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POSSIBILITIES FOR MEASURING THE PASSIVE GRAVITATIONAL MASS OF ELECTRONS AND POSITRONS IN FREE HORIZONTAL FLIGHT

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Abstract

We present a preliminary design study for an experiment to measure the gravitational deflection of electrons and positrons in horizontal free flight, as suggested by R. M. Santilli and under consideration for the Molise Laboratory of Antimatter in Italy. Our main conclusion is that the experiment is indeed feasible with current technology via the use of a 100 m long x 0.5 m diameter (inside dimensions) evacuated horizontal flight tube. The principle requirements are: (1) the exclusion of unwanted electric and magnetic fields using various concentric shields; (2) the production of extremely bright pulsed sources of electrons and positrons; (3) the use of time of flight and single particle detection to determine the displacement of a trajectory from the horizontal as a function of the particle velocity; and (4) the comparison of measurements using both electrons and positrons traversing the flight tube in both directions with various weak applied electric and magnetic fields to search for and eliminate unwanted systematic effects. The use of particles with 25 μeV kinetic energy would yield a vertical displacement of 5 mm at the end of the 100 m free horizontal flight, which should be distinguishable from the fluctuations induced by the residual stray fields. The results of this experiment should provide a definitive value for the passive gravitational mass of the positron.

INTRODUCTION - According to our current experimental knowledge, antiparticles bound to an ordinary material particle are gravitationally attracted to a large mass of ordinary matter such as the earth or the sun. In fact, the experimental verification of the weak equivalence principle by Dicke and collaborators [1] shows that Au and Al fall identically in the gravitational field of the sun to within an uncertainty of less than 3 parts in 10^{11}. An argument by Schiff states that the contribution to the mass of a gold atom from the small components of the K electron Dirac wave function is roughly 20 keV out of the total atomic mass of about 200 GeV, or about one part in 10^7. A similar contribution comes from virtual electron-positron pairs in the nuclear potential. The Dicke-Eötvös experiment thus shows that the contribution of virtual positrons to the passive gravitational mass of gold atoms is the same as that of electrons to a precision better than 1 part in 10^3.

While matter and antiparticles bound to matter are thus constrained by experiment to experience equal gravitational accelerations, we currently have no final experimental evidence on the behavior of isolated antiparticles in a gravitational field. In the latter respect we have a theoretical argument suggesting that antiparticles are attracted in the same way as particles from the conservation of the total energy, else one could derive energy from a gravitational potential via an ideal engine based on electron-positron annihilation and pair-production.

Nevertheless, the latter theoretical argument does not appear to have a final character, thus necessitating an experimental resolution of the issue. Indeed, the apparent violation of energy nonconservation could be resolved by introducing one or more new fields, for example new degrees of freedom for gravitation as done by Goldman, Hughes and Nieto [2] and effectively in the theory of Santilli [3,4]. It could be that there are two flavors of gravity for free particles and antiparticles, but that the flavors become mixed for bound states when the particle-antiparticle binding energy exceeds the gravitational field energy in the volume occupied by the bound state. On earth, the relevant energy density, $g^2/G = 1\,\mathrm{eV}\,\mathring{A}^{-3}$, would suggest that a definitive test of the equivalence principle for antimatter would need to examine either free antiparticles or hydrogenic particle-antiparticle systems in high Rydberg states where the binding energy is small.

An experiment was initiated by Witteborn and Fairbank [5] to test the behavior of electrons and positrons in free vertical fall, but its results were not definite because of uncertainties inherent in the test at the time (1967).

In view of the above scenario, Santilli [3,4] recently proposed to measure the gravity of positrons, this time in free horizontal flight in a high vacuum tube which is sufficiently shielded from stray electric and magnetic fields and of such a length for a given energy of the positrons to yield a definite displacement due to gravity at the end of the horizontal flight. A related proposal [6] would involve measuring the gravitational deflection of slow positronium atoms (bound e^+-e^- pairs) in high n states in which their annihilation lifetime would be very long. The advantage of using electrically neutral atoms for a test would be a reduced sensitivity to stray fields. The high n states would be very susceptible to gradients, and the necessary shielding would be nearly as stringent as for tests on bare particles. Given also the added complexity of a laser system for preparing the slow high n positronium atoms and the questions about the role of bound states in gravitation, it seems most appropriate to directly measure the separate deflections of positrons and electrons as suggested by Santilli.

In this paper we conduct a preliminary study of the experimental design needed to carry out Santilli's proposal which is currently under consideration for realization at the Molise Laboratory of Antimatter in Central Italy. Our main conclusion is that the latter experiment is feasible with current technology and, when realized according to certain specifications identified below, it is expected to yield a definitive result.

It is to be noted that Santilli has originated a new theoretical representation of antimatter (treated in detail in ref 4) based on a concept known as "isoduality", and which it is claimed yields a natural representation of Dirac's negative-energy states without the need for the hole theory. Santilli's theory predicts that particle-antiparticle bound states as well as particle-antiparticle neutral objects like the photon are attracted by the fields of either matter or antimatter, as expected in the ordinary Einstein description of gravitation. However, Santilli's isodual theory predicts that isolated elementary antiparticles such as positrons in the field of the earth should experience a reversal of the gravitational attraction of the corresponding particles in a way compatible with the conservation of the total energy [3,4].

We conclude from the above discussion, that the question of antimatter free fall may only be answered by experiment. In the present report, we find that an electron and positron free fall experiment is technically feasible. It is the opinion of the author that the implications of a definitive measurement of the effect of gravity on isolated elementary antiparticles in the field of the earth would amply compensate for the difficulties of performing the experiment.

EXPERIMENTAL DESIGN CONSIDERATIONS - The pioneering experiment of Witteborn and Fairbank [5] demonstrated that is it possible to obtain a sufficient number of cold electrons to study their free fall and that the unwanted stray electric and magnetic fields can be reduced to a negligible level. Since that time we have learned how to manipulate positrons in phase space [7-9] sufficiently well to make possible the complementary experiment using antiparticles. The vertical geometry with a flight path of only 2 m used by Witteborn and Fairbank was acceptable because of their good fortune to discover a near perfect shielding of the electric fields in a Cu enclosure at 4 K [10-12]. An acceptably low magnetic field effect was achieved by using only electrons that were in the lowest Landau level of the applied 7-20 gauss magnetic field.

The electric field that would cancel the earth's gravitational force on an electron, $E=m_e g/e$, is only 5.6×10^{-11} V/m. Our understanding of the low temperature zero electric field effect in Cu does not seem sufficient at this time to guarantee perfect shielding. A conservative approach would be to compare the trajectories of both electrons and positrons in order to measure both the gravitational effects and the stray electric and magnetic fields. Assuming the shielding enclosure is composed of randomly oriented grains of diameter λ, the statistical variations in the potential on the axis of a tube of diameter d would be $\Delta V\approx\frac{\lambda}{d\sqrt{\pi}}$. Given work function variations of 0.5 eV, 1 μm grains and d=30 cm would imply 1 μV variations in the potential on the axis. Differences in strain or composition could cause larger variations. To obtain significant results without relying on the shielding effect of low temperature Cu we would like therefore to use electrons and positrons with kinetic energies significantly higher than 1 μeV. This in turn dictates the use of a flight path significantly longer than the 2 m used by Witteborn and Fairbank.

Santilli's proposal [3,4] for a horizontal flight tube would have the double advantage of allowing equivalent measurements to be done in both directions and providing simpler construction. Rather than measuring changes in the time of flight, such an experiment would measure the vertical deflections of the horizontal beam. Thus, one could independently determine the kinetic energy of the particles by their time-of-flight through the tube, rather than relying solely on an applied potential difference.

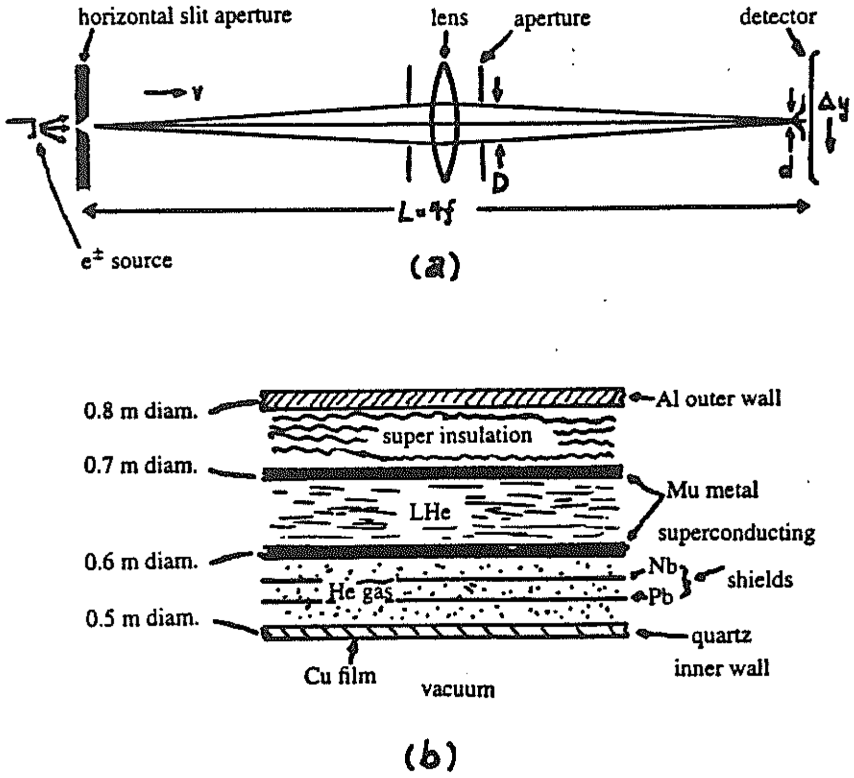
The magnetic field must also be shielded very well. Mu metal shields can reduce the earth's 0.5 gauss field to tens of μgauss [13,14]. Superconducting shields can make further reductions to possibly ngauss levels [14-18]. Small temperature gradients in normal metals can lead to trapped flux [18], but very slow cooling to achieve a uniform temperature may overcome this difficulty.

PROPOSED APPARATUS - We are thus lead to a falling $e^{\pm}$ experiment that makes use of a horizontal flight tube whose length we fix at 100 m, sufficient to observe the gravitational deflection of a 25 μeV electron. As shown in Fig 1, the tube would be a long LHe dewar, consisting of concentric shells of Al, Mu metal and quartz, with Pb and Nb superconducting shields and an inner surface coated with an evaporated Cu film. According to Cabrera [18], only quartz tubing would be suitable inside the superconducting shields. There would be two such shields so that they would go superconducting in sequence [Nb (9.25 K), Pb (7.196 K)], hopefully for better expulsion of flux. One would need trim solenoids within the inner shield and a multitude of connections to the Cu film for trimming the electrostatic potential.

As also shown in Fig 1, the flight tube would be configured with an electrostatic lens in its center to focus particles from a source at one end onto a position sensitive detector at the other. The de Broglie wave length of the particles results in a position resolution $d\approx2.4\pi\alpha a_B\frac{c}{v}\frac{L}{D}$, where $\alpha\approx1/137$ is the fine structure constant, $a_B\approx0.529\,\text{Å}$ is the Bohr radius of hydrogen, c is the velocity of light, v is the lepton (positron or electron) velocity, L is the length of the flight tube and D is the diameter of the lens aperture in the center of the flight tube. The free fall distance is $\Delta y=\frac{1}{2}g\frac{L^2}{v^2}$. Given L=100 m, D=10 cm, $v/c=10^{-5}$ (i.e. for 25 μeV particles), we find d=300 μm and Δy= 5 mm. For 1 meV particles, the resolution becomes d=40 μm and the deflection Δy=125 μm. Thus, one should be able to observe a meaningful deflection using particles with kinetic energies well above the expected untrimmed fluctuations in the potential. Note that the lens diameter should be roughly 3 times D in order to minimize the effects of lens aberrations. This requirement in turn dictates the minimum inside diameter of the flight tube.

The electron source should be a cooled field emission tip. A sufficient positron source would be provided by for example 0.5 Ci of ^{22}Na from which we expect (extrapolating to a source 5 times stronger than we have used [9]) 3×10^7 e^+/s in a 1 cm diameter spot. The positrons would be bunched [19-21] into pulses of 10^4 e^+ at a rate of 10^3 bunches per sec. Groups of 10^3 bunches would be collected into macro bunches containing 10^6 e^+ and 20 nsec in duration. The positrons would be removed from the magnetic field and triply brightness enhanced [7] using a final cold Ni film remoderator [8] to give bunches with 10^4 e^+, 10 meV energy spread, an ellipsoidal emission spot 0.1 μm high and 10 μm

Figure 1 - Schematic drawing of a horizontal flight apparatus for measuring the gravitational acceleration of electrons and positrons. (a) Overall plan showing the pulsed e$^{\pm}$ source, the horizontal slit aperture, an electrostatic lens with apertures in the center of the flight tube, the detector and the imaged spot of resolution *d*. (b) Detail of the horizontal flight tube, an evacuated liquid He dewar constructed from concentric shields made of Al, double walls of Mu-metal, double shells of superconducting Nb and Pb, a quartz inner vessel, and an inside evaporated fine-grained film of Cu.



wide, and a 1 radian divergence. The beam would then be expanded to 100 μm x 1 cm cross section and a 1 mrad divergence, still at 10 meV. Using a time dependent retarding potential we would then lower the beam energy spread and mean energy to 100 μeV with a 2 μs pulse width. Even assuming a factor of 1000 loss of particles due to imperfections in this scheme, we would then have pulses of about 10 positrons that could be launched into the flight tube with high probability of transmission at energies of 0-100 μeV.

The determination of the gravitational force would require many systematic tests. The most significant would be four measurements of the deflections as a function of the time of flight (and hence the velocity v) $\Delta y(e^{\pm},\pm v)$ for both positrons and electrons and for both signs of the velocity relative to the axis of the flight tube, $v>0$ and $v<0$. The vertical force on a lepton of charge q is

$$F_y=-mg+qE_y+qv_zB_x/c.$$

The net deflection is

$$\Delta y=\int_0^L\int_0^{z'} q\{E_y(z'')+vB_x(z'')/c\}dz''dz'/(mv^2)-\tfrac{1}{2}gz^2/v^2.$$

In lowest order, we neglect the transverse variations in E_y and B_x and write for the average fields

$$\varepsilon=\frac{1}{L^2}\int_0^L\int_0^{z'} E_y(z'')\,dz''dz'$$

$$\beta=\frac{1}{L^2}\int_0^L\int_0^{z'} B_x(z'')\,dz''dz'.$$

Note that these are not simple averages, but the averages of the running averages. They depend on the direction of the velocity. In the approximation that they are not significantly different from simple averages, the average of the four deflections Δy for both positrons and electrons and for both signs of the velocity is independent of ε and β and is given by

$$<\Delta y>=(g^{+}+g^{-})L^2/v^2,$$

where $g^{\pm}$ refers to the gravitational acceleration of $e^{\pm}$. Since we also have the velocity dependence of the Δy's, and can manipulate E and B by means of trim adjustments, it will be possible to unravel the gravitational effects from the electromagnetic effects in this experiment.

CONCLUDING REMARKS - We have presented a preliminary design study for an experiment to measure the gravitational deflection of electrons and positrons in horizontal free flight, as suggested by R. M. Santilli [3,4] and under consideration for the Molise Laboratory of Antimatter in Italy. Our main conclusion is that the experiment is indeed feasible with current technology via the use of a 100 m long x 0.5 m diameter (inside dimensions) evacuated horizontal flight tube. The principle requirements are: (1) the exclusion of unwanted electric and magnetic fields using concentric shields made of Al, double walls of Mu-metal, double shells of superconducting Nb and Pb, and an inner evaporated fine-grained film of Cu; (2) the production of extremely bright pulsed sources of electrons by the use of field emission at low temperature and of positrons by means of phase space manipulation techniques including brightness enhancement; (3) the use of time of flight and single particle detection to determine the displacement of a trajectory from the horizontal as a function of the particle velocity; and (4) the comparison of measurements using both electrons and positrons traversing the flight tube in both directions with various weak applied electric and magnetic fields to search for and eliminate unwanted systematic effects. The use of particles with 25 μeV kinetic energy would yield a vertical displacement of 5 mm at the end of the 100 m free horizontal flight, which should be distinguishable from the fluctuations induced by the residual stray fields. The results of this experiment should provide a definitive resolution to the problem of the passive gravitational mass of the positron.

REFERENCES

[1] P. G. Roll, R. Krotkov and R. H. Dicke, "The equivalence of inertial and passive gravitational mass", *Annals of Physics* **26**, 442 (1964).

[2] T. Goldman, R. J. Hughes and M. M. Nieto, "Gravitational acceleration of antiprotons and of positrons", *Phys. Rev. D* **36**, 1254 (1987).

[3] R. M. Santilli, "Antigravity", *Hadronic J.* **17**, 257 (1994).

[4] R. M. Santilli, "Elements of Hadronic Mechanics", Vol. 1 (1993) and II (1994), Ukraine Academy of Sciences, Kiev.

[5] F. C. Witteborn and W. M. Fairbank, "Experimental comparison of the gravitational force on freely falling electrons and metallic electrons", *Phys. Rev. Lett.* **19**, 1049 (1967).

[6] A. P. Mills, Jr., "Positron moderation and remoderation techniques for producing cold positron and positronium sources", *Hyperfine Interactions* **44**, 107 (1988).

[7] A. P. Mills, Jr., "Brightness enhancement of slow positron beams", *Appl. Phys.* **23**, 189 (1980).

[8] G. R. Brandes, K. F. Canter and A. P. Mills, Jr., "Submicron-resolution study of a thin Ni crystal using a brightness-enhanced positron reemission microscope", *Phys. Rev. Lett.* **61**, 492 (1988).

[9] A. P. Mills, Jr., S. S. Voris, Jr. and T. S. Andrew, "Solid Kr Moderator for producing slow positrons", *J. Appl. Phys.* **76**, 2556 (1994).

[10] J. M. Lockhart and F. C. Witteborn, "Near zero electric field: free fall of electrons and positrons and the surface shielding effect", in *Near Zero: New Frontiers of Physics*, edited by J. D. Fairbank, B. S. Deaver, C. W. F. Everitt and P. F. Michelson (W. H. Freeman, New York, 1988) p. 843.

[11] C. A. Waters, H. A. Fairbank, J. M. Lockhart and K. W. Rigby, "Low temperature transition in the microwave surface impedance of copper", in *Near Zero: New Frontiers of Physics*, edited by J. D. Fairbank, B. S. Deaver, C. W. F. Everitt and P. F. Michelson (W. H. Freeman, New York, 1988) p. 861.

[12] J. Bardeen, "Comments on shielding by surface states", in *Near Zero: New Frontiers of Physics*, edited by J. D. Fairbank, B. S. Deaver, C. W. F. Everitt and P. F. Michelson (W. H. Freeman, New York, 1988) p. 874.

[13] D. Cohen, "Large volume conventional magnetic shields", *Revue de Physique Appliquee* **5**, 53 (1970).

[14] A. F. Hildebrandt, "Shielding with superconductors in small magnetic fields", *Revue de Physique Appliquee* **5**, 49 (1970).

[15] R. E. Brown and W. M. Hubbard, "Magnetic field reduction in an expandable superconducting enclosure", *Rev. Sci. Instr.* **36**, 1378 (1965).

[16] R. E. Brown, "Device for producing very low magnetic fields", *Rev. Sci. Instr.* **39**, 547 (1968).

[17] W. O. Hamilton, "Superconducting shielding", *Revue de Physique Appliquee* **5**, 41 (1970).

[18] Blas Cabrera, "Near zero magnetic fields with superconducting shields", in *Near Zero: New Frontiers of Physics*, edited by J. D. Fairbank, B. S. Deaver, C. W. F. Everitt and P. F. Michelson (W. H. Freeman, New York, 1988) p. 312.

[19] A. P. Mills, Jr., "Time bunching of slow positrons for annihilation lifetime and pulsed laser photon absorption experiments", *Appl. Phys.* **22**, 273 (1980).

[20] A. P. Mills, Jr. and S. Chu, "Excitation of the positronium $1^3S_1-2^3S_1$ two photon transition", *Atomic Physics 8*, edited by I. Lindgren, A. Rosen and S. Svenberg (Plenum, New York, 1983).

[21] A. P. Mills, Jr., E. D. Shaw, R. J. Chichester and D. M. Zuckerman, "Production of slow positron bunches using a microtron accelerator", *Rev. Sci Instrum.* **60**, 825 (1989).