Probing antigravitational effects through CP violation on the Moon

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Abstract

The environment on the Moon has numerous features that make it interesting not only for the study of astrophysical phenomena, but also elementary particle physics. In fact, vacuum conditions, low gravity, and exposure to a relatively intense irradiation of cosmic protons covering a large energy spectrum, make the lunar environment attractive for a wide range of particle physics experiments otherwise unworkable on Earth. We suggest one such experiment measuring the difference between the amount of CP violation as measured on the surface of the Earth and on the surface of the Moon, which could indicate quantum gravitational effects.

1 Introduction

The response of antimatter to a gravitational field has not yet been measured in any experimental test. A relatively large number of experiments on the gravitational interaction of anti-matter have been proposed and even started, e.g., ASACUSA [36, 37, 38, 39, 40], ATHENA [27, 33], AEGIS [1], ALPHA [2], ATRAP [3], and GBAR [4], to name only a few. Most of them are related with direct measurements of the interaction of anti-protons and of anti-nuclei and had, or have to, face technical difficulties due to copious electromagnetic noise and the difficulties of producing and confining anti-atoms. All of the ongoing experiments are still in the preliminary step of attempting to confine the anti-atoms in order to perform their measurements [26]..[66]. This paper is focused on a different aspect of the problem; we are looking for a variation in CP violation as a function of gravitational field intensity. Two experiments, CPLEAR [5] and KLOE [6], dealt with CP violation in the neutral kaon system, both looking for a time modulation of CP violation due to tidal contributions of the Moon, Sun, and galaxy to the gravitational field involved in kaon decays. The results were not incompatible but too weak to see any correlation.

In this paper, we propose a new approach to the problem, motivated by recent scientific interest in constructing a research village on the moon [7, 8, 9]. In fact, the European Space Agency's (ESA) Di-

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rector General recently suggested the creation of a human-robotic lunar outpost as a logical next step in human space exploration [10, 11]. Our approach takes advantage of the large difference between the gravitational field on the surface of the Earth and that on the Moon. On the Moon, the gravitational acceleration $g_{\mathrm{Moon}} = 1.622\ \mathrm{m/s^2}$ is only 16.54% of the corresponding acceleration on Earth. Such a difference should be extremely useful to our investigation on the contribution of gravity to the mixing in the neutral kaon system.

2 Antimatter and Gravitation

Any kind of relativistic and quantum theory of interactions, in the limit of perfectly static interactions, from the point of view of a Galileian inertial frame of reference, must converge to the classical expressions for the electromagnetic and gravitational fields,

$$F_{q,q'} = \frac{1}{4\pi\varepsilon_0}\frac{qq'}{r^2}\widehat{U}_{q,q'} \tag{1}$$

where $\varepsilon_0 = 8.85 \times 10^{12}\ \frac{\mathrm{C}^2}{\mathrm{N\cdot m^2}}$, and

$$F_{m,m'} = \frac{1}{4\pi g_0}\frac{mm'}{r^2}\widehat{U}_{m,m'} \tag{2}$$

where $g_0 = -1.1935 \times 10^9 \frac{\mathrm{kg}^2}{\mathrm{N\cdot m^3}}$.

The different sign of the two constants, e_0 and g_0, means that similar charges repel for the electromagnetic interaction but attract for the gravitational interaction. This means that there is an electromagnetic screening effect, i.e., a bound state of electric charges seems to have less charge than the sum of the individual charges, while on the contrary a bound state of massive particles seems to have more mass from the point of view of an external observer.

In the Newtonian formulation the definition of inertial mass is related to the definition of force and acceleration. Therefore this implies a dependence on the definition of time. Negative mass should be possible in the case of negative time. Particles with intrinsic reversed time evolution are classically possible if reinterpreted as classical antimatter or tachyons from the point of view of a Galileian reference frame so that in this frame it is possible to consider a repulsion between particle and antiparticle mediated by gravitation [17]. The definition of antimatter in quantum field theories was provided by Feynman and Stueckelberg [12, 13]. It implies that matter-antimatter transformations are equivalent to charge conjugation and time reversal in a flat space-time. When General Relativity (GR) is considered, space-time is not in general flat, however the GR equations remain symmetric in the time coordinate even if it is not explicitly concerned about antimatter. Several theories that allow repulsion between matter and antimatter have been proposed []. In fact, this hypothesis may overcome many of the open problems in astrophysics and cosmology:

i. In the observed universe, matter prevails over antimatter (Matter-Antimatter Asymmetry);

ii. The Cosmic Microwave Background (CMB) is neither anisotropic nor inhomogeneous enough to be compatible with the Big Bang model without the introduction of an unknown interaction (Inflation);

iii. Given the attractive gravitational interaction, we expect a slowing of the acceleration of the expansion of the universe. On the contrary the acceleration seems to be increasing (Dark Energy); and

iv. The gravitational field of galaxies, clusters, and even our own solar system seems much stronger than expected due to visible matter (Dark Matter).

Most of them could be addressed by the same hypothesis. In fact, the net force in a universe with matter-antimatter symmetry should be repulsive because in such a case the forces do not necessarily cancel out. In an ionic solid, a very similar physical system, the same number of positive and negative charges are present, but the overall electrostatic force on the crystal is attractive (compensated by the Fermi exclusion principle). If we now visualize each positive ion as a particle, and each negative ion as an antiparticle, and replace the electrostatic interaction by the gravitational potential, we obtain from the Madelung-like model:

$$U_g = \frac{1}{2}N\alpha\frac{m^2}{R}, \tag{3}$$

where U_g is the total gravitational energy, N is the total number of particles with mass m, R the separation between nearest antimatter, and α is the Madelung constant. For simplicity, and to keep the analogy with a crystal, m and R are assumed to be the same for the entire matter-antimatter mixture. The Madelung constant has values between 1.6 and 1.8 for most crystal structures. The overall force on the universe ($\mathrm{d}U_g/\mathrm{d}R$) is repulsive [25]. Therefore, gravitational repulsion between matter and antimatter may have dramatic consequences in astrophysics and cosmology.

Several authors [14, 15, 16] have studied possible consequences of anomalous antimatter gravity if we live in a symmetric universe, i.e., a universe with the same amount of matter and antimatter, with antimatter somehow hidden (for instance in the vacuum). According to a radically different direction of research [17], we live in an asymmetric universe (i.e., matter dominates antimatter) but the gravitational properties of antimatter (negative gravitational mass) may have a major impact because of the quantum vacuum fluctuations interpreted as virtual gravitational dipoles with the potential to explain the nature of what we call dark matter. According to this model of the universe, the only matter-energy content of the universe is the Standard Model matter (i.e., matter composed of quarks and leptons interacting through the exchange of gauge bosons). Thus, the phenomena usually attributed to hypothetical dark matter may be considered as a consequence of the local variation of the gravitational polarization due to the baryonic matter immersed in the quantum vacuum.

3 Antigravity and CP Violation

In 1961, Good [18] calculated, using absolute potentials, that a repulsive gravitational interaction of antimatter should introduce a regeneration of kaons, thus resulting in an anomalously large level of CP violation. At the time of his paper, CP violation in the neutral kaon system was unknown and the argument appeared strong and elegant, but in light of the measurement of CP violation [19], Good's paper has instead turned out to be a strong argument in favor of antigravity. Chardin reformulated Good's argument in terms of relative potentials and showed that the gravitational field on the surface of the Earth is of the right intensity, i.e., of the required order of magnitude to cause CP violation. In particular, the mixing time of the kaon,

$$\Delta\tau = 5.9 \times 10^{10}\ \mathrm{s}\ \simeq 6\tau_{k_s} \tag{4}$$

is long enough for the gravitational field of the Earth to attract the matter and repel the antimatter components of the K meson to induce a separation,

$$\Delta\zeta = g\Delta\tau^2 \ , \tag{5}$$

between them inducing regeneration, thus providing a mechanism for indirect CP violation. The amount of such a contribution should be roughly the same order of magnitude as the spatial sepration divided by the Compton wavelength:

$$\begin{aligned} \chi &= \frac{\Delta\zeta}{\Delta L_{\mathrm{K}}} = \frac{g\tau_{k_l}}{\dfrac{\hbar}{m_{\mathrm{K}}c}} = \Omega\frac{g\dfrac{\pi^2\hbar^2}{\Delta m^2c^4}}{\dfrac{\hbar}{m_{\mathrm{K}}c}} \\ \chi &= \Omega\frac{\pi^2\hbar g m_{\mathrm{K}}}{\Delta m^2 c^3} = \Omega \times 0.88 \times 10^{-3} \ , \end{aligned} \tag{6}$$

which happens to be the same order of magnitude as the CP violation parameter, ε, as measured on Earth's surface. If we calculate (6) given the gravitational strength on the Moon's surface we would expect the measured ε to be 80% smaller than the ε measured on Earth's surface, assuming gravitational repulsion beween matter and antimatter.

4 Moon Surface Experiment

As mentioned above, we expect only 16% of the CP violation induced by gravity in an experiment performed in the gravitational field on the Moon. Since

$$R = \frac{\Gamma(\mathrm{K_L} \to \pi^+\pi^-)}{\Gamma(\mathrm{K_L} \to \pi^+\pi^-\pi^0)} \tag{7}$$

is quadratic in ε, we expect a very large difference in the value of R when measured on the surface of the Moon. In order to produce the $\mathrm{K_L}$ on the Moon we plan to take advantage of the flux of cosmic protons continuously hitting the Moon's surface. A direct measurement of the flux of protons on the lunar surface has not yet been made, but Ackermann et al. [20] fit the data of the gamma albedo from the Moon surface due to the incoming proton flux finding it to be equal, within a 10% uncertainty, to the proton flux measured by AMS-02 [21] and PAMELA [22]. In the following, we considered the proton flux as determined by AMS-02.

In [23] and [24], we considered an experimental apparatus with cosmic protons incident upon a cylindrical target followed by a detector region consisting of a cylindrical tracking volume (1 meter diameter, 1 meter deep) in a Low Earth Orbit (LEO). On a satellite in LEO, the effect due to gravity on R is $\sim 20\%$. If instead we place the apparatus on the surface of the Moon, we expect a significant improvement in the results, with an effect on R of $\sim 85\%$.

We performed Geant4 simulations using the angular and energy spectrum of the incident cosmic protons as measured by AMS-02 spectrometer. We simulated incident protons with $\theta_{\max} = 45°$ over a target surface corresponding to a $\pi/4$ solid-angle acceptance. We used the same apparatus as in [23] and [24], with the exception of the target. There, we used a cylindrical Tungsten target (1 m diameter, 9 cm deep), while here we considered an active target consisting of alternating layers of Tungsten and scintillating crystals (Stolzite, $PbWO_4$) for a total depth of 18 cm), to be read with photodiodes.

We studied the production of K_L that would decay inside the volume of a detector and their distribution on the detector cross section. The particles decaying before $z = 18$ cm decay inside the $PbWO_4$ target and are lost, however those decaying inside a downstream cylindrical tracking region could potentially be reconstructed. At this stage in evaluating the the feasibility of performing the experiment, we made no attempt to fully reconstruct the K_L decay products inside the detector. We just took as a crude approximation the reconstruction efficiency as equal to 1 inside the fiducial volume of the tracking region. With protons incident on the target distributed in angle and energy as cosmic protons, we estimate the number of K_L decays per year inside two possible tracking volumes, listed in Table 1, with and without additional kinematical cut on the axial momentum at the decay vertex. Table 2 shows the length of time it would take to record sufficient K_L decays to provide 3σ and 5σ measurements of R.

Volume, kinematics	(r < 50 cm)	(r < 50 cm, p_z < 0.5 GeV/c)	(r < 100 cm, p_z < 0.5 GeV/c)
$\frac{N(K_L \text{decays})}{\text{year}}$	3.54×10^6	1.50×10^6	3.36×10^6
$\frac{N(K_S \text{decays})}{N(K_L \text{decays})}$	3.03×10^{-1}	4.15×10^{-5}	

Table 1: Number of K_L that decay within various tracking region volumes 50 cm downstream of the target ($50 < z < 150$ cm, $r < 50$ cm or $r < 100$ cm), with and without a kinematical cut on the axial momentum at the $K_{S,L}$ decay vertex.

	Requirement		Simulation result	
	3σ	5σ	3σ	5σ
$N\,(K_L$ decays)	$> 2.5 \times 10^4$	$> 7 \times 10^4$	6 days	17 days
$\frac{N(K_S \text{ decays})}{N(K_L \text{ decays})}$	$< 1 \times 10^{-4}$	$< 5.7\times 10^{-5}$	4.15×10^{-5}	
$\frac{\delta N(K_L \to \pi\mu\nu)}{N(K_L \to \pi\pi)}$	$< 4 \times 10^{-2}$	$< 2\times 10^{-2}$	kinematical cuts	

Table 2: Critical parameters necessary for 3σ and 5σ measurements of a gravitational modulation in the level of CP violation (85% change in R) along with the values obtained from our Monte Carlo simulation. The results take into account a basic geometrical event selection of $K_{S,L}$ decay vertices within a 1 m $\times$ 1 m cylindrical tracking volume 50 cm downstream of the target ($50 < z < 150$ cm, $r < 50$ cm), and axial momentum at the $K_{S,L}$ decay vertex of $p_z < 0.5$ GeV/c. These values assume a 100% detection efficiency, 2% (4%) statistical and 2% (4%) systematic fractional uncertainties for 5σ (3σ).

5 Conclusions

By constructing a detector consisting of a 1 m diameter, 18 cm thick active target and a 1 m diameter $\times$ 1 m deep tracking and particle identification system, and placing it on the surface of the Moon, we could perform a direct measurement of the ratio of the number of K_L decaying to two charged pions to those decaying to three pions in a low-gravity environment. We estimate that it will take 6 days (17 days) to record sufficient K_L decays for a 3σ (5σ) measurement. Any difference between the amount of CP violation on the surface of the Moon compared to the level of CP violation on the surface of Earth would be an indication of a quantum gravitational effect.

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