Why is \( \bar{g} \) (not) equal to \( g \)?

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8 November 2012

Abstract: In this note I briefly summarize some of the arguments found in the literature favoring (or disfavoring) the weak equivalence principle for antimatter in the gravity field generated by matter.

Several theories suggest a difference between the acceleration of matter \( g \) (9.81 ms\(^{-2}\) at sea level) and that of antimatter \( \bar{g} \) which are disputed by others ([1], for a more recent review see [2]). Predictions for the relative difference \( \Delta g/g \) between 200\% (antigravity with \( \bar{g} = -g \)) and less than \( 10^{-13} \) can be found in the literature, based on indirect measurements and depending on theoretical assumptions. We now discuss a few pros and cons.

In quantum field theories forces mediated by the exchange of scalar bosons (graviscalar, S) or tensor bosons (graviton, T) are attractive for matter-matter gravity, while forces mediated by vectors (graviphoton, V) are repulsive for matter-matter and attractive for matter-antimatter gravity. Thus attractive coherence between S, V and T is expected in antimatter-matter while at least partial cancellation between S and V is expected in matter-matter, leading to \( \bar{g} > g \). However, recent torsion balance experiments searching for a 5\(^{th}\) force with a sensitivity better than \( 10^{-13} \) [3], and which are sensitive to V but not S, rule out any significant V contribution in matter-matter, unless there is a nearly perfect cancellation of V by S [4]. Precise cancellations are deemed to be possible [1] or on the contrary excluded, torsion balance experiments then leading to \( \Delta g/g < 10^{-7} \) [5]. In any case these arguments all rest on CPT which has not been tested for gravity\(^1\).

An argument invoked against \( g \neq \bar{g} \) is the contribution from virtual (anti-)see quarks in nuclei which depends on the atomic number and which should lead to a violation of the WEP in torsion balance experiments\(^2\). However, the coupling strength of gravity to virtual particles is not well established. If gravity couples to virtual particles and antiparticles then gravity should also couple to particle-antiparticle pairs in the vacuum fluctuation. This then leads to the famous 120 orders of magnitude excess in the vacuum energy when compared to the density required by dark energy observations (*cosmological constant problem* [7]). Along the same line of arguments is the statement that photons which are “matter neutral” (meaning superpositions of equal quantities of matter and antimatter) behave as expected from General Relativity in the gravitational fields. Indeed photons produce positron-electron pairs, but they are virtual.

The famous Morrison argument against antigravity goes as follows [8]. Assume that a low energy \( e^+e^- \) pair is raised above ground. In the case of antigravity (\( \bar{g} = -g \)) this is done at no energy cost. The pair then annihilates into 2\( \gamma \)'s which can be reflected to ground level with the corresponding blue shift. A new pair of more energetic \( e^+e^- \) is then produced (perpetuum mobile of the first kind). According to the Pound-Rebka experiments, the photon behaves as expected from General Relativity. Taking into account the Morrison argument one could then argue that \( g \) and \( \bar{g} \) differ by no more than the precision of Pound-Rebka type experiments, which are at the level of \( 10^{-4} \) [9]. However, the Morrison argument about apparent energy violation has been disputed, e.g. in ref. [10], in which the extractable energy is claimed to be as tiny as the vacuum fluctuations. In extensions of the standard model (SME [11]) there is also no contradiction with energy conservation.

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\(^1\) According to CPT antimatter would fall on an anti-earth with the same acceleration as matter on the earth. However, CPT does not make any statement on the acceleration \( \bar{g} \) of antimatter by the earth.

\(^2\) The gravitational acceleration of the neutron has been checked to a precision of 0.1\% [6].
Another argument against $g \neq \bar{g}$ is the tiny mass difference in the $K^0 - \bar{K}^0$ system. Assuming CPT invariance (which is established at the level of $8 \times 10^{-19}$ in this system), ref. [12] arrives at an upper limit of $\Delta g/g = 8 \times 10^{-13}$. However, the neutral kaons are a mixture of matter-antimatter ($d\bar{s}$, resp. $\bar{d}s$) and are not baryons. Hence cancellations could happen for mesons but not for baryons. In fact the SME models of ref. [11] - based on field theories - contain tiny CPT flavour dependent violations which could become apparent in baryons while remaining hidden in mesons.

Another possible indirect test of the WEP is to measure frequencies. For example, the $p$ and $\bar{p}$ cyclotron frequencies have been shown to be equal with good precision [13]. If $g \neq \bar{g}$ then the frequency shift between a measurement at zero gravity and on the surface of the earth will differ since time does not elapse at the same rate for matter and antimatter in the gravitational field. The precision with which the cyclotron frequencies have been measured leads together with CPT invariance [$m(p) = m(\bar{p})$] to a possible violation of the WEP at a level below $\sim 5 \times 10^{-4}$ [13].

In the same line of reasoning one can measure the $1s - 2s$ transition frequency in positronium [14]. The frequency $\nu$ is redshifted for hydrogen at the surface of the earth by

$$\nu_0 - \nu = \frac{v^2}{c^2} \simeq 10^{-8},$$

where $\nu_0$ is the frequency at infinity and $v$ the velocity of the earth around the sun [15] (30 km/s). On the other hand, there is no shift for positronium under the assumption of antigravity since the electron and the positron contributions cancel. Of course, the shifts cannot be measured directly because the measuring clock is subject to the same shift. However, one can predict the shift for positronium by using the measured values for hydrogen (which are known to very good accuracy). The best measured value for positronium [16] is somewhat below the predicted value (assuming $\bar{g} = g$), while the assumption of antigravity ($\bar{g} = -g$) would blueshift the frequency above the predicted value by $\simeq 10^{-8}$, see eqn. (1). This makes antigravity quite unlikely. However, the experimental result needs to be checked and, furthermore, the above arguments assume the existence of an absolute gravitational potential.

Finally, we mention ref. [17] in which antigravity is shown to be consistent with astronomical observations (e.g. age, nucleosynthesis, CMB) without resorting to the concepts of dark matter and dark energy. This again raises the old question of the relation (if any) between antimatter and dark matter in the universe.

Thus, theoretical predictions for the relative difference $\Delta g/g$ vary strongly between antigravity ($\bar{g} = -g$) and less than $10^{-13}$. The issue of CPT and the validity of WEP for antimatter eventually rests on direct measurements.

**Experimental status**

The WEP has never been tested experimentally directly with antimatter. Attempts using positrons or antiprotons failed due to stray electric or magnetic fields (the so-called patch effect) [18]. The PS200 experiment [19] at the Low Energy Proton Ring (LEAR) was planned in the 1990’s to measure the time-of-flight (TOF) with an antiproton fountain, but was never realized. Indirect experiments such as a measurement of transition frequencies in positronium (previous section) are underway. Incidentally, a measurement of atomic transitions in $\bar{H}$ would obtain twice the frequency shift in eqn. (1) in the presence of antigravity. Measurements of the ground state hyperfine splitting and of the $1s - 2s$ transition are underway at the CERN-AD.

The AEgIS experiment [20] at the CERN-AD (AD6) is the first attempt to measure directly $\bar{g}$ with an initial precision of 1%, starting its run in 2014. An alternative experiment (GBAR [21]) has recently been approved to be installed later on the ELENA very low energy antiproton beam to start
operation in 2018. The latter will attempt to generate very cold $\bar{H}$ by trapping $\bar{H}^+$-atoms, with the goal of reaching a precision of 0.1% on $\bar{g}$.

References

[7] see for example http://ned.ipac.caltech.edu/level5/March01/Carroll/Carroll1.html
[14] P. Crivelli, SNF-Ambizione grant PZ002P2-132059
[20] G. Drobychev et al., AEGIS proposal