EPJ Web of Conferences **142**, 01023 (2017) DOI: 10.1051/epjconf/201714201023
Advances in Dark Matter and Particle Physics

Measuring gravitational effects on antimatter in space

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Abstract. A direct measurement of the gravitational acceleration of antimatter has never been performed to date. Recently, such an experiment has been proposed, using antihydrogen with an atom interferometer and an antihydrogen confinament has been realized at CERN. In alternative we propose an experimental test of the gravitational interaction with antimatter by measuring the branching fraction of the CP violating decay of K_L in space. In fact, even if the theoretical Standard Model explains the CPV with the presence of pure phase in the KMC Kobaiashi-Maskava-Cabibbo matrix, ample room is left for contributions by other interactions and forces to generate CPV in the mixing of the neutral K and B mesons. Gravitation is a good candidate and we show that at the altitude of the International Space Station, gravitational effects may change the level of CP violation such that a 5 *sigma* discrimination may be obtained by collecting the K_L produced by the cosmic proton flux within a few years.

1 Introduction

Even if the Standard Model has proved capable of explaining all phenomena with which its predictions have been compared, many unanswered questions, or at least with an unsatisfactory answer, still remain in the official description of the Physical Universe.

First of all we know that in the observed Universe the ordinary matter prevails on antimatter even if both are always created together.

Cosmic Microwave Background is not anisotropic nor inhomogeneous enough to be compatible with the Big Bang model without the introduction of a still unknown interaction driving the inflation.

Furthermore, given the gravity we expect a negative acceleration of the expansion of the Universe. On the contrary it seems to accelerate. The gravitational field of Galaxies, clusters and even of the Solar system seems much stronger of the one due to the visible matter.

The suggested possible solutions are not modules of a general theory nor are capable of explaining the phenomena without an empirical tuning. For example the Sakarov suggested mechanism for matter/antimatter asymmetry, connected to CP violation (CPV) is contradicted by the fact that experimentally such phenomenon is far too weak to generate the present asymmetry. Models have been proposed to justify inflation by supersymmetric vacuum energy and SuperSymmetry Breaking but at present no evidence for supersymmetry has been found yet. Dark Energy has been introduced by hand in order to give a motivation to the accelerated expansion of the Universe. Finally Dark Matter has been introduced in order to give a motivation to the observed discrepancies between theory and measurements of the orbital speed of the stars of the external part of the Galaxies.

Too many different and independent motivations:

From the point of view of the elegance the situation is far from being satisfactory: There are as many hypothesis as problems this sounds extremely artificial especially because most of them are just put by hand into the theory.

Dark Matter and Dark Energy hypotheses, as an example, are similar in nature to that of Luminiferous aether for the transmission of the electromagnetic signals. All of them would not survive to the “Ockham’s razor” criterion. This “lex parsimoniae” is due to the English Franciscan Scholar William of Ockahm (1287-1347), who inspired the character of William of Baskerville in the Umberto Eco’s novel “The name of the Rose”. It can be presented as follow:

“If there are several competing Hypotheses in order to explain a phenomenon or create a theory, The one that needs the fewest assumptions and parameters should be selected”.

In this paper we show how all these problems can all be mastered with a single Hypothesis and will suggest an experiment capable to settle or at least put a limit on the applicability of the same Hypothesis. In order to understand the motivation of this Hypothesis, let’s start from considering matter-antimatter symmetry:

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At a very short distance, matter is always produced with the corresponding antimatter but only matter seems to dominate the landscape of the Universe, no stable antimatter seems to populate our Galaxy nor the Universe in general at large distance. Strong and Weak Interactions are limited in range. At the scale of 10^6 m even the Electromagnetic interaction is mostly screened and the only residual interaction is the gravity. At this scale no significant presence of antimatter can be find. Is there any connection between absence of antimatter and presence of the dominion of gravitation as interaction? Antimatter particles correspond to negative energy solution. Could this correspond to a negative gravitational mass and to a consequent gravitational repulsion between matter and antimatter? We simply suppose that gravitational interaction between matter and antimatter is repulsive and suggest that this could explain matter-antimatter asymmetry and also the nature of Dark Energy.

Gravitational repulsion between matter and antimatter could have powered the Inflaction because an equal mix of matter and antimatter would give rice to a net repulsive force. Dark Matter also could originate from quantum gravitational vacuum [1–15].

Most of people could be worried about the compatibility of this hypothesis with General Relativity (GR) but GR is not explicitly concerned about antimatter. Furthermore GR and Quantum Mechanics are incompatible so that we already need to revise our theoretical system. Many new ideas are suggested as MOND theories [12], possible new forces i.e. Gravivector and Graviscalers, Kerr-Newman Universe, where, as suggested by G. Chardin, repulsion could be connected with a negative proper time of antiparticles [1–4].

2 The repulsive Hypothesis of the interaction between matter and antimatter

We consider a simple interaction of the kind:

$$F = -G\frac{m_1 m_2}{r^2}\hat{r} \tag{1}$$

$$m_{matter} > 0\,;\ m_{antimatter} < 0$$

$F < 0$, attractive for masses of the same sign

$F > 0$, repulsive for masses of opposite sign

2.1 Gravitational dipoles

In this hypothesis the quantum vacuum around a large gravitational mass, populated as it is by virtual couples of particle antiparticle, can develop a gravitational polarization. If we consider that the distance between particle and antiparticle in a dipole should be of the order of the Compton wavelength, we obtain that the dipolar charge of each pair is independent of the mass of the particle:

$$\vec{P}_g = m\vec{d}$$

$$|\vec{d}| \approx \chi = \frac{\hbar}{mc} \tag{2}$$

$$|\vec{P}| \approx m\chi = \frac{\hbar}{c}$$

2.2 Energy of the dipoles

If the vacuum is permeated by an external gravitational field of intensity $\vec{g_0}$ the interaction energy is given by:

$$\eta = -\vec{p}\cdot\vec{g_0}$$

$$\eta = -\frac{\hbar}{c}g_0 \tag{3}$$

or in the case of a field of a spherical mass M_0

$$\eta = -\frac{\hbar}{c}\frac{GM_0^2}{r^2}$$

The polarization is the result of the competing action of the external Field and of the thermal agitation and as usual is described by a Langevin-like equation:

$$P = NP\left[coth\theta - \frac{1}{\theta}\right] \tag{4}$$

Where N is the number of dipoles/volume and

$$\theta = \frac{pg_0}{KT} = \frac{\hbar GM_0}{cr^2}\frac{1}{KT} \tag{5}$$

Of course in the Langevin equation the reference energy KT must be replaced by the one related to the phenomenon. That is:

$$KT \approx \frac{\hbar}{c}g_{dip} = \frac{\hbar}{c}\frac{G\rho_{dip}}{r} \tag{6}$$

where $g_{dip} = \frac{G\rho_{dip}}{r}$ and $\rho_{dip} = \frac{dM_{dip}}{dr} = constant$
So that the polarization can be written as:

$$\vec{P} = -N\frac{\hbar}{c}\left[\coth\left(\frac{M_b}{\rho_{dip}r}\right) - \frac{\rho_{dip}r}{M_b}\right]\hat{r} \tag{7}$$

where $\hat{r}$ is the radial versor.

In order to estimate N, we can consider that at low energy the dipoles can be considered a pure pion gas so that the density can be written:

$$N = \frac{1}{\lambda_\pi^3} = \left[\frac{m_\pi c}{2\pi\hbar}\right]^3 \tag{8}$$

So for the mass density due to polarization we have:

$$\rho_P = \nabla\cdot\vec{P} = \frac{1}{3}N\frac{\hbar}{c}\frac{M_B}{\rho_{dip}r^2} \tag{9}$$

So the mass due to polarization is:

$$M_p(r) = \frac{4\pi}{3}N\frac{\hbar}{c}\frac{M_B}{\rho_{dip}}(r - R_B) \tag{10}$$

where R_B is the radius of the bare mass M_B that produces the polarization, ρ_{dip} is the density of dipoles at the saturation. This is the same behavior of the Dark Matter around a large mass. As it is well known the accelerated expansion of the universe can be accomplished introducing a positive cosmological constant:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} + \Lambda g_{\mu\nu} \tag{11}$$

Now in our model energy and mass density of gravitational dipoles of the vacuum can accomplish for the positive cosmological constant:

$$\Lambda = \frac{8\pi G}{c^4} \rho_{Edipol} \tag{12}$$

3 Antimatter gravitational experiments

The problem of the gravitational interaction of antimatter is not new. Whitteborn and Fairbanks attempted to measure gravitational force on positrons. Los Alamos-led team proposed (1986) to measure gravitational force on antiprotons ($\overline{H}$) at the CERN Low Energy Antiproton Ring (LEAR) [16]. Both the Projects ended inconclusively but the problem is interesting and several efforts are in progress at CERN in order to measure the gravitational interaction of $\overline{H}$. The experiments AEgIS [17], ALPHA [18], ATRAP [19], ASACUSA, GBAR [20] are all in advanced state but the way to have a final answer is still a long one.

4 CPV and Gravity

We consider a different approach to the problem, looking at phenomena connected to the gravitational interaction of antimatter but, even if indirect, more sensitive. In the 1958, eight years before the discovery of CPV, Philip Morrison [21] published on the American Journal of Physics a paper showing that a strong difference in the gravitational interaction for matter and antimatter could generate a CPV in neutral Kaons system. At present even if the phenomenon is well described by the CKM formalism, space is left to other contribution to CPV that could contribute to the matter-antimatter asymmetry in the Universe as suggested by Sakharov.

4.1 The Sakharov conditions

In 1967, a Russian physicist Andrei Sakharov outlined that CPV could explain the matter antimatter asymmetry of the Universe. We would expect any reaction to produce antibaryons at the same rate as baryons For overall baryon production, antibaryon-producing reactions must be suppressed. This implies different treatment of matter and antimatter, which is exactly what the mechanism of CP violation describes.

Let us restrict to CPV in the $K_S - K_L$ system considering the possible contribution to CPV in this system of neutral mesons. The gravitational field is described by the acceleration g so the components of antimatter and matter of a meson are divided by a distance growing with the time that can be written as:

$$\Delta\zeta = gt^2 \tag{13}$$

The time useful for the phenomenon is a fraction $\Omega^{-1/2}$ of the mixing time $\Delta\tau$ where:

$$\Delta\tau = \frac{\pi\hbar}{\Delta mc^2} \approx 5.9 \times 10^{-10} s \approx 6\tau_s \tag{14}$$

Where τ_s is the life time of K_S
The dimension of a K meson is about 0.5 fm or:

$$\Delta L_k = \frac{\hbar}{m_k c} \tag{15}$$

The ratio $\frac{\Delta\zeta}{\Delta L_k}$ is the adimensional constant that characterizes the phenomenon. So we obtain the CPV parameter as:

$$\epsilon = \Omega \frac{g \frac{\pi^2\hbar^2}{\Delta m^2 c^4}}{\frac{\hbar}{m_k c}} = \Omega \frac{\pi^2\hbar^2 g m_k}{\Delta m^2 c^3} = \Omega \times 0.88 \times 10^{-3} \tag{16}$$

This means that gravity could be responsible for most of the CPV in the neutral K seen on the Earth.

4.2 CPV and Gravity

In 1992 Gabriel Chardin [2] showed that gravity on Earth has the right intensity to generate CPV in the mixing of the neutral K and B mesons. He also demonstrated that the phenomenon of antigravity for antimatter could be compatible with the General Relativity and that it could be the motivation of an instability of quantum vacuum in the presence of strong gravitational fields, mimic of the Hawking radiation.

In order to understand if gravitational contribution is present in the CPV of the neutral Kaons we propose an experiment in orbit. In fact, on a circular LEO at 500 Kilometers, gravity is about 10% less than on Earth. On a GEO orbit the intensity of the of the Earth's gravitational field is of the order of few percent. This is likely to cause a large fluctuation of any gravitational contribution to the CPV in the 2-state system of the neutral K mesons. The production of the kaons should not be a problem because, in orbit, a large flux of energetic protons is present and is only mildly modulated by the Earth's magnetic field.

On a square target of 70 cm of side, about $1.4x10^4$ protons per second will impact, the energy of the cosmic protons ranges from a few MeV to 200 GeV with the maximum flux around 1 GeV and several smaller local maxima at 5, 13, and 31 GeV. This spectrum can produce the neutral Kaons. The total number of K mesons decays over the predicted mission lifetime (> 2 years) will yield the required physical measurement.

5 A dedicated Satellite

Our payload is aimed at performing a particle physics experiment in orbit and is composed of the following parts:

Active Target: we simulated [22, 23] the production of the K_L ("long" decay neutral mesons) and K_S ("short")

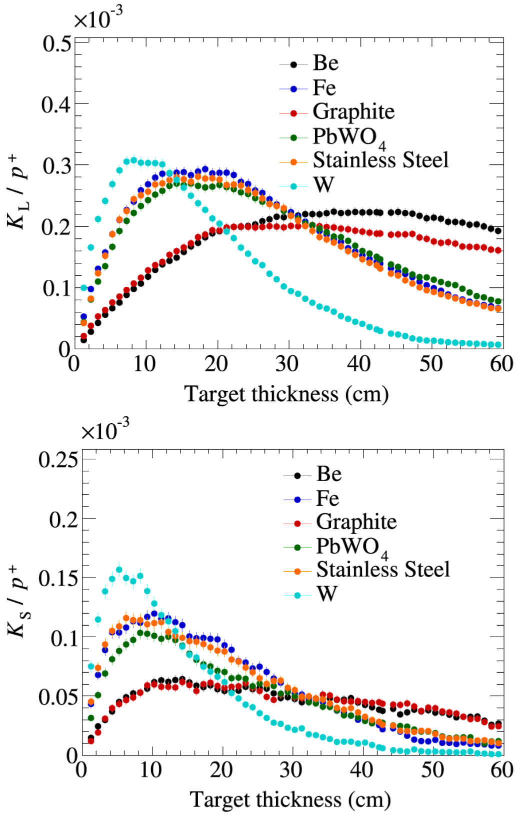

Figure 1. K_L production (Color on line). Number of K_L (top) and of K_S (bottom) which exit the downstream face of the target versus target thickness for several materials.

mesons by the cosmic protons on an active target made of alternate layers of tungsten and scintillating fibers, read by photodiods, for a total thickness of few cm of *W* (see Figs. 1 and 2.

"Empty" structure: (necessary for the decay of the K_S) from our simulations we expect that 50 cm vacuum, in which the K_S may decay, are needed to separate the K_L from the K_S.

Spectrometer Magnet: will be made of neodymium/iron/boron permanent magnets, magnetized at 1.3 T. The spectrometer diameter will be 50 *cm*. The required 1.3 kGauss field needs a 25 mm × 500 mm cylindrical magnet.

Tracker: will consist of five silicon layers similar to those used in other satellites.

Calorimeter: the 4-radiation-length calorimeter uses a lead scintillating fibers array, and permits the absorption of about 90% of the electromagnetic shower.

The veto detector: consists of a layer of scintillator surrounding the entire detector.

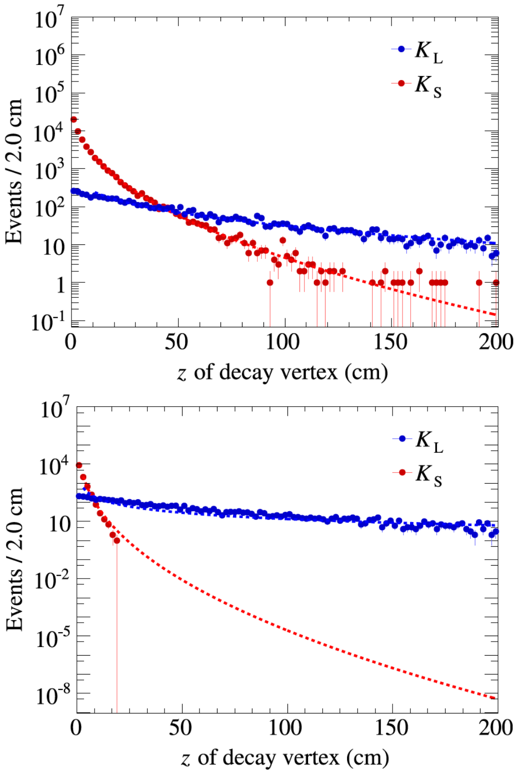

Figure 2. (Color on line) Axial position of the decay vertex (top) and the same with the additional constraint $pz < 0.5$ GeV/c (bottom).

6 Conclusions

We have proposed a possible test of the gravitational [24] behavior of antimatter by measuring the rate of the CP violating decay in space. We estimate that a 5σ measurement on a possible change in the CP violation parameter ε could be obtained within few years, depending on the detection efficiency, if one places a detector with thick tungsten target, a 1 m diameter by 1 m deep tracking region, a magnetic field for charged-particle identification, time-of-flight counters, and electromagnetic calorimeters for energy measurements, on a Leo or better on Geostationary orbit. Any difference between the amount of CP violation in orbit with respect to the level CP violation on the Earth's surface would be an indication of the nature of the gravitational interaction between matter and antimatter. A positive result may offer an explanation for the cosmic baryon asymmetry as well as a contribution to the observed effects thought to come from dark matter and dark energy.

ACKNOWLEDGMENTS

I WOULD LIKE TO THANK:
Gabriel Chardin CEA Saclay France

Erasmo Recami University of Milan Italy
Giovanni Fabrizio Bignami INAF
Thomas j. Phillips- Duke University NC USA
Anthony Palladino Boston University
Luca Latronico INAF Torino Italy
Patrizia Caraveo INAF Milano Italy
Graziano Venanzoni INFN LNF Italy
Dragan Slavkov Hajdukovic CERN
Dan Kaplan Illinois Institute of Technology

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