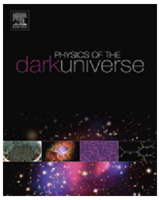
Physics of the Dark Universe 13 (2016) 162–165

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark



Measuring gravitational effects on antimatter in space

G.M. Piacentino[a,b,c], A. Palladino[d,e,*], G. Venanzoni[d]

[a] *Università degli Studi del Molise, Campobasso, Italy*
[b] *INFN, Sezione di Lecce, Lecce, Italy*
[c] *INAF, Sezione di Milano, Milano, Italy*
[d] *Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy*
[e] *Boston University, Boston, USA*

ARTICLE INFO

Article history:
Received 7 November 2015
Received in revised form
4 July 2016
Accepted 5 July 2016

Keywords:
Gravity
CP violation

ABSTRACT

We propose an experimental test of the gravitational interaction with antimatter by measuring the branching fraction of the CP violating decay $K_L \rightarrow \pi^+\pi^-$ in space. We show that at the altitude of the International Space Station, gravitational effects may change the level of CP violation such that a 5σ discrimination may be obtained by collecting the K_L produced by the cosmic proton flux within a few years.

1. Introduction

The hypothesis that antimatter could have a different coupling to the gravitational field has fascinated physicists since the discovery of the first antiparticles. Various theoretical efforts have been put forth to demonstrate both the possibility of a different behavior or, on the contrary, the necessity of equal coupling. Several authors have shown that the possible gravitational repulsion between matter and antimatter could offer at least a partial explanation for a number of cosmological problems, including those connected to dark matter and dark energy [1–15].

At present, the state-of-the-art is not very different from the framework summarized in the article by Nieto et al. in 1991 [16]. Limits on repulsive gravity have been calculated based on measurements [17,18]. A relatively large number of experiments on the gravitational interaction of antimatter have been proposed and even started, e.g. AEGIS [19], ALPHA [20], ATRAP [21], and GBAR [22]. In addition, the muonium experiment proposed at PSI [23,24] is the first to involve a second generation fermion. Furthermore, aside from direct measurements in laboratories there are emerging astronomical tests as pointed out by [9,10] and supported by a feasibility study [25] on a trans-Neptunian Binary System. Our proposal of measuring CP violation in a weaker gravitational field is complementary to both laboratory experiments and astronomical observations; it is simply a direct test of the dependence of CP violation on the gravitational field. Should such a dependence exist it would be a strong indication of particles and antiparticles having opposite coupling with gravity. Ultimately the only measurements related to the topic at hand came from CPLEAR in 1999 [26] and proposed at KLOE in 2000 [27] where they looked for a modulation of CP violation due to gravitational tidal contributions from the Moon, the Sun, and the galaxy.

The experiment proposed in this article is based on Good's argument [28]. Good initially noted that the absence of CP violation in neutral kaon decays would experimentally rule out any possible gravitational repulsion between matter and antimatter. The discovery of CP violation has greatly limited the validity of Good's argument and various authors have considered variants of it both in favor and in opposition to the possible existence of a different gravitational coupling between matter and antimatter.

This topic deserves experimental tests and current investigations are ongoing in various laboratories on Earth. We instead propose to study a possible dependence of CP violation on the gravitational interaction in the K_S–K_L system in space. The magnitude of any difference between the CP violation parameter, ε, measured in orbit and that measured on Earth's surface would give important indication on the nature of the gravitational interaction between matter and antimatter as well as provide evidence for a quantum gravitational effect. In this paper we outline a new approach to the problem capable of providing a 5σ measurement.

---

* Corresponding author at: Boston University, Boston, USA.
E-mail addresses: nanni@fnal.gov (G.M. Piacentino), palladin@bu.edu (A. Palladino), graziano.venanzoni@lnf.infn.it (G. Venanzoni).

http://dx.doi.org/10.1016/j.dark.2016.07.002
2212-6864/

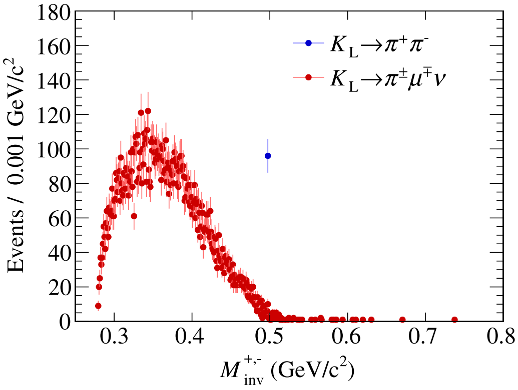


Fig. 1. (Color online) Invariant mass calculated from the charged daughters of the K_L decays. For the 2-body decay we recover m_{K_L}. A fit to this distribution and other kinematical observables can easily provide knowledge of our background contributions with an uncertainty at the percent level, $\delta B/S < 0.02$.

2. Possible experimental setup

The mean gravitational field strength in a Low Earth Orbit (LEO) is about 10% less than on the Earth's surface. Following Chardin [1,2] we consider a dependence of ε only on the local acceleration due to gravity, g, not on the gravitational potential. In circular orbits, such as a LEO, $(g_{\text{orbit}} - g_{\text{surface}})/g_{\text{surface}}$ is stable and all external perturbations are at least an order-of-magnitude less and will not be considered in this paper. The rate of incoming protons in a LEO has been measured [29,30], and when integrated on the permitted entrance to the detector can reach as many as 2.2×10^4 protons per second. 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.

The incident proton spectrum is energetic enough for the production of K_L allowing for a measurement of

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-\pi^0)} \tag{1}$$

which is quadratic in ε. If CP violation depends linearly on the gravitational field [1,2] we expect a 10% effect in ε to translate to a 20% effect on R.

To make a 5σ measurement of a 20% effect on R we would need to record at least $12.5 \times 10^5 K_L$ decays, with $N\,(K_S \text{ decays})\,/N\,(K_L \text{ decays}) < 5.7 \times 10^{-5}$, while keeping the uncertainty in the background at less than 0.02 of our signal, $\delta B/S < 2\%$. The background contribution from $K_L \to \pi^\pm\mu^\mp\nu$ can be easily obtained with an uncertainty at the percent level by fits to kinematical observables such as the invariant mass calculated from the two charged tracks (Fig. 1). The corresponding values necessary for a 3σ measurement are listed in Table 1. As we will see in the following section this yield can be achieved on the proposed LEO within a few years of data taking.

3. Detector structure

The detector geometry consists of a target composed of layers of tungsten and thin planes of active detectors with the tungsten having a cummulative depth of 9 cm and a radius of 50 cm. Downstream of the target is a ∼50 cm deep charged-particle detector such as the Transition Radiation Detector (TRD) in AMS-02. Next comes a cylindrical tracking volume with 1 m diameter and 1 m length, followed at the downstream end by an electromagnetic calorimeter. The tracking region would be surrounded by a veto system to identify cosmic rays entering from the side. The active layers sandwiched in the target would identify the parent incident proton and record the time and position of the interaction point. Charged-particle backgrounds produced in the target would be identified in the charged-particle detector between the target and the tracking region. The neutral $K_{S,L}$ produced in the target, would travel into the cylindrical tracking region where they then decay. Data analysis will select $K_L \to \pi^+\pi^-$ and $K_L \to \pi^+\pi^-\pi^0$ events with interaction vertices inside the tracking region which has a >50 cm displacement with respect to the target thereby significantly reducing background contamination.

Table 1
Critical parameters necessary for 3σ and 5σ measurements of a 10% change in the level of CP violation (20% 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 × 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).

	Requirement		Simulation result	
	3σ	5σ	3σ	5σ
$N\,(K_L \text{ decays})$	$>3 \times 10^5$	$>12.5 \times 10^5$	73 days	304 days
$\frac{N(K_S \text{ decays})}{N(K_L \text{ decays})}$	$<1 \times 10^{-4}$	$<5.7 \times 10^{-5}$	4.1×10^{-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	

4. Simulation

We performed a GEANT4 [31,32] Monte Carlo simulation using the angular and energy spectra of the incident cosmic protons as measured by AMS-01 spectrometer. We simulated incident protons with $\theta_{\max} = 45°$ over a 50 cm radius target surface corresponding to a $\pi/4$ solid-angle acceptance.

Fig. 2 shows results from an optimization study of target material and depth. Even though more K_L are produced for thicker targets, the probability that they exit the thicker targets is reduced due to regeneration and nuclear interactions.

We found that the axial momentum (p_z) distributions, Fig. 3, for the K_L and K_S in the tracker differ such that we can suppress the $K_S \to \pi^+\pi^-$ background with the cut $p_z < 0.5$ GeV/c. Fig. 4 shows the effect of the momentum cut. Considering a cylindrical tracking region with 1 m diameter, 1 m deep, and offset 0.5 m downstream of the target, we would obtain the results given in Table 1.

The simulation also provided estimates for the rate of background particles exiting the downstream face of the target. Events with charged particles entering the tracking region can easily be excluded from data analysis by relying on the charged-particle detector between the target and the tracker. Protons are the most abundant of the charged particles exiting the target with an estimated rate of about 4.5 kHz, the second highest rate comes from e^- with a rate of about 360 Hz, followed by π^+ with a rate of 230 Hz, e^+ at 210 Hz, and π^- at 180 Hz. All other charged particles leave the target at a rate $\mathcal{O}(1 \text{ Hz})$ or less. The neutral background particles, other than neutrinos, exiting the downstream face of the target are n at ∼100 kHz and γ at ∼20 kHz. The K_L exit the target at 3.5 Hz and K_S at 1.8 Hz. Proper data analysis including particle track reconstruction, time-of-flight detection, and mass reconstruction, can select pions from the K_L that decay inside the tracking region.

5. Conclusions

We have proposed a possible test of the gravitational behavior of antimatter by measuring the rate of the CP violating decay $K_L \to \pi^+\pi^-$ in space. We estimate that a 5σ measurement on a possible change in the CP violation parameter ε could be obtained within a year, depending on the detection efficiency,