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SUBMITTED TO Proceedings of the "Workshop on Traps for Antimatter and Radioactive Nuclei", TRIUMF, Vancouver, CANADA, 25-27/FEB/93, ed. by A.I. Yavin

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ABSTRACT

The reconciliation of quantum mechanics and gravity on varying distance scales requires changes to General Relativity that may have testable implications. We briefly review the status of tests with matter of the inverse square law and the principle of equivalence, then report on progress on the drift tube measurement section of PS 200, the experiment to measure the gravitational acceleration of antiprotons.

1. Introduction

We now know, from a general point of view referred to as “effective Lagrangians”, that Einstein’s Theory of General Relativity (GR) can only be an approximation. To know this, we need only assume that quantum mechanics does apply to GR as it does to all other physical theories.

The argument is best seen by analogy with Quantum Chromodynamics (QCD). If we integrate out the short distance (ultraviolet) degrees of freedom in QCD, quarks and gluons, down to some infrared cutoff, we can construct an effective intermediate theory described by a chiral Lagrangian^[1] of mesons and baryons with an infinite series of terms. This new theory is valid at longer distance (lower momentum) scales than the infrared cutoff, and it may be consistently expanded in powers of the (low) momentum factors, which allows truncation of the effective Lagrangian to a finite number of terms for a given problem. There are still infrared quantum mechanical corrections, calculated by integrating over loops of virtual mesons and baryons. These loops are a (relatively) easy way of integrating and summing the many (and correlated) quark and gluon loops that would be needed to describe the same physics which dominates the infrared scale amplitudes. If some term has been inadvertently left out of our calculation, the **ultraviolet** divergences (cutoff dependence) of the loop calculations using the effective degrees of freedom will reveal this by generating a cutoff dependent term which cannot be absorbed into a

renormalization of one of the existing terms. When the set of terms is complete to the given order, the renormalization group may be applied to the vertex coupling strengths because the approximation is consistent with quantum mechanics.

So too for General Relativity: We imagine that the theory is an effective one produced by integrating out degrees of freedom over short distance scales and expanding in powers of momentum. We then find that the Einstein Lagrangian

$$L = \Lambda - \kappa R \tag{1}$$

where Λ is the cosmological constant, κ is $(16\pi G)^{-1}$ where G is Newton's constant, and R is the usual scalar curvature, are only the first two terms in an infinite series related by the renormalization group. The next terms consistent at the one loop level are given by^[2]

$$L \rightarrow L + aW + \frac{bR^2}{3} + \alpha_V R^* R^* + \kappa D^2 R \tag{2}$$

where W is the Weyl term, R^* is the dual of the full curvature tensor, and D^2 is the fully covariant d'Alembertian.

A major difference from QCD is that instead of there being a natural scale of $\approx 1 fm$, defining the separation between short and long distances, here we must make a choice of scale. To avoid introducing uncertain short distance degrees of freedom, we choose the laboratory scale, $\approx 10 cm$, as the reference scale. This also eliminates the need to include any 'matter' degrees of freedom except the photon, possibly the neutrinos, and any massless scalars such as a dilaton. When the evolution of G with scale, according to the renormalization group equations of Fradkin and Tseytlin and Avramidy and Barvinsky^[2], is taken into account, effects are found which bear a strong resemblance to those usually attributed to 'dark matter'.^[3]

2. History

Our interest in gravity goes back to 1980 when Michael Nieto and I were discussing the beautiful neutron interferometry experiments of Colella, Overhauser and Werner^[4] which showed that neutrons experienced the expected change in quantum mechanical phase from changes the (classical) gravitational potential through which they passed. Nieto then asked, "How do we know what the gravitational acceleration is of antimatter (in the Earth's field)?"

An examination of the literature showed that this question had not been satisfactorily answered: The result was guaranteed if and only if gravity is exactly the metric theory proposed by Einstein.^[5] At that time, the conflict of that theory of gravity and quantum mechanics was only crudely expressed by the statement that General Relativity required a knowledge of both positions and velocities to define the metric, that is, a knowledge of trajectories. However, the uncertainty relations between positions and momenta prohibit such knowledge. Signals of this conflict included Hawking radiation and the loss of quantum coherence at the surface of black holes.

Another way of phrasing the problem is that General Relativity is not renormalizable. The search for renormalizable quantum gravity theories has so far always produced theories that are **not** metric theories. Applications of local supersymmetry, or the introduction of (super)string theory, higher dimensions, or higher derivatives as discussed above all produce non-Einsteinian terms which have one or both of two related effects: They violate the weak equivalence principle, and the inverse square law. These effects are found explicitly to be due to the presence of vector and scalar interactions which are symmetry partners of the usual tensor interaction, but which are generally finite ranged and do not couple to the stress energy tensor in the usual way (or even at all).^[6] Thus, the gravitational behaviour of antimatter becomes an experimental question, as indeed, does the detailed behaviour of matter, which has long been recognised as a valid experimental question. There is now a huge literature^[7] surrounding these questions.

3. Matter Experiments

Equivalence principle tests go back to the beginning of Physics, with several exciting hints recently of violations. None of these has been confirmed, and most have been contradicted by later and better experiments. The only notable exception has been the experiment of P. Tieberger. It has been argued that other equivalence principle violation experiments do not contradict this positive result, due to the peculiar geology in the region of the experimental site.^[8] A recent coherent neutron scattering experiment^[9] is a particularly nice example of a measurement on single particles and provides strong bounds.

Inverse square law tests are almost as old as equivalence principle tests, and have a similarly chequered recent history, with all positive reports of a signal later being shown to be false or inconclusive due to experimental biases discovered after the completion of data taking. I mention only the latest and largest scale of these, the “Ocean Big G” experiment.^[10] This was conducted as a Gauss’ law test on a scale of several km in the Pacific Ocean. The experiment measured the local acceleration of gravity field on several planes from the ocean surface to its bottom,

and the density of the seawater as a function of depth throughout. There was no evidence for an inverse-square-law-violating signal at a level below 10^{-3} of Newton's constant. [10]

4. Antimatter Experiments

First, I should mention experiments with photons, since opposite polarizations are CPT conjugates and so antimatter to each other in the conventional sense. An old argument^[6] due to Morrison and Gold raises a matter-antimatter pair of particles in the gravitational field, annihilates them and blueshifts the photons as they return to the initial level of the pair. Energy conservation requires an exact cancellation between the nonmetric contributions to the energy change, except for the net nonmetric effect on the photons. This is exactly what occurs for new vector gravitational forces. Since they are essentially selfconjugate (unless a splitting between polarizations is observed in the blueshift of the photon energy), the photons are expected to be affected only by new scalar gravitational forces. The agreement between experiment and expectation based on the measured local value of the acceleration due to gravity implies the difference between this coupling and the corresponding one to matter is small.

I will not comment in detail on experiments involving $K^0 \rightarrow \bar{K}^0$ transformations for lack of space. I only mention that the question of the quantum coherence length of the wavepacket must be considered as well as the effect of the $\Delta S = 2$ weak interactions, which convert K^0 's to $\bar{K}^0$'s and so reverse any effects that would tend to separate or distinguish the two states. [11]

5. PS-200 Experiment

The PS200 experiment^[12] is designed to measure directly the effect of gravity on antimatter. Antiprotons (and H^- ions for direct comparison) are released vertically into a field free region and their time of flight spectrum measured. The effect of gravity is to produce a cutoff in this spectrum corresponding to the slowest particles that may travel in the one direction allowed and still reach the detector. The cutoff is sharper for a colder spectrum of particles. Thus the experiment requires collection of a large enough number of antiprotons to measure a spectrum, a means to cool them to very low temperatures, and a field free region. The collection part of this effort is now very advanced at LEAR and has been discussed by M. Helzlsouer elsewhere in these Proceedings. Collection and cooling of smaller numbers of particles has also already been demonstrated. [13]

At Los Alamos, a drift tube test stand has been constructed to study the problem of providing an electric field free region. Since the gravitational interaction changes the energy of a proton by only 10^{-5} eV per metre, the constraints on

the field-free region are very stringent. A magnetic guide field with a uniformity of better than one part in 10^5 has been achieved and is sufficiently uniform. A 'Faraday cage' of a conducting drift tube almost does the rest of what is needed. The remaining problem is due to the so-called 'patch effect', where surface dirt or nonuniformities produce small fluctuations in the potential seen by charged particles travelling along the central axis of the drift tube.

Early experiments using a Kelvin probe had found two candidate surfaces which are too flat (electrically) to produce a response in that instrument. So now what is being done is to use gravity on ions passing through the drift tube to study the surfaces. An ion source launches the ions downward into the tube, and the arrival time spectrum is measured at the bottom. Tests comparing results with and without a blocking voltage on the drift tube eliminate false signals from neutrals. So far, despite very limited statistics (as the ECR ion source is by no means 'cold'), there is some initial evidence for ions with energies as low as 10^{-6} eV traversing the drift tube. If verified, this would strongly suggest that there are no potential 'bumps' larger than this size, and so a very small, if any, residual patch effect. Following is a more detailed discussion of these points.

6. The Drift Tube Test Experiment

6.1. The Drift Tube

The most critical problem in the proposed measurement of the gravitational acceleration on charged particles is the shielding of all forces other than gravity which could be acting on the antiproton. Obviously, the forces we need to worry about are the electrical force acting on the charge and the magnetic gradient force acting on the magnetic moment of the antiproton (or the negative hydrogen ion).

The magnetic moment of antiprotons and negative hydrogen ions are — due to the presence of the strong magnetic field — dominated by the orbital magnetic moment and therefore nearly identical. Computer modeling of the motion of ions through a spatially fluctuating magnetic field shows that homogeneities dB/B of about 10^{-5} are needed to avoid adversely affecting the time of flight spectrum. This requirement has been met by a commercial magnet, obtained from Oxford Instruments, which exhibits a homogeneity of 5×10^{-6} in a volume of 0.50 m length and 1 cm diameter. This magnet was commissioned at Los Alamos two years ago and has been used in the drift tube test experiment described below. We anticipate purchasing a magnet with the same specifications but twice as long for the actual gravity experiment at LEAR.

To sufficiently reduce the electric force acting on the antiproton, stray electric fields must be reduced to a level below 10^{-2} V/m. For this purpose, the gravity

measurement itself will take place inside a cylindrical, conducting tube, the “Drift Tube”. This tube shields all external fields exponentially with axial distance into the tube, and after about 2 - 3 diameters penetration into the interior of this tube, all fields are reduced well below the critical value. Special attention must be given to eliminating, or compensating for, electric fields produced in the drift region by such causes as crystalline patches (“patch effect”) on the tube’s inner surface and strains in the drift tube material. On normal materials, one finds areas with work functions differing by 100 mV or more between such patches. The dipole fields created by these work function variations generate electric potential variations on the axis of the tube which will affect the time-of-flight of the particles and possibly obscure the effect of gravity.

6.2. Surface Studies

To reduce the patch effect, special surface coatings have been studied which will reduce the variations in work function. The main ideas guiding these studies have been to keep the patch size small, so the particles would average over a larger number of patches, and to generate a surface as non reactive as possible to reduce the build up of adsorbed material on the surface, a common cause of the patch effect. In earlier studies, a Kelvin probe assembly was used to test different types of surface coatings on small test samples^[14]. Through these studies we have identified two candidate surfaces for the drift tube coating: graphite and gold (on a sub layer of germanium). At the resolution limit of the Kelvin probe system of 1 mV, no variation could be detected. This is equivalent to potential variations on the axis of a tube with the geometry of our drift tube of less than 5×10^{-3} mV. This is still three orders of magnitude larger than the requirement for a measurement of gravity on antiprotons and negative hydrogen ions, but compares to the equivalent restriction if one wants to study gravity on xenon ions ($\sim 10^{-5}$ V/m). Searching for a more sensitive instrument to study surface effects, we have initiated further work using a model of the actual drift tube and gravity on xenon ions.

An apparatus has been constructed (see Figure 1) that consists of four main modules: (1) A commercial ECR ion source and beam optics capable of furnishing ions of differing masses and charge states. (2) 4 Drift tubes, about 50 cm in length, that will have several different types of interior surface coatings to study the patch effect. Small electric fields generated in the drift region by running electric currents along the tube (IR drop) will enable us to study systematic effects under controlled conditions. (3) A superconducting magnet that surrounds the drift tube and produces a field of up to 2 T. It is necessary to generate a magnetic field along the tube axis for the ions to maintain central paths through the tube. High field uniformity is required in order to avoid gradient forces on the ions. (4) A particle detector to measure the flight time as the ions pass through the drift tube after having been released at the ion source. A microchannel plate detector (MCP) is being used for

initial studies. At a later stage the ion source will be replaced by a small Penning trap to study the launch process and the effect of the inter-particle forces on the time-of-flight distribution.

6.3. The Detector

An identical copy of the MCP detector was used to study the performance of such a detector at low temperature and at high magnetic field. We found no gain shift down to ambient temperatures of 4 Kelvin, provided the count rate was kept below 1 kHz. A gain drop of 60% was observed at an axial magnetic field of 2 T. We did conclude that the MCP detector should be fully functional under the conditions expected in the experiment^[15].

Recent work with the detector in the actual drift tube test experiment has pointed towards possible problems arising from neutral particles or excessive gas loading from the ion source. Continued studies to identify the exact cause of these problems are under way, and we have also initiated a search for alternative detection schemes. Additionally, we are making modifications to the ion source to reduce the gas load into the cryogenic vacuum system.

6.4. Time-of-Flight Measurements on Heavy Ions

Using a retarding field method, we determined the energy spread of the ion source to be less than 10 eV. We conclude that this will allow us to produce a sufficient number of ions with near zero kinetic energy at the top of the drift tube in a short pulse.

To determine the presence of electric fields inside the tube to a higher level of accuracy than previously possible with the Kelvin probe, we plan to use the free fall through the drift tube of these slow ions. To do this, a short pulse of ions from the ion source is sent towards the drift tube and retarded at the entrance. Using the MCP we can sample the time of flight distribution for the ions arriving at the detector and search for late arriving particles. These are the candidates for particles which have been moving very slowly through the drift tube and therefore have sampled the electric field distribution with high sensitivity.

We have obtained time spectra of ions exhibiting particles arriving with a significant delay in comparison to the ion pulse being released from the source. Figure 2 gives a typical example of such a spectrum. During the first 60 msec, charged particles are deflected away from the MCP, thereby avoiding saturation of the detector from promptly arriving particles. One still sees a large number of counts caused by neutral particles during the time of the pulse from the ion source. At about 60 msec, the deflector is turned off, and charged particles are

admitted to the MCP. An increase in counts over the background rate out to 200 msec can be observed (the cut-off time caused by gravity is expected at 305 msec for this drift-tube). The spectrum shown represents 50 individual samples added together. The background rate therefore is about 150 Hz, which is roughly a factor of 200 higher than the quiescent background rate if the ion source is turned off and much too high to extract an endpoint for the TOF spectrum. Improvements in the differential pumping to reduce the gas load from the ion source into the drift tube are expected to reduce this background drastically. Ultimately, when a Penning trap is used instead of the ion source, the background rate will approach the quiescent rate.

More studies are necessary to assure that these late arriving particles are particles which have been moving slowly through the drift tube and not ones that have been captured and released at a later time from internal traps. For this purpose, we can vary the effective force on the particles inside the drift tube by generating small, controlled electric fields through an electrical current run symmetrically through the drift tube wall. Once this has been established, we have an instrument capable of studying the patch-effect with a resolution about 10 times higher than the Kelvin probe. This resolution can then be increased by using ions of lower inertial mass.

6.5. The Launch Trap

For ions below approximately 20 *amu*, we will replace the ion source by a small Penning trap (the "Launch trap"). This change is necessary to reduce the magnetic mirror effect on the ions from the ion source (operating at around 800 Gauss) entering the strong magnetic field. It will also provide us with a source of ions with a much lower energy spread and therefore allow us to use a smaller number of ions thereby reducing the effect of inter particle Coulomb forces which will become important at these lower energies.

In the gravity measurement on antiprotons, the launch trap will serve the purpose of storing the sample of antiprotons in preparation of their launch in individual samples of 100 antiprotons each from a thermal distribution at 4 Kelvin. We have designed, constructed, and tested an open end cap, cylindrical Penning trap and have successfully generated clouds of nitrogen ions, helium ions, and protons. The observed storage times were several hours.

In this trap, antiprotons will be cooled by coupling the signals induced in the trap electrodes to an effective resistance, comprised of a high Q inductor paralleled by the trap capacitance. We have constructed superconducting inductors with Q values of several thousand and have installed such an inductor in the trap. By tuning resonance frequency of the particles to the central frequency of the tuned circuit, the time constant for dissipating the energy of the cloud into the effective

resistance formed by the tuned circuit can be made reasonably short.

For our parameters, we anticipate a total cooling time from several eV to 4 Kelvin of a few seconds. This is somewhat slower than the electron cooling time, but has the advantage that no electrons have to be introduced into the gravity experiment, where they could easily be trapped in small wells produced by contact potentials and mask the time of flight distribution for antiprotons. (Note that approximately 10^4 times as many electrons than antiprotons are needed for effective electron cooling.)

7. Summary

For the shielding of stray electric fields by a metal tube we have identified two possible candidates for surface coatings to reduce the "patch effect". We have studied these surfaces with a vibrating tip electrometer and have constructed a test experiment to use gravity on heavy ions as a surface probe. We look forward to setting up this final component of the first experiment to directly measure the acceleration of gravity for antimatter in about one year.

8. Acknowledgements

Part of the theoretical work described here was done together with Juan Perez Mercader, Michael Martin Nieto, and Fred Cooper. The work on degrading and trapping antiprotons at CERN would not have been possible without the excellent support we obtained from the entire LEAR staff. Special thanks go to Jean-Yves Hemery for his continued interest in improving the beam tune in line S4 and his close collaboration with our team on all issues concerning the operation of our experiment in the LEAR environment. The generous support by G. Smith from Penn State University is gratefully acknowledged. This work was supported by the Department of Energy under contract W7405 ENG-36.

9. References

1. J. Gasser and H. Leutwyler, *Nucl. Phys. B* **250** (1985) 465.
2. E. S. Fradkin and A. A. Tseytlin, *Nucl. Phys. B* **201** (1982) 469; I. G. Avramidy and A. O. Barvinsky, *Phys. Lett.* **B159** (1985) 269.
3. T. Goldman, J. Perez Mercader, F. Cooper and M. M. Nieto, *Phys. Lett.* **B281** (1992) 219.
4. R. Collida, A. W. Overhauser and S. A. Werner, *Phys. Rev. Lett.* **34** (1975) 1472.
5. T. Goldman and M. M. Nieto, *Phys. Lett.* **B112** (1982) 437.
6. T. Goldman, R. J. Hughes and M. M. Nieto, *Phys. Lett.* **B171** (1986) 217.

7. M. M. Nieto and T. Goldman, *Phys. Rep.* **205** (1991) 221; (E) **216** (1992) 343.
8. M. E. Ander, T. Goldman, R. J. Hughes and M. M. Nieto, *Phys. Rev. Lett.* **61** (1988) 2273.
9. H. Leeb and J. Schmiedmayer, *Phys. Rev. Lett.* **68** (1992) 1472.
10. M. A. Zumberge, et al., *Phys. Rev. Lett.* **67** (1991) 3051.
11. T. Goldman, M. M. Nieto and V. D. Sandberg, *Mod. Phys. Lett. A* **37** (1992) 3455; G. Chardin and J. M. Rax, *Phys. Lett. B* **282** (1992) 256.
12. N. Beverini et al. *CERN Proposal PSCC/86-2/P94* (1986).
13. G. Gabrielse, et al. *Phys. Rev. Lett.* **63** (1989) 1360.
14. J. B. Camp, T. W. Darling, and R. E. Brown, *J. Appl. Phys.* **69** (1991) 7126 and *J. Appl. Phys.* **71** (1992) 783.
15. J. A. Schecker, M. M. Schauer, K. Holzscheiter, and M. H. Holzscheiter, *Nucl. Instrum. Methods A* **320** (1992) 552.

Figure 1 Schematic of the Drift-Tube-Test-Experiment showing the main components

Figure 2 Time spectrum of neon ions from a 50 msec pulse from the ion source retarded to zero kinetic energy at the entrance of the drift tube