genoa and tests are planned this year. The cooling time constant is expected to be a few hundred seconds. The annihilation lifetime at a pressure (as achieved in Genoa) of 10^{-13} Torr is many hours (fig. 1).

A limitation in the performance of this technique occurs if the re-

TABLE 1 PENNING TRAP SIZES ETC. VS BUNCH DURATION

τ (ns)	z_o (cm)	f_z (Mhz)	f_c (Mhz)	f_m(Mhz)
100	2.7	5.0	15.1	0.83
150	4.05	3.33	15.56	0.305
200	5.4	2.5	15.72	0.2

sonance envelope of the trapped sample broadens on account of trap imperfections (due to finite electrode size) or space charge effects. Effectively the resonant circuit becomes much less efficient if the Q-factor of the particles is not matched to its own Q-factor. Calculations show that this limit will not be reached for samples containing less than 10^8 antiprotons.

2.3 COOLING FROM T ~ 13.6 eV TO CRYOGENIC TEMPERATURES

At a few times the Rydberg energy, we can expect that the capture cross section will become the dominant effect and that therefore the sample will have to be transferred to a second trap designed for very rapid cooling. Fortunately, cooling by mixing the antiprotons with a stored electron cloud is likely to be extremely effective at these energies. The method has been discussed several times (eg [11]). The principle is similar to the mixing of hot and cold liquids. If the rate of cooling of the electron 'liquid' by synchrotron radiation is faster than the rate of transfer of energy from the antiproton 'liquid', the cooling process is sustained, and in fact accelerates as the temperature decreases. For effective cooling, there must be about 10^4 electrons per antiproton. This is compatible with a strategy in which samples of 10^3 - 10^4 antiprotons at a time are 'spilled' into the second trap containing about 10^7 electrons per cm^3 (a practically attainable level), and are cooled with a time constant of the order of 1 s and then launched into the drift tube in groups of about ten at a time.

2.4 LAUNCHING AGAINST GRAVITY, MEASURING THE TIME OF FLIGHT

The vertical launch tube is of similar design to that used in the heroic attempt to test the WEP on electrons and positrons some 25 years ago [12] (This experiment may soon be repeated with the better methods now available for producing cold positrons [13]. As suggested above, screening of electromagnetic effects is the principal function of the launch tube. The tube will be located in a magnetic guide field. The condition on the homogeneity of this to reduce magnetic moment interactions to less than the gravitational level is one part in 10^4. The main residual electrostatic effects are a) the Patch effect (the statistical average of contact potentials between crystal surface 'patches' on the inside surface of the tube is not zero) b) the lattice compression effect (the lattice is compressed more by gravitational stresses at the bottom than at the top). The expected fields from both these effects are much larger than gravity. Kelvin probe studies of amorphous coatings to reduce the first effect to the required level are well advanced at Los Alamos. For reasons which are still not perfectly understood, the residual fields in the positron-electron experiment [12] were reduced at cryogenic temperatures to 10^{-11} V/m. New studies of nature's bonus in this matter are under way and will be discussed elsewhere.

Although a simple scintillator would detect antiprotons by their annihilation, the detection of H^- ions at 1 m/s velocity requires reacceleration through at least several hundred volts to secondary emission energies. A multichannel plate detector will therefore measure the particle arrival time at the top of the tube. Penetration of its field into the drift tube is calculated to give a further residual effect at the few percent level. This and many other small effects will be calibrated away by the comparison of the H^- ion and antiproton time of flight spectra.

3. CONCLUSIONS

I have tried to present a description of the present status of this exciting but difficult experiment in a form intelligible to the audience of non-specialists which I believe is assembled here. This is quite appropriate : this is a somewhat unusual experiment for particle physicists, bordering in its techniques as well as its import on a number of disparate disciplines, so that in a sense most of the people involved in it are themselves non-specialists.

The title of this morning's session is 'Fundamental Principles'. It is our job as experimentalists to examine and test our basic principles in wider and wider domains. As you have no doubt noticed, some of the experimental problems are close to a solution and some are less close. We believe that in spite of the immense difficulties involved, we shall be able to do this job with the WEP, which could hardly be more fundamental to all our endeavours.

ACKNOWLEDGEMENTS

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