Letter of Interest for Snowmass 2021:
Dedicated Experiment Exploring Gravitational Effects on CP Violation

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ABSTRACT

The environments in orbit around the Earth and on the surface of the Moon have numerous features (vacuum conditions, low gravity, and exposure to a relatively intense irradiation of cosmic protons covering a large spectrum of energy) that make them interesting not only for the study of astrophysical phenomena, but also for particle physics. We suggest an experiment sensitive to a possible difference between the amount of CP violation as measured on the surface of the Earth and in a lower gravity environment.

INTRODUCTION

A relatively large number of experiments on the gravitational interaction of anti-matter have been proposed and even started, e.g., AEGIS [1], ALPHA [2], ATRAP [3], GBAR [4], which deal with antihydrogen, and MAGE [5], which deals with muonium, to name only a few. We propose to measure a dependence in the magnitude of CP violation as a function of gravitational field intensity. An experiment in Low Earth Orbit (LEO) would provide an environment with $g_{\mathrm{LEO}} \cong 0.9 g_{\mathrm{Earth}}$, while the surface of the Moon would provide an environment with $g_{\mathrm{Moon}} \cong 0.165 g_{\mathrm{Earth}}$.

GRAVITATION AND ANTIMATTER

The hypothesis of gravitational repulsion between matter and antimatter [6, 7, 8, 9, 10, 11, 12, 13, 20] is interesting because it may have relevance in many open problems in astrophysics and cosmology. Independent of the theoretical assumption, however, we think it is worthwhile to experimentally explore the connection between CP violation and gravity. To motivate the value of such an experiment, we note that gravity-generated CP violation could potentially help to explain "missing" antimatter in the universe (cosmic baryon asymmetry). Sakharov's conditions are satisfied in the Standard Model (SM) [14, 15, 16], while many non-SM theories imply a large CP violation and antigravity [6, 17, 18]. In 1961, Good [19] calculated that a repulsive gravitational interaction of antimatter should introduce a regeneration of kaons thus resulting in an anomalously large level of CP violation, at that time unknown. Chardin [17] reformulated Good's argument and showed that the gravitational field on the surface of the Earth is of the required order of magnitude to cause CP violation during the mixing time. Specifically, the mixing time of the K^0-$\bar{K}^0$ system, $\Delta\tau = 5.9 \times 10^{-10}\mathrm{s} \cong 6\tau_{K_S}$ 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, $\Delta\zeta = g(\Delta\tau)^2$, between them. When compared to the Compton wavelength of the kaon we obtain an adimensional measure of the phenomenon on Earth, $\chi = \Omega \times 0.88 \times 10^{-3}$ which is the same order of magnitude as epsilon. If we calculate χ given the gravitational strength on the Moon's surface, we expect the measured effect to be ∼97% smaller than the effect measured on Earth's surface, assuming a linear dependence of the CP violation parameter, ε, with the gravitational acceleration (as in the case of repulsion between matter and antimatter [17, 19]).

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EXPERIMENT ON THE SURFACE OF THE MOON

We propose to measure $R = \Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_L \to \pi^+\pi^-\pi^0)$ in LEO or on the surface of the Moon where, due to the lower gravity, R is expected to be reduced by ~20% or ~97%, respectively. To produce the K_L in either environment, we plan to use the flux of cosmic protons. A direct measurement of the flux of protons on the lunar surface has not yet been made, but the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) aboard the Lunar Reconnaissance Orbiter [21, 22] measured the gamma albedo from the Moon surface due to the incoming cosmic proton flux and found it to be equal, within a 10% uncertainty, to the proton flux measured by AMS-02 [23] and PAMELA [24], both in LEO. We performed a Geant4 simulation with this spectrum of cosmic ray protons originating on a hemispherical surface with cosine-law biasing and incident upon a cylindrical target. We used a partially active cylindrical target, consisting of alternating layers of lunar regolith and scintillating material for a total depth of 18 cm (we used layers of $PbWO_4$ in our previous study, described in [24, 25]). We studied the amount of K_L that would decay inside various sizes of downstream cylindrical tracking regions where the decay could potentially be reconstructed; for our initial estimate we used a reconstruction efficiency equal to 1 inside the fiducial volume. Table 1 shows the estimated the number of K_L decays inside a 1 m radius 4 m deep cylindrical tracking volumes with an offset between the target and the tracking volume of 2 m to allow the K_S to decay. Much of the remaining K_S background contamination can be significantly reduced by selecting only $K_{S,L}$ that decay with low forward momentum (e.g., $p_z < 1$ GeV) with minimal loss in the number of signal K_L decays, as described in [25, 26]. The additional background from misidentified $K_L \to \pi\mu\nu$ decays will be rejected with kinematic cuts during data analysis. Table 1 also lists the minimum amount of time it would take to collect a sufficient number of K_L for 3σ and 5σ measurements of R, in each environment, with (and without) an assumed gravitational dependence on the CP violation parameter, ε.

Table 1: Requirements for 3σ and 5σ measurements of R in low gravity environments assuming either a linear dependence of ε on g, or assuming ε is independent of g.

Measurement	N(K_L decays)		$T_{\min}$ to collect sufficient K_L decays	
	3σ	5σ	3σ	5σ
R on Surface of the Moon, if $\varepsilon \propto g$	3.3×10^5	9.1×10^5	158 days	439 days
R in Low Earth Orbit, if $\varepsilon \propto g$	1.1×10^4	3.1×10^4	6 days	15 days
R in either LEO or on the Moon, if ε is independent of g	9.0×10^3	2.5×10^4	5 days	12 days

SUMMARY

By placing a detector in either Low Earth Orbit or 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 $\mathcal{O}$(days) to record sufficient K_L decays for a 3σ measurement of R, and $\mathcal{O}$(tens of days) for a 5σ measurement. For the experiment on the Moon, if there is a dependence of ε on g, within the first $\mathcal{O}$(tens of days) we would expect to measure only background contamination, with a null signal measurement confirming the existence of a gravitational dependence. Any difference between the amount of CP violation in a low gravity environment with respect to the level CP violation on the surface of Earth could be an indication of a quantum gravitational effect.

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