ANTIMATTER AND GRAVITATION

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Three experiments et CERN are about to "weight" antihydrogen. We describe the objectives of the experiments trying to measure the gravitation effect on antimatter, we review some of the theoretical constraints on a possible different gravitational behavior between matter and antimatter, and give an overview of the existing experimental limits and proposals.

1 Scientific aim

1.1 The Equivalence Principle

The main objective of the measurement of the action of gravity on antimatter is to perform a direct test with antimatter of the Einstein Equivalence Principle which states that the trajectory of a test particle is independant of its composition and internal structure when its is solely subject to gravitational forces. This principle has been verified with many materials. A very high precision of around 10^{-13} has been reached. A torsion pendulum experiment [1] with Beryllium and Titanium test bodies led to the following difference between their gravitational acceleration:

$$(\Delta a/a)_{\mathrm{Be/Ti}} = (0.3 \pm 1.8) \times 10^{-13}. \quad (1)$$

A precise follow up of the relative motion of the Earth and the Moon ("Lunar Laser Ranging" [2]) gave:

$$(\Delta a/a)_{\mathrm{Earth/Moon}} = (-1.0 \pm 1.4) \times 10^{-13}. \quad (2)$$

1.2 Antimatter

In the Standard Model of particle physics, every particle comes with its own antiparticle which carries an opposite charge but, as stated by the CPT theorem, has exactly the same inertial mass and the same lifetime. The most stringent limit on the inertial mass equality is [3]:

$$(M_{K^0} - M_{\bar{K}^0})/M_{\mathrm{average}} < 6 \times 10^{-19} \text{ (90 \% CL)}. \quad (3)$$

As we will see, there is nos such comparison for the particle and its antiparticle *gravitational* mass, a quantity which we define in the next section.

1.3 The measured $\bar{g}$ parameter

We define the gravitational mass of an antimatter test body $\bar{m}_g$ by the following equation:

$$F = G\frac{M_E \bar{m}_g}{R_E^2}, \tag{4}$$

where F is the force acting on the body, G is the Newton gravitational constant and M_E and R_E are the mass and radius of the Earth. We define its inertial mass by:

$$F = \bar{m}_i a, \tag{5}$$

where a is its acceleration. The $\bar{g}$ parameter is then defined by:

$$\bar{g} = a = G\frac{M_E}{R_E^2}\frac{\bar{m}_g}{\bar{m}_i} = g\frac{\bar{m}_g}{\bar{m}_i}, \tag{6}$$

where g is the usual terrestrial acceleration.

Any difference between the measured $\bar{g}$ parameter and g arises from a difference between the gravitational and inertial mass of the test body and signs a violation of the Equivalence Principle or the presence of additional unknown forces.

2 Theoretical constraints

2.1 The Morrison argument

It is well known that in the framework of General Relativity, the violation of the Equivalence Principle by antimatter would lead to the violation of energy conservation [4]. Assuming that antimatter undergoes antigravity, on can raise a particle-antiparticle pair at rest at the height H without any energy cost (see fig. 1). Their annihilation gives two photons of energy $E = mc^2$, where m is the particle inertial mass. If one recombines them at the original height to form the pair again, because of the variation of the gravitational potential, the two photons have gained an energy EgH/c^2: the net balance is an energy increase of $2mgH$!

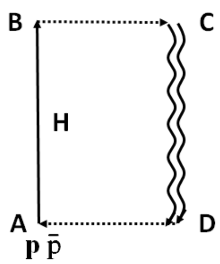

Figure 1 – Illstration of the Morrison argument (see text).

It is straightforward to extend this argument to any difference between matter and antimatter gravitational behaviour.

However, it has been shown in a seminal paper by J. Scherk [5] that antigravity may arise naturally in extensions of General Relativity, where additional fields can couple to baryon number. The potential between two test masses can be written as [6]:

$$V = -G\frac{mm'}{r}(1 \mp a\exp(-r/v) + b\exp(-r/s)). \tag{7}$$

The non-newtonian terms arise from the exchange of so-called gravi-vector and gravi-scalar fields. G is the Newton constant, m and m' are the masses of the interacting bodies and r their distance, v and s are the range of the vector and scalar interactions, and a and b measure their intensity. In the case of matter, the first term is repulsive and may be cancelled by the second one, while both terms are attractive for one antimatter test body. As a consequence, tests of the Equivalence Principle with matter only are mostly sensitive to $|b - a|$ and do not exclude measurable effects with antimatter.

2.2 Indirect theoretical constraints

The cancellation mentioned in the previous section between scalar and vector interactions cannot be perfect since the latter has a 4-velocity dependence which is not present in the former. This fact can been exploited [7] to put very stringent limits on $|\bar{g} - g|/g$. They are based on three observations:

1. the radiative damping of binary pulsar systems depends on the nature of the gravitational interaction;
2. the vector field couples to the baryon number which is not exactly proportional to the nucleus mass;
3. the mean velocity of the nucleons within the nucleus depends on the element.

These effects are constrained by the tests of the Equivalence Principle with matter which thus lead to limits ranging from 10^{-4} to 10^{-7}.

In the same paper [7], a second class of limits is derived from an argument originally formulated by L.I. Schiff [8]: in quantum field theory, vacuum polarization effects arise from virtual particles and antiparticles (figure 2). One can say that any matter object carries an antimatter content,

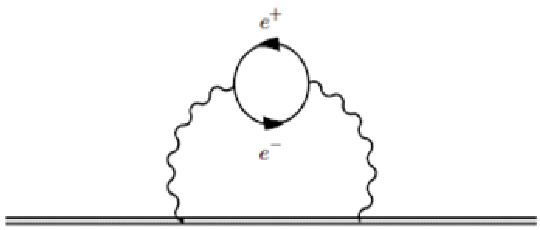

Figure 2 – Loop contribution to the self-energy of the nucleus.

the amount of which being of order of the correction on the binding energy of nuclei within the nucleus or of electrons within atoms due to these virtual pairs. Assuming this reasoning is correct, which is not obvious because of the needed renormalization of the indefinite loops in quantum field theory, the tests of the Equivalence Principle with matter translate directly to limits ranging from 10^{-2} to 10^{-9} by simply scaling them by the inverse relative energy correction.

2.3 Standard Model Extension

Models to analyze the experimental tests of CPT and Lorentz invariance have been developped. In the Standard Model Extension [9,10,11], CPT and Lorentz violating operators are introduced. This gives a framework to quantify and compare the many existing experimental constraints. Within this framework, all the previous limits can be evaded.

However, within the specific Isotropic Parachute Model [12], other limits can be put, using atomic interferometry experiments or using again the kinetic energy of the nuclei within the nucleus, down to 10^{-6} to 10^{-8}.

All these limits are strongly model dependant [13].

References to other models can be found in the presentations made at the 2015 Workshop on Antimatter and Gravity [14].

3 Cosmology

One of the fundamental questions in physics today is the origin of the matter-antimatter asymmetry of the Universe. Three minimal conditions were formulated by A. Sakharov in 1967 [15] to understand it: C and CP symmetry violation, baryon number violation, evolution out of thermal equilibrium. All of them are met within the theoretical framework of the Standard Models of particle physics and cosmology. However, the asymmetry which can be quantitatively derived is too low by many orders of magnitude [16].

The main ingredients of the today's Standard Model of cosmology needed to explain the observations are: General Relativity with a non zero cosmological constant, or equivalently dark energy; a large cold dark matter content; inflation. This model fits experimental data extremely well at large scales, but its ingredients have no observed counterpart in particle physics, and in addition, tensions with observations exist at small scales [17,18].

Motivated by these facts, some authors [19] have tried to build a cosmology without dark matter and dark energy, with as much matter as antimatter, but with a repulsive interaction between them, the origin of which is not addressed. Although this model cannot reproduce all astrophysical observations, it is rather successful in reproducing some of them: the Hubble diagram of SNIa; the abundance of ^{4}He; the order of magnitude of the baryonic acoustic scale.

In summary, whether or not one can build such a model, the question of the interplay between matter, antimatter and gravitation appears as a very relevant question for cosmology.

4 Constraints from experiments

4.1 The $K^0 - \bar{K^0}$ system

The CPLEAR experiment at CERN was dedicated to the study of discrete symmetries with the neutral kaon system [20]. $K^0 - \bar{K^0}$ pairs were produced by the annihilation of antiprotons at rest in a hydrogen target.

A very high number of K decays were recorded, and this allowed a systematic study of the $K^0 - \bar{K^0}$ oscillation parameters as a function of time and also as a function of the direction of the flying neutral kaons [21].

The CP violation parameters $\eta^{\pm}$ and $\Phi^{\pm}$ depend on the neutral kaon mass, and are sensitive to an effective mass difference $\delta m_{\rm eff}$ which would originate from a different apparent gravitational potential energy, which can be written as:

$$\delta m_{\rm eff} = M_{K^0}(\frac{g-\bar{g}}{g})\frac{GM}{rc^2}\exp(-r/r_I)f(I), \tag{8}$$

where M is the mass of the gravitationally attracting body, r its distance to the neutral kaon system, I the spin of the particle exchanged in the interaction, r_I the range of the force, $f(I)$ a spin dependant factor.

The study of the time variation of $\eta^{\pm}$ and $\Phi^{\pm}$ or its dependence upon the flight direction of the kaons allow to test the effect of the Earth (flight direction), the Moon (monthly modulation) and the Sun (annual modulation) gravitational fields as a function of I and r_I. Depending on the assumptions made on I and r_I, limits can be put on $|g-\bar{g}|/g$ ranging from a few 10^{-5} to few 10^{-9}.

In addition, the (absolute) potential from the Galaxy or the Supercluster changes the energy (the inertial mass) of the K^0 and $\bar{K^0}$. As a consequence, the measurement by CPLEAR of the $K^0 - \bar{K^0}$ mass difference:

$$\delta m = (-2.6 \pm 2.8) \times 10^{-19} \text{ GeV} \tag{9}$$

can be used to place limits on $|g-\bar{g}|/g$ of a few 10^{-12} to a few 10^{-14}.

4.2 The antiproton cyclotron frequency

Gabrielse and collaborators have measured the cyclotron frequencies of simultaneously trapped $\bar{p}$ and H^- ions [22] and get from this measurement the following relative difference between the antiproton and the proton cyclotron frequencies:

$$|\omega(p) - \omega(\bar{p})|/\omega(p) = (9 \pm 9) \times 10^{-11}. \tag{10}$$

In the framework of General Relativity, the cyclotron frequencies can be seen as local clocks, the rates of which undergo a shift depending on the gravitational potential U [23]:

$$\omega = \frac{qB}{m}(1 + (3\alpha - 2)U/c^2), \tag{11}$$

where B is the magnetic field, q and m the charge and mass of the (anti)particle, and $\alpha = 1$ for a particle and $\alpha = \bar{g}/g$ for an antiparticle.

The frequency measurement leads to a limit on $|g - \bar{g})|/g$ which depends on the range of an anomalous gravitational interaction which would distinguish matter and antimatter and of the potential source at stake. It is around 10^{-6} if one chooses the potential of the local Supercluster.

4.3 Neutrinos

The time arrival of photons and neutrinos produced by the explosion of the SN1987A supernova has been recorded by several detectors [24]. The gravitationally induced time delay in arrival of these particles is approximately given by [25]:

$$\delta t = MG[-R/\sqrt{R^2 + b^2} + (1 + \gamma)\ln[[R + \sqrt{R^2 + b^2}]/b]], \tag{12}$$

where M is the mass of the galaxy, R is the distance from Earth to SN1987A, b the impact parameter, and γ the post-Newtonian factor which is equal to 1 for all particles in General Relativity. Paksava et al [26] argue that the "neutrino" events are an admixture of at least one neutrino-electron scattering and 18 antineutrino-proton capture events with 90 % confidence level; under this hypothesis, the observed times of the events yield:

$$\gamma(\nu_e) - \gamma(\bar{\nu}_e) < 10^{-6}. \tag{13}$$

While the other experimental constraints give limits on $|g - \bar{g})|/g$ which can be considered as indirect because they are subject to theoretical assumptions to be translated into a test of the Equivalence Principle with antimatter, (13), if its assumption is acknowledged, can be seen as a direct test.

5 Past attempts and proposals

Positrons

The measurement of the gravitational acceleration of positrons has been proposed, but only preliminary measurements with electrons have been performed [27], the interpretation of which was questioned. This experiment is indeed extremely difficult, since the Earth gravitational acceleration on an electron is overwhelmed by a single charge closer than 5 m.

Antiprotons

A gravitation experiment with antiprotons has been proposed [28] to be performed at the Low Energy Antiproton Ring at CERN, but the latter was shutdown before the start of the experiment.

Antineutrons

The antineutron being neutral, it may be thought to be a better candidate. However, an experiment with antineutrons would be very difficult because they are produced at high energy [29] and cannot be easily slowed down.

Positronium

Positronium (Ps) is the bound $e^+ - e^-$ system. It is neutral, and its composition is a real admixture of a particle and an antiparticle, but it has a very short lifetime in its ground state (τ = 125 ps for the para-positronium, 142 ns for the ortho-positronium). This can be easily overcome if on excites it at a higher level n since the lifetime varies as:

$$\tau \simeq (n/25)^{5.236} \times 2.25 \text{ ms}. \tag{14}$$

However, Ps in a Rydberg state is highly polarisable and sensitive to stray electric fields. It is also difficult to cool and can be easily ionised by thermal radiation. The feasibility of a gravitation experiment with positronium is thoroughly discussed by Mills and Leventhal [30] and a project is being contemplated by Cassidy [31].

Muonium

An experiment with muonium (M), the $\mu^+ - e^-$ bound system, is in an R&D stage [32]. A slow M beam (6 km/s) of muonium is under development at the Paul Scherrer Institute in Switzerland. The M beam is formed by stopping muons in a thin film of superfluid helium. M formed within the film are ejected perpendicular to the film with a small energy spread at around 6 km/s velocity. They will intercept a three grating atom interferometer. The aim is to measure the gravitational deflection to better than a nanometer. It requires a very precise alignement and caliration of the gratings, at the picometer level. As acknowledged by the authors, "*the technical challenges are significant*".

6 Experiments with antihydrogen

Antihydrogen is the next simplest system to perform a gravitation experiment. Antihydrogen atoms are produced at CERN since 1995 [33]. Antiprotons of 1.94 GeV/c momentum impinged on a Xe cluster target. The production mechanism is dominated by the reaction (Z represents the target nucleus):

$$\bar{p}Z \rightarrow \bar{p}\gamma\gamma Z \rightarrow \bar{p}e^+e^-Z \rightarrow \bar{H}e^-Z, \tag{15}$$

which has a very low cross section and gives hot antihydrogen atoms, not suitable for precision experiments. Nowadays, experiments use the 3 body reaction:

$$\bar{p}Ps \rightarrow \bar{H}e^-, \tag{16}$$

which allows the production of slower antihydrogen atoms.

It took many years to improve the production mechanism, and to cool, trap and control the antiatoms to prepare for precise measurements. The confinement of antihydrogen for 1000 seconds by the **ALPHA** collaboration provided a major step forward [34], as stressed in the abstract of the article: "*These advances open up a range of experimental possibilities, including precision studies of charge-parity-time reversal symmetry and cooling to temperatures where gravitational effects could become apparent*". And indeed, they were able two years later to put a direct limit on $\bar{g}$ [35]:

$$-65 < \bar{g}/g < 110 \text{ (95 \% CL)}. \tag{17}$$

This result is derived from the distribution of the annihilation position in the ALPHA apparatus of 434 antihydrogen atoms after they were released from the magnetic trap. The ALPHA Collaboration has a project to do a 10 % measurement of $\bar{g}$ using the same technique but with a vertical detector, and a longer term project for a precise measurement using the method of atom interferometry [36].

Two other experiments are under preparation at the CERN/AD (Antiproton Decelerator): AE$\bar{g}$IS [37] and GBAR [38]. Their status is described in these proceedings respectively by Pierre Lansonneur and P. Indelicato. Both experiments will eventually take advantage of the Extremely Low Energy Antipronton ring under construction in the AD hall [39].

The **AE$\bar{g}$IS** experiment will measure the deflection of a slow (500 m/s) $\bar{H}$ beam using a Moiré deflectometer with a few μm precision. It has crossed important steps towards a few % precision measurement.

GBAR will use a novel technique to produce antihydrogen atoms: they will first produce $\bar{H}^+$ ions (an antiproton with two bound positrons, the antimatter counterpart of the H^- ion) with the successive reactions:

$$\bar{p}Ps \rightarrow \bar{H}e^- \text{ followed by } \bar{H}Ps \rightarrow \bar{H}^+e^-. \tag{18}$$

$\bar{H}^+$ ions can be sympathetically cooled to around 10 μK. The excess positron is laser photodetached to perform the free fall of $\bar{H}$ "at rest" (0.5 m/s).

Both experiments aim at an initial few % precision on $\bar{g}$. GBAR will improve this precision to better than 10^{-3} by using quantum reflection of antihydrogen atoms [40,41,42]. The experiment has just started installation at CERN.

7 Conclusion

We are convinced that the conclusions of the review by Nieto and Goldman [43] on gravity measurements on antimatter remain quite relevant and instructive in spite of its old publication date. One can still state with them that "*whether or not one now accepts the existence of non-Newtonian gravitational forces, the possibility of new non-inverse-square and/or composition-dependent components of gravity must be thoroughly studied*".

However, we have shown that any anomalous effect is expected to be quite small. All the experiments are extremely challenging. A 1 % measurement will be a major breakthrough, but should be the first step towards a much higher precision.

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