Test of the weak equivalence principle from particle-antiparticle cylotron frequencies

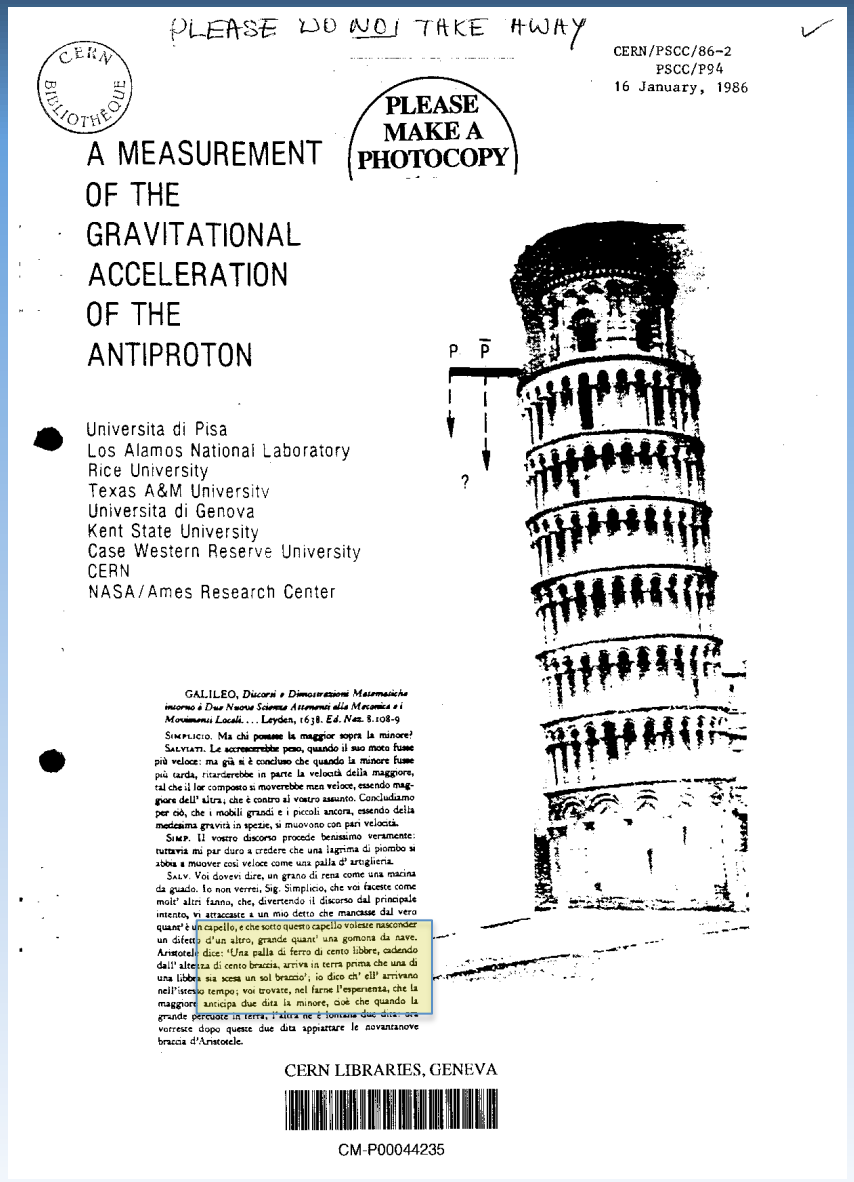
R. J. Hughes and M. Holzscheiter; PRL 66 (1991)

The Situation of Gravity

and

The Gravity of the Situation

Dr. Ron Brown, LANL (1986)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16 January, 1986

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A MEASUREMENT OF THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON

Universita di Pisa
Los Alamos National Laboratory
Rice University
Texas A&M University
Universita di Genova
Kent State University
Case Western Reserve University
CERN
NASA/Ames Research Center

P $\bar{P}$

?

GALILEO, *Discorsi e Dimostrazioni Matematiche intorno à Due Nuove Scienze Attenenti alla Mecanica e i Movimenti Locali*. . . . Leyden, 1638. *Ed. Naz.* 8.108-9

SIMPLICIO. Ma chi possase la maggior sopra la minore?

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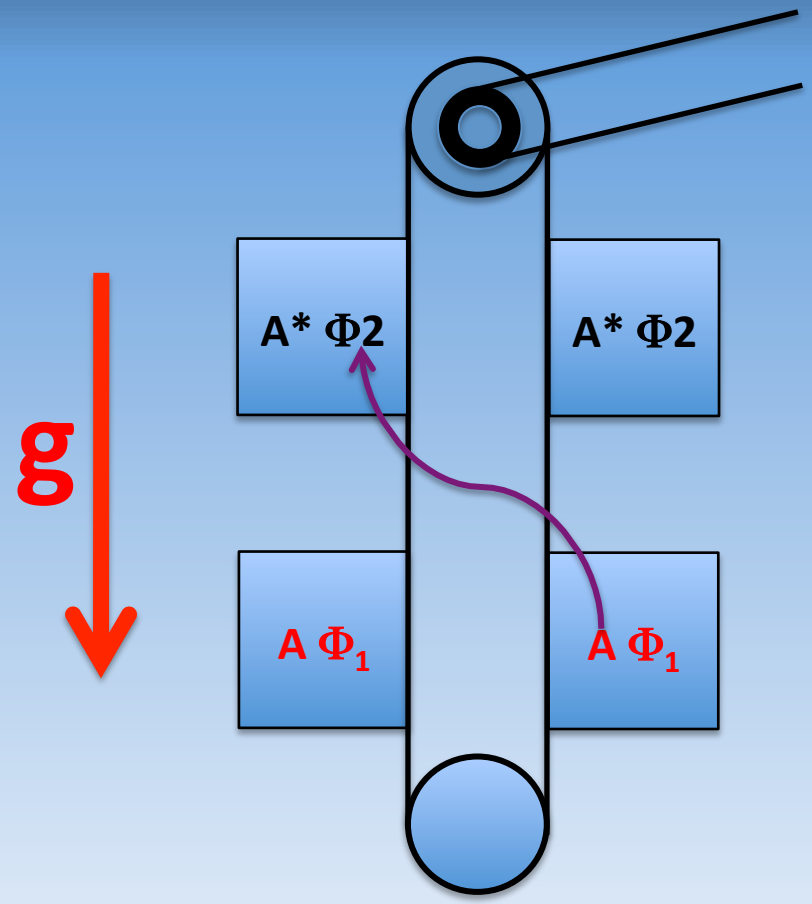
LEAR Experiment PS200.

In 1986 an international group proposed to measure Earth's gravitational force on antiprotons using a Galileo's Free Fall Experiment similar to the one originally pioneered by Bill Fairbanks and Fred Witteborn. ***(Experiments to determine the Force of Gravity on Single Electrons and Positrons; Nature 220 (1968) 436)***

Aristotel says: 'An iron ball of one hundred pounds , falling from a height of one hundred cubits, reaches the ground before a one-pound ball has fallen a single cubit.' I say that they arrive at the same time. You find, on making the experiment, that the larger precedes the smaller by two finger-breadths; that is when the larger one has struck the ground, the other is short of it by two fingers. Now you would not conceal behind these two fingers the ninety-nine cubits of Aristotle. ***(Dialogues and Demonstrations concerning Two New Sciences; Leyden 1638)***

(1 cubit = 520 mm ➔ 40/52000 = 0.08 % !!!!!!)

A. Einstein:
Über den Einfluß der Schwerkraft auf die Ausbreitung des Lichtes; Ann. Phys. 35, 898 (1911)



"Einstein's Dumb Waiter"
Frictionless Atwood Machine

Energy Storage Device

Upper Pan is heavier by $g\Delta E/c^2$ and will fall : stop acceleration by extracting energy

When upper Pan reaches bottom A* decays, photon reaches A, and excites it to A*

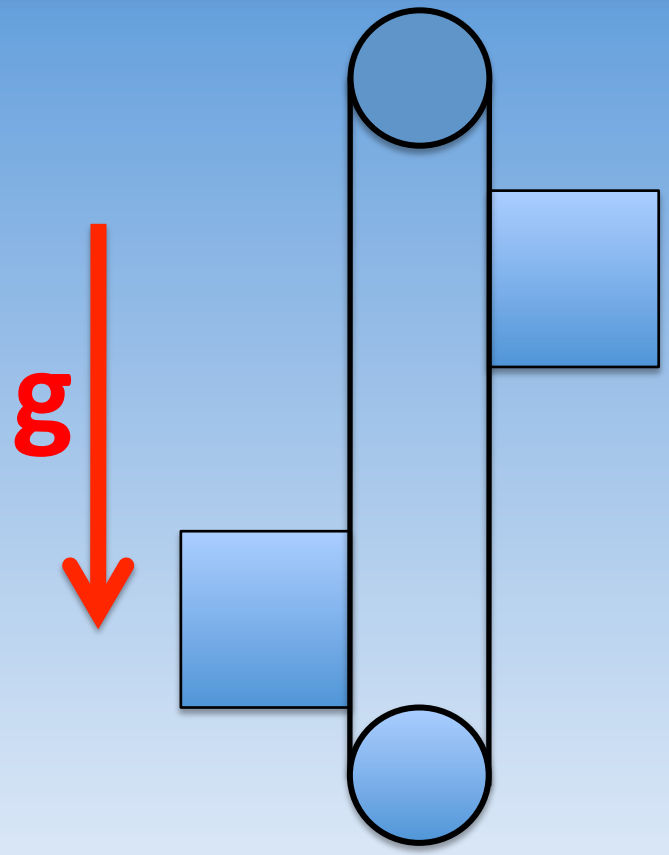
Initial condition is restored AND energy has been extracted:
THIS MUST BE AVOIDED!!!!!!!

SOLUTION:
Require redshift of photon to make it have insufficient energy to excite A by exactly the amount of energy in the storage device

$$\Delta\nu/\nu(1\rightarrow 2) = (\Phi 2 - \Phi 1)/c^2$$

Equivalence Principle directly yields redshift

P. Morrison: Approximate Nature of Physical Symmetries; Richtmyer memorial address of the American Association of Physics Teachers, January 1958



"Einstein's Dumb Waiter"
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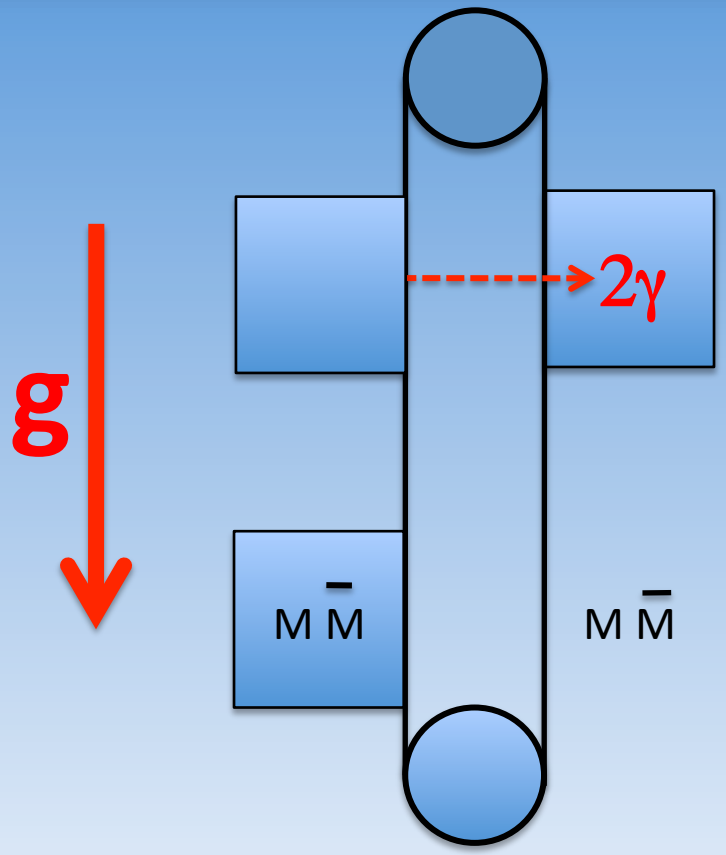
What about Antimatter?

Why is there an asymmetry between matter and antimatter in the Universe?

Is it because of boundary conditions? We wouldn't know the origin of it, but we know it would be self perpetuating.

Or is the asymmetry local? Do particles of antimatter carry a gravitational charge of –q. Then a gravitational plasma would not condense but rather un-mix!

The Morrison Argument:



"Einstein's Dumb Waiter"
Frictionless Attwood Machine

Consider **regular attractive tensor gravity for matter and antimatter** and load lower pan with matter-antimatter pair

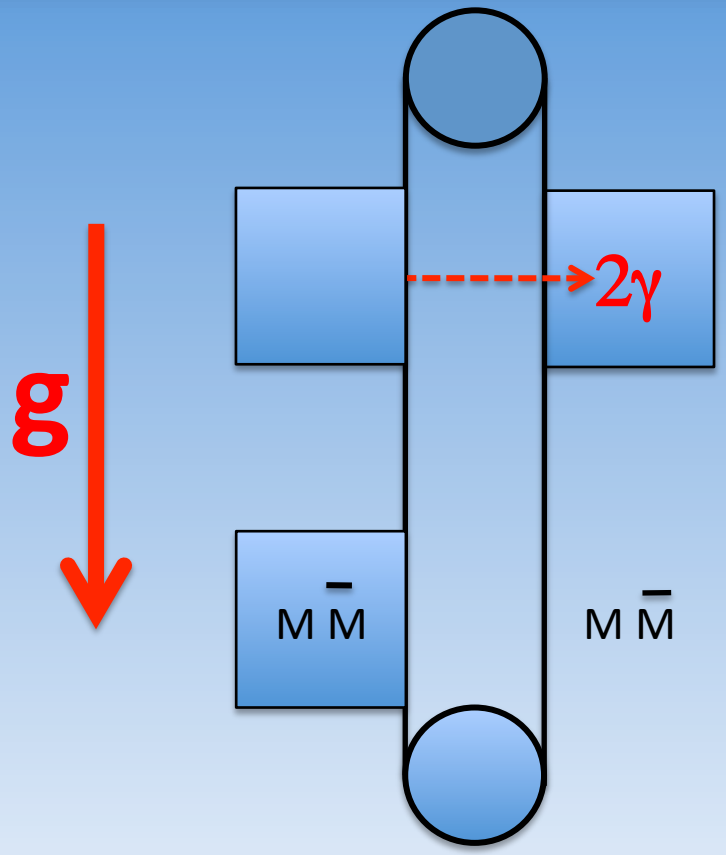
Raise the matter-antimatter pair by distance L where it has energy $E = 2mc^2 + 2mgL$ and let it annihilate into a photon pair. The photon pair does not measure absolute potentials and therefore has energy $2mc^2$

Photon drops in gravity field and gains energy
$h\Delta\nu = h\nu(gL/c^2) = 2mgL$

Now the photon can recreate a matter-antimatter pair with total energy
$E' = h\nu = 2mc^2 + 2mgL$

Which now can rise back up and continue the loop!

The Morrison's Antigravity Analysis



"Einstein's Dumb Waiter"
Frictionless Attwood Machine

Consider **regular attractive tensor gravity for matter but opposite sign for antimatter**.
Load lower pan with matter-antimatter pair

Adiabatically raise the matter-antimatter pair and let it annihilate into a photon pair

$E = 2mc^2 = h\nu$

Photon drops in gravity field and gains energy

$h\Delta\nu = h\nu(gL/c^2) = 2mgL$

Now the photon can recreate a matter-antimatter pair with total energy

$E' = h\nu + h\Delta\nu$

and energy conservation is violated!

How about other forms of gravity couplings?

Gravivector field: ***(ignoring any tensor gravity contributions)***

The arguments stay the same up to the creation of the photon, but then the photons do not gain any energy while returning to the bottom as photons do not couple to vector gravity, it does not blueshift, and energy is conserved.

Graviscalar field: ***(again ignoring any tensor gravity contributions)***

Here we need to remember that the force on both matter and antimatter is attractive and we need to add energy to lift the particles up to height L. Again, the photons have energy $2mc^2$ and upon returning to the bottom will blue-shift by 2mgL. Now they have enough energy to continue the cycle of creation, raising, annihilation…..

more details in: M.M.Nieto and T. Goldman; Phys. Reports 205 (1991) 221-281

SCHIFF's ARGUMENT

L.I. Schiff, Sign of the gravitational acceleration of a positron; PRL 1 (1958) 254

Coulomb field in atom polarizes vacuum and produces virtual electron-positron pairs. These virtual positrons contribute to the both the mass and the weight of the atom.

IF Gravitational rest mass of positrons is equal and opposite to electron mass

AND kinetic energy of positrons is acted upon normally by gravitational field

$$m_I - m_G = (\alpha - 1) \times 4m/3\pi^2 \times (Z/137)^2 \ln(h/mcR_{nuc} + 0.338)$$

Eötvös et al. measured Magnalium, Copper, Platinum at

$$\Delta m/m \approx 0.5 \times 10^{-8}$$

Schiff's calculation gives **10, 20, and 43 x 10^{-8}** respectively

$$\frac{g(Be) - g(Cu)}{g} < 10^{-11} \longrightarrow |\alpha - 1| < 10^{-6}$$

Adelberger et al. Phys. Rev. D42 (1992) 3267

GOOD's ARGUMENT

M. L. Good, K^0 and the equivalence principle; Phys. Rev. 121 (1961) 311 - 313

K_L is a linear combination of K_0 and $\overline{K}_0$

If there were "antigravity" K_0 and $\overline{K}_0$ would undergo different phase shifts, and

K_L would regenerate into K_S

As this was not observed, Good ruled out antigravity

(this was pre-CP violation)

Even from the point of view of modern theories, this argument rules out some, but not all theories on gravity.

See.: M.M. Nieto and T. Goldman; The Arguments against "Antigravity" and the Gravitational Acceleration of Antimatter; Physics Reports 205 (1991) 221-281

Richard Hughes:

Are there limits on anomalous gravity set by existing precision experiments?

PRL 66 (1991) 854 - 857

***Inertial* masses of protons and antiprotons were shown to be equal to 4×10^{-8}**

G. Gabrielse et al. ; Phys. Rev. Lett. 63 (1989) 1360

Similar results existed for electrons and positrons for 10 years at lower precision

P.B. Schwinberg, R. S. vanDyck Jr., and H. G. Dehmelt; Phys. Rev. 81A (1981) 119

These experiments are considered precision tests of CPT

But

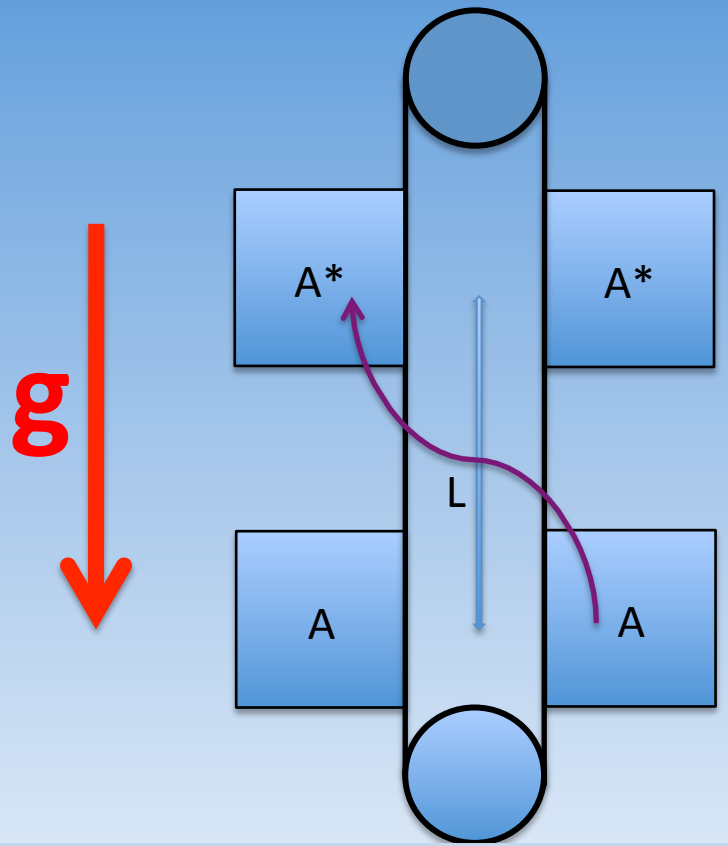
Assuming CPT is conserved, they provide tests of the weak equivalence principle for a gravitational coupling to the energy of positrons and antiprotons

Why?

The frequencies used to study the inertial mass equalities constitute "local clocks" which are subject to the gravitational redshift, which can be formulated as a test of the weak equivalence principle for their energy content

K. Nordvedt, Phys. Rev. D 11 (1975) 245

Back to (a slightly modified version) of A. Einstein's "Dumb Waiter"



Exchange A and A* and generate energy

$$E_{out} = (m^*g^* - mg)\,L$$

A* decays and emits photon with

$$h\omega_1 = (m^* - m)\,c^2$$

defining the local clock frequency

Photon propagates up by a distance L, experiencing a redshift and has frequency

$$h\omega_2 = h\omega_1(1 - g_R L/c^2)$$

To recover initial condition photon energy must be augmented by

$$E_{in} = h\omega_1 g_R L/c^2 = (m^* - m)g_R L$$

Conservation of energy commands $E_{in} = E_{out}$

$$g_R = \frac{m^* g^* - mg}{m^* - m} = \frac{\Delta\,(\text{clock weight})}{\Delta\,(\text{clock mass})}$$

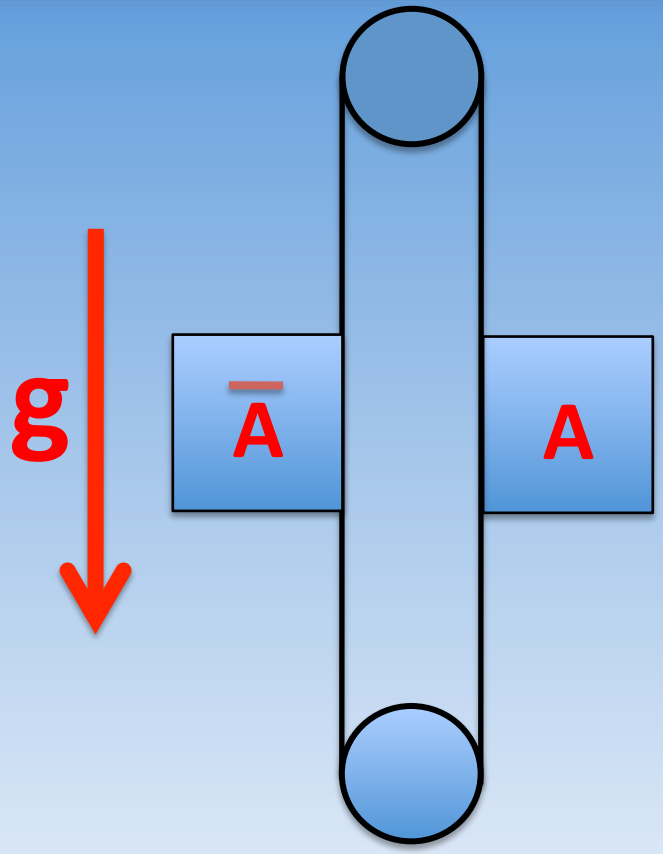
Conventional redshift ($g_R = g$) ONLY for $g^* = g$

Gravitational redshift tests weak equivalence principle for energy content of clock and conventional redshift ($g_R = g$) only arises if $g^* = g$

Now consider Antimatter

Assuming CPT symmetry is exact, particle and antiparticle clocks will have identical rates beyond the range of any equivalence-principle-violating interaction at ("infinity"). If the proton (electron) respects the equivalence principle and any violation of equivalence for the antiproton (positron) arises from anomalous coupling of gravity to its energy, their cyclotron frequencies will redshift differently when lowered to the same height in the gravitational field resulting in a measurable frequency difference.

(valid for tensor fields coupled to energy momentum tensor and for scalar fields coupled to the trace)



Assuming CPT symmetry is exact, particle and antiparticle clocks will have identical rates at "infinity" (i.e. in the absence of gravity)

When lowered to the same height in the gravitational field they will redshift differently if the coupling to the gravitational field differs between antimatter and matter.

This will result in a measurable effect when comparing cyclotron frequencies of protons and antiprotons

valid for both a tensor field coupled to the energy momentum tensor and for a scalar field coupled to its trace

Let's try to be quantitative by using a phenomological model:

Protons, electrons, and electromagnetism experience conventional gravity

$$L = \tfrac{1}{2} h_{\mu\nu} T^{\mu\nu}$$

through the (weak) tensor gravitational field

$$h_{\nu\mu} = (2U/c^2)diag(1,1,1,1)$$

where U is the Newtonian gravitational potential

Violation of weak equivalence for antimatter can be introduced by an adjustable coupling constant

$$L' = \tfrac{1}{2} \alpha h_{\mu\nu} T^{\mu\nu}$$

Matter experiences gravity *g*, antimatter αg

Adding L and L' to the action integral of a single particle with charge e and mass m in an electromagnetic field to include the effect of gravity on the particles cyclotron frequency leads to the following replacements:

$m \rightarrow m\,(1 - 3U/c^2)$ and $B \rightarrow B\,(1-2U/c^2)$ and

$\omega_c \rightarrow \omega_c\,(1+U/c^2)$

for protons

and

$\bar{m} \rightarrow m\,(1 - 3\alpha U/c^2)$ and

$\bar{\omega}_c \rightarrow \omega_c\,(1+[3\alpha-2]U/c^2)$

Frequency difference between matter and antimatter clock

$$(\bar{\omega}_c - \omega_c)/\omega_c = 3(\alpha - 1)U/c^2$$

The dependence of $\Delta\omega$ for $\alpha \neq 1$ of the potential is an inescapable consequence of the violation of equivalence, not just a model feature.

For a massless field this means that we no longer are free to change the value of the potential by a constant as implied by the Newtonian field equations.

What are possible choices of U?

U shall be zero at "infinity"

←→

Field is mitigated by massive particle

Mass of graviton ≤ 1.1×10^{-29} eV ≈ Range of 580 kpc

Potential of local Supercluster: $|U/c^2| \approx 3 \times 10^{-5}$

G. Gabrielse et al., Phys. Rev. Lett. 82 3198 (1999):

$M_{\bar{p}}/M_p$ = 0.999 999 999 91 ± 0.000 000 000 09

$\longrightarrow$ $|\alpha - 1| < 1 \times 10^{-6}$

(If the gravitational force is mediated by a single tensor field).

Other possible scenarios:

Usual tensor gravitational field couples to antimatter with normal strength but there is an additional hypothetical tensor field $h'_{\mu\nu}$ of finite range which acts only on antimatter. Now U depends on the assumed range of the new interaction:

$$(\bar{\omega}_c - \omega_c)/\omega_c = 3\alpha U/c^2$$

If range is large compared to our Galaxy, but small compared to the separation of galaxies, U shall assume the value of our Galaxy's Newtonian potential at the surface of the Earth

$$|U_{Galaxy}/c_2| \approx 10^{-6} \rightarrow |\alpha - 1| < 5 \times 10^{-4}$$

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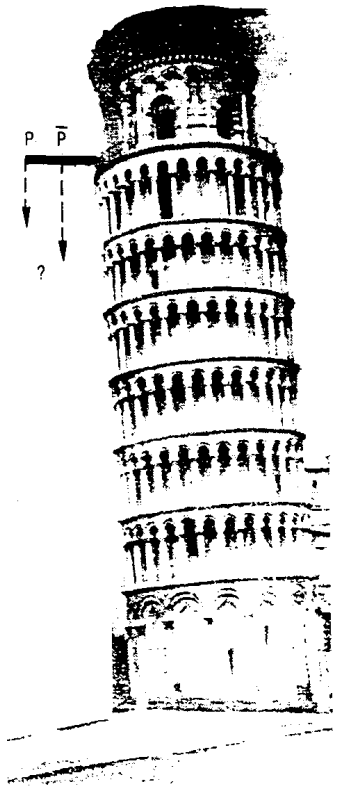

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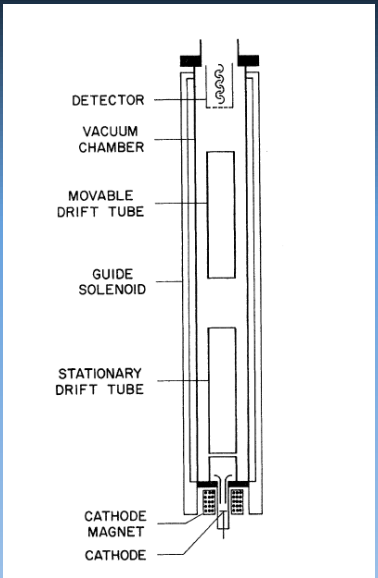
One Experiment speaks more than a thousand words:

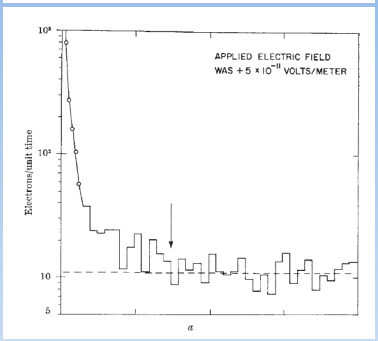
Phase 0:
Wind is stronger than gravity
Auxillary forces need shielding

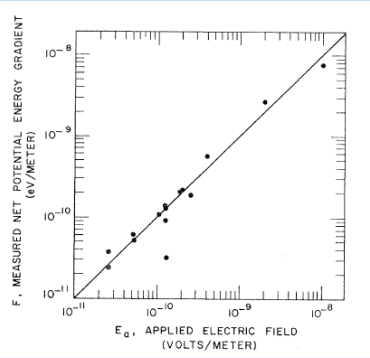
- **Source must have low energy spread**
- **Free fall environment must suppress all stronger forces**
- **Detection must not disturb experiment**

Can this really be done with charged particles?

We believed so (and still do)







Shield charged particles with a metal tube

Electric fields inside the tube due to:

Sagging of free electron gas (Schiff-Barnhill Effect)

$g_{eff} = g[1 - m_e Q/Me]$

Compression of atomic lattice (Dessler et al. 1968)

DMRT ≅ 1836 SB

Patches in the crystal structure on the inner surface

expected to be larger than SB, but were not observed in experiments by W.M. Fairbank and F.C. Witteborn

The Results

Electrons: $g_{eff,\ e-} = 0.09\ g$

Positrons: no measurement (lack of source)

$g_{eff,\ e+} = 2.0\ g$????

"By use of the clever techniques developed by the Stanford and Los Alamos/CERN groups, most spurious interactions can be rendered negligible. However, uncertainty remains over electric fields produced by the patch effect and gravitationally induced strain gradients in the drift tube (the DMRT field).

While the temperature-dependent shielding effect claimed by the Stanford group may be genuine, it has not been independently verified, despite various attempts to do so.

The preliminary experiments by the Los Alamos/CERN group with H^- and heavier ions may shed more light on this issue. A great advantage of the antiproton experiment is that only a differential measurement against H^- is proposed.

We anticipate exciting results that may be forthcoming in the near future."

(T.W. Darling et al. Rev. Mod. Phys 64 (1992))

Thank you for your attention

....Science, I now understand, never contradicts herself absolutely, but she is always busy in revising her classifications and touching up and rephrasing earlier cruder statements. Science never professes to present more than a working diagram of fact. She does not explain, she states the relations and associations of facts as simply as possible.

H. G. Wells, Science and Ultimate Truth