Dedicated Experiment to Explore Gravitational Effects on CP Violation

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The physics / basic idea of the LOI

- We aim to measure CP-violation in the Kaon system in a low-gravity environment (in low Earth orbit or on the Moon) in order to:
    - Explore a possible link between CP violation and gravity, as suggested by:
        - G. Chardin, *CP violation and antigravity (revisited)*, Nucl. Phys. A 558 (1993)
        - M.L. Good, K_2^0 *and the Equivalence Principle*, Phys. Rev. 121 (1961)
    - Understand possible sources of CP violation in the neutral Kaon system beyond the standard model
    - Probe gravitational interactions of antimatter
- Physics reach / outcome
    - First measurement of a gravitational effect at the quantum scale
    - Exclude or confirm cosmological implications;
    - Are there gravitational systematics that we should consider for other experiments on the Earth?
- Does your LOI cross frontiers (energy, neutrinos, cosmic, computing, ...)?
    - Yes. ‘Cosmic’ and ‘Precision’ frontiers, experimentally linking GR and QM and setting limits on many theories of cosmic phenomena

What is required for the LOI to succeed

- What are the common data sets, joint efforts, and/or benchmarks that you need to accomplish your plans?
  - In principle, the AMS-01/AMS-02 detector may be able to distinguish between $K_L \rightarrow 2\pi$ and $K_L \rightarrow 3\pi$, however it was not designed to do so
    - We extend an invitation to AMS-02 collaborators to join our collaboration to help perform simulation studies
  - Benchmarks:
    - Design an improvement/upgrade for AMS-02, or
    - Design a new dedicated detector for placement on the ISS (and/or the Moon)
    - Run high-statistics simulation studies to understand systematics
- Does your LOI require new detector technologies, instrumentation, facilities, computing, etc. to succeed
  - No new technologies are required
    Particle physics detectors operating in space: AMS, PAMELA
  - May need to design new instrumentation (as above)

What do you plan to do during Snowmass

- Plans for participation / studies / simulation / contributed papers in the Snowmass process
  - Participation:
    - Attend all ‘Rare Processes and Precision Frontier’ working group meetings
    - We hope to enlarge the participation in our collaboration
  - Studies:
    - Design detector / upgrade
    - Understand systematics (via simulations)
  - Contributed papers:
    - We already published one paper on the topic and performed some initial simulations (see final slide for citations)
    - Two papers (detector design/upgrade and systematics studies)
    - A portion of PhD Dissertation
- Schedule for these goals
  - Dec 2020 / Jan 2021: Submit first paper
  - Spring 2021: Submit second paper
  - Multiple conferences

What do you hope to get out of Snowmass

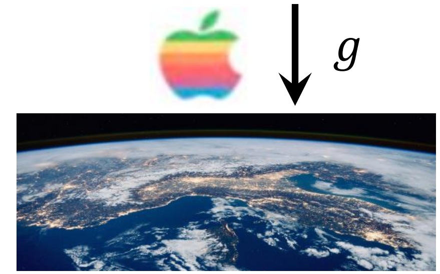
- Gain interest from the physics community
- Grow our collaboration
- Further theoretical work to help understand the cosmological implications of a gravitational dependence of CP-violation
- Increase likelihood of obtaining funding for this experiment

Additional slides

Background

- Matter is self-attractive

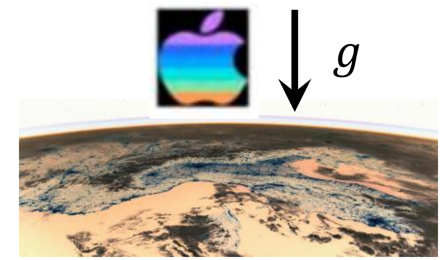
$$\frac{d^2x^\lambda}{d\tau^2} = -\frac{dx^\mu}{d\tau}\frac{dx^\nu}{d\tau}\Gamma^\lambda_{\mu\nu}$$



- Antimatter is self-attractive

$$CPT : dx^\mu \to -dx^\mu$$
$$CPT : \Gamma^\lambda_{\mu\nu} \to -\Gamma^\lambda_{\mu\nu}$$

$$-\frac{d^2x^\lambda}{d\tau^2} = -\left(-\frac{dx^\mu}{d\tau}\right)\left(-\frac{dx^\nu}{d\tau}\right)(-\Gamma^\lambda_{\mu\nu})$$



- Is there a mutual repulsion between matter and antimatter?
  - No experimental conclusion yet
  - GR predicts a ***repulsion*** when CPT is applied [M. Villata, 2011]

$$-\frac{d^2x^\lambda}{d\tau^2} = -\left(-\frac{dx^\mu}{d\tau}\right)\left(-\frac{dx^\nu}{d\tau}\right)\Gamma^\lambda_{\mu\nu}$$

Motivation for a CP-violation Experiment

- A gravitationally-induced separation of the matter and antimatter components of the neutral kaon would be proportional to the mixing time

Neutral Kaon Mixing Time	Induced Separation
$\Delta\tau = \frac{\pi\hbar}{\Delta m_K c^2} \simeq 5.9 \times 10^{-10}$ s	$\Delta\xi \sim gt^2$

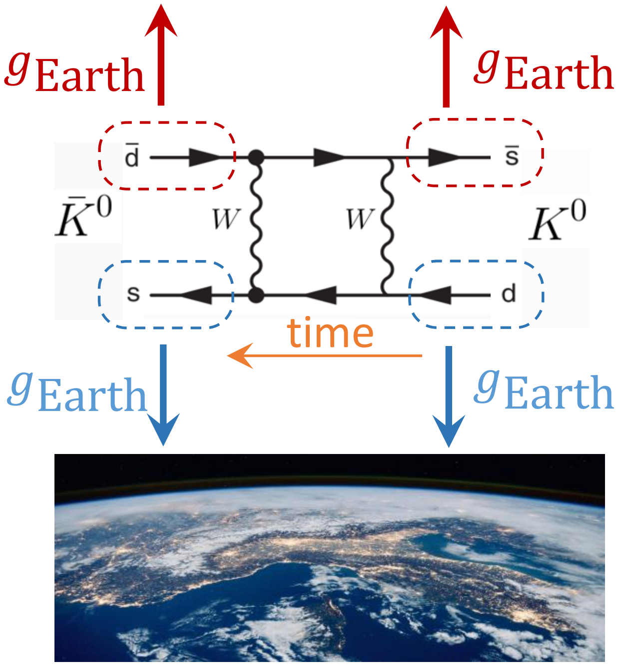
- This separation would cause a regeneration of the K_S component
- The amount of CP violation induced by this phenomenon would be:

$$\chi \sim \frac{\Delta\xi}{L_{Compton}} \sim O(1) \times g \, \frac{\hbar \, m_K c}{(\Delta m_K c^2)^2}$$

$$\chi \sim O(1) \times 0.88 \times 10^{-3}$$

- This is the same order of magnitude as the observed level of CP violation on the surface of Earth:

$$\varepsilon \simeq 2.2 \times 10^{-3}$$



Motivation for a CP-violation Experiment

How can we test this hypothesis?

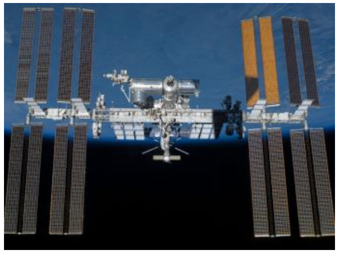
- Measure *R* in a low-gravity environment!

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^+\pi^-\pi^0)} \propto \varepsilon^2$$

if $\varepsilon \propto g \longrightarrow R \propto g^2$

- Low Earth Orbit (e.g., aboard the International Space Station, like AMS-02)

$$g_{LEO} \simeq 90\% g_{\oplus} \rightarrow \Delta R_{LEO} \simeq -20\% R_{\oplus}$$



- On the surface of the Moon

$$g_{Moon} \simeq 16\% g_{\oplus} \rightarrow \Delta R_{Moon} \simeq -97\% R_{\oplus}$$

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.

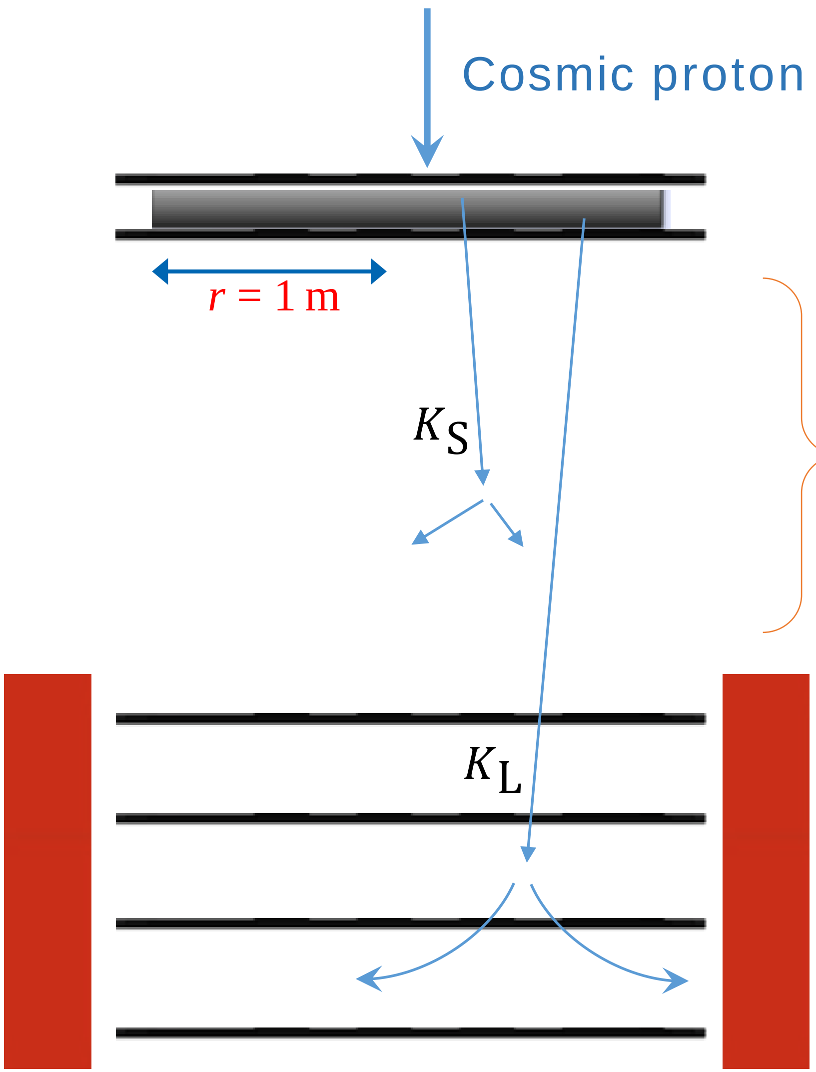
Measurement	$N(K_L$ decays)		T_{min} to collect sufficient K_L decays	
	3σ	5σ	3σ	5σ
R on Surface of the Moon, if $\varepsilon \propto g$	3.3×10^5	9.1×10^5	158 days	439 days
R in Low Earth Orbit, if $\varepsilon \propto g$	1.1×10^4	3.1×10^4	6 days	15 days
R in either LEO or on the Moon, if ε is independent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

- With only < 1-month of data collection we will either:
  - Produce a 5σ result showing CP violation is independent of gravity, or
  - Show conclusive evidence of a gravitational effect at quantum scale

Comparison to other experiments

- Other experiments measuring the direction of gravitational pull(or push) on antimatter
  - First attempt 1967 [free fall of electrons and positrons: F. C. Witteborn & W. M. Fairbank, "Experimental Comparison of the Gravitational Force on Freely Falling Electrons and Metallic Electrons," Phys. Rev. Lett. 19,1049 (1967)]
  - Second attempt 1986 [Los Alamos-led team proposed to measure gravitational force on antiprotons at the CERN Low Energy Antiproton Ring (LEAR) with a similar experiment to that of Fairbank]
  - T. Phillips's Interferometric experiment proposal at FERMILAB (1997)
    T. Phillips, Hyp. Int. 109 (1997) 357 [Never started]
  - CERN: AEGIS, ALPHA-g, GBAR [all involve antihydrogen; all ongoing now]
  - PSI: MAGE experiment with Muonium at PSI, First with leptons; low binding energy. First proposal (D. Kaplan & K. Kirsch): arXiv:physics/0702143v1 [physics.atom-ph]
- Our approach has low systematics for phenomenon of interest:
  - Not sensitive to binding energy
  - No need to create anti-atoms
  - No need to confine or transport anti-atoms
  - No new technology (standard particle physics detectors will suffice)
- Our main difficulty is placing/operating the detector in space

Notional Detector



Active Target: Alternating layers of lunar regolith (13 cm total) and scintillating material

Empty Region: let the K_S decay (to suppress the $K_S \to 2\pi$ background)

Tracking Region: Si tracking layers and permanent magnet

Veto System: Scintillators surrounding the whole detector

Questions?

- G.M. Piacentino, A. Palladino, G. Venanzoni. *Measuring gravitational effects on antimatter in space*. Physics of the Dark Universe 13, 162-165 (2016). DOI: 10.1051/,01023 (2017) 7142010. 142. arXiv: 1605.01751 [hep-ph]
- G. M. Piacentino, A. Gioiosa, A. Palladino, G. Venanzoni. *Measuring gravitational effects on antimatter in space*. International Symposium Advances in Dark Matter and Particle Physics (ADMPP16), Messina, Italy, October 24-27, 2016. European Physical Journal Conferences. 142 (2017) 01023 DOI: 10.1051/epjconf/201714201023
- G. M. Piacentino, A. Gioiosa, A. Palladino, V. Testa, G. Venanzoni. *Probing antigravitational effects through CP violation on the Moon*. (Jul 16, 2019) arXiv: 1907.06866 [astro-ph.HE]

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Measuring gravitational effects on antimatter in space

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

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