Gravitational mass of positron from LEP synchrotron losses

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Team 14

The Weak Equivalence Principle

"The quantity of matter is the measure of the same, arising from its density and bulk conjunctly."

-Isaac Newton

The Weak Equivalence Principle

- The effect of a gravitational field on a given mass is independent of its internal structure and properties.
- (Possibly) tested by Galileo at the Leaning Tower of Piza c. 1600

https://en.wikipedia.org/wiki/Leaning_Tower_of_Pisa

Equivalence Principle Tests

Equivalence Principle Tests

- Rarity makes the gravitational mass of antimatter difficult to constrain.
- Direct tests with antihydrogen constrain the mass ratio near ±60:1
- Neutral kaons give much stricter bounds (inequality $O(10^{-9})$) but are subject to unknowns about gravitation of strange particles.

https://doi.org/10.1016/S0370-2693(99)00271-3 https://doi.org/10.1038/ncomms2787

Theoretical Expectations

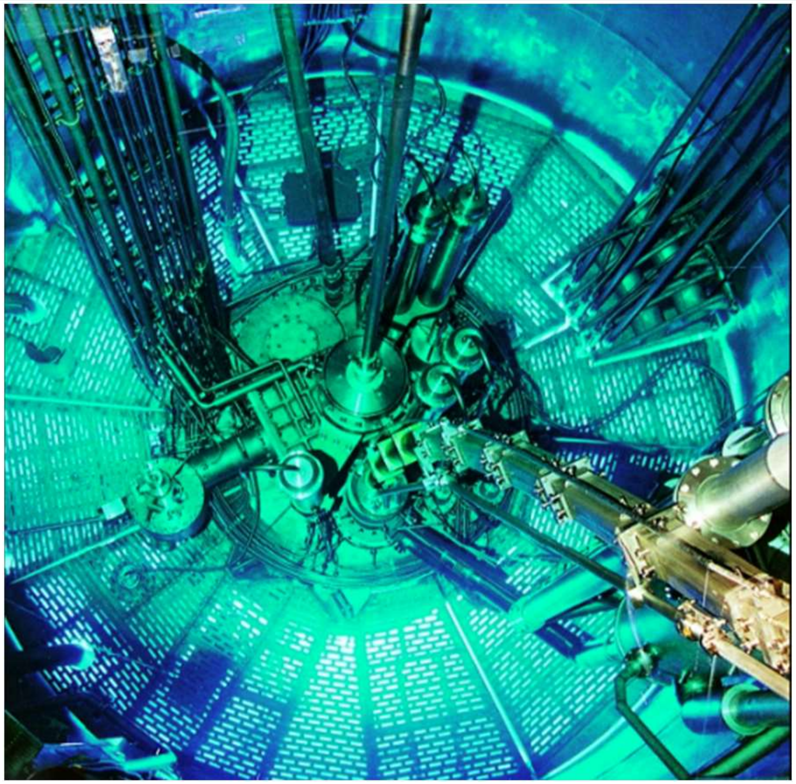
- Considered quantum field-theoretic corrections to a quantum field theory of gravity coupled to matter.
- Schiff took a divergent perturbation calculation.[a]
- Nieto and Goldman argue his calculation is moot in modern theories of quantum gravity.[b]
- Provide other justifications

[a] Schiff, L I., Proc Natl Acad Sci U S A (1959)

[b] Nieto & Goldman, Physics Reports (1991)

Kalaydzhyan's Previous Work

- Constrain deviations from weak equivalence principle
- Based on the absence of Cherenkov radiation at the LEP at CERN.
- Not rely on astrophysical models.
- Expected significant improvements using synchrotron losses.



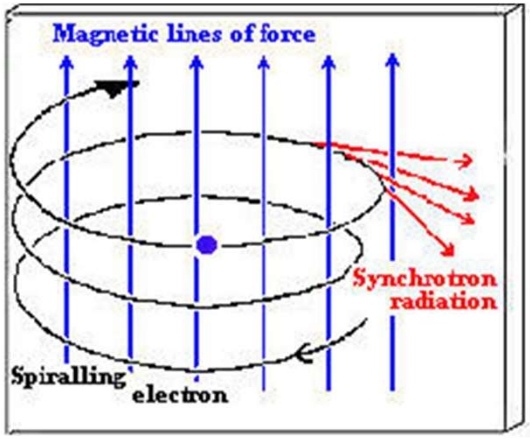
Kalaydzhyan, T. Phys. Lett. B (2015)

Motivation

- **Main scientific goal**: Could antimatter be described by GR?
- Establish a bound on the difference between the gravitational and inertial masses of the positron from synchrotron losses
- Why an accelerator experiment?
  - Large γ factor
  - Don't need to make any assumptions about high-energy astrophysics

Synchrotron radiation

- Magnetic field accelerates the particle in a closed path
- Gravitational field effects energy losses



https://universe-review.ca/R05-02-synchrotron.htm

$$P = \frac{2}{3}\frac{e^2\dot{\mathbf{v}}^2}{c^3}\left(\frac{\mathcal{E}}{m_e c^2}\right)^4$$

Metric for a static weak field

For a massive particle, the gravitational potential is

$$ds^2 = \mathcal{H}^2 dt^2 - \mathcal{H}^{-2}(dx^2 + dy^2 + dz^2)$$

$$\Phi_m = \Phi \frac{m_{e,g}}{m_e}, \quad \mathcal{H}_m^2 \equiv 1 + 2\Phi_m$$

Uncertainty in power loss

From the dispersion relation of the positron we can write the uncertainty in the power loss:

$$\Delta P/P = 4\kappa\gamma^2$$

$$\kappa = 2\Phi\Delta m_e/m_e,\ \Delta m_e = m_{e,g} - m_e$$

Restriction on gravitational mass

Two sets of experimental data "1" and "2" will restrict the values

$$|\kappa| < \kappa_{1,2} \equiv |\Delta P/P|_{1,2}/(4\gamma^2)$$

$$\left|\frac{\Delta m_e}{m_e}\right| < \frac{\kappa_1 + \kappa_2}{2|\Delta\Phi|}$$

Relation between mass deviation and power loss

Eccentricity in earth's orbit causes a variation in gravitational potential

$$\Delta\Phi = -\,\Phi_{\odot}\Delta d_{SE}/d_{SE}$$

$$\left|\frac{\Delta m_e}{m_e}\right| < \frac{\left|\Delta P/P\right|_1 + \left|\Delta P/P\right|_2}{8\gamma^2|\Phi_{\odot}\Delta d_{SE}[\mathrm{AU}]|}$$

Measuring positron power loss at the LHC

-**Central activity**: measure power loss with NMR and the quality factor Q_s

$$\left|\Delta P/P\right|_{1,2} < 9 \times 10^{-4}$$

$$\left|\frac{\Delta m_e}{m_e}\right| < 1.3 \times 10^{-3}$$

-**Key finding**: 0.13% limit on a possible deviation from WEP!

Critique

☺

- Concise
- Reports and source data given → calculations can be reproduced
- Assumptions seem well motivated
  - Eg. weak field approximation, small anomalous redshift κ $(=2\Phi(m_{e,g}-m_e)/m_e)$, ...

Critique

- Only two measured values are used out of a large data set
  - But the paper is very transparent as to which data points were used
- Disregarding other sources of loss ⟶ more conservative bound
- 0.13% limit is not a drastic improvement over an earlier 4% limit

Energy Loss Mechanism	Energy Loss [MeV]		
	50 GeV	61 GeV	80 GeV
Offsets in quads ($\Delta U_{E_b} + \Delta U_{quad}$)	-0.1	-0.3	-0.9
Closed orbit distortions (ΔU_{closed})	0.1	0.2	0.6
Beam size (ΔU_{σ})	0.1	0.3	1.7
Parasitic mode losses (ΔU_{PML})	1.1	1.1	1.0
Correctors (ΔU_{cor})	0.1	0.1	0.3
Total correction ($\sum \Delta U$)	1.3	1.4	2.7

Paper Impact

- No more than 9 citations
- Testing well-accepted assumptions, while important, is not “profitable.”

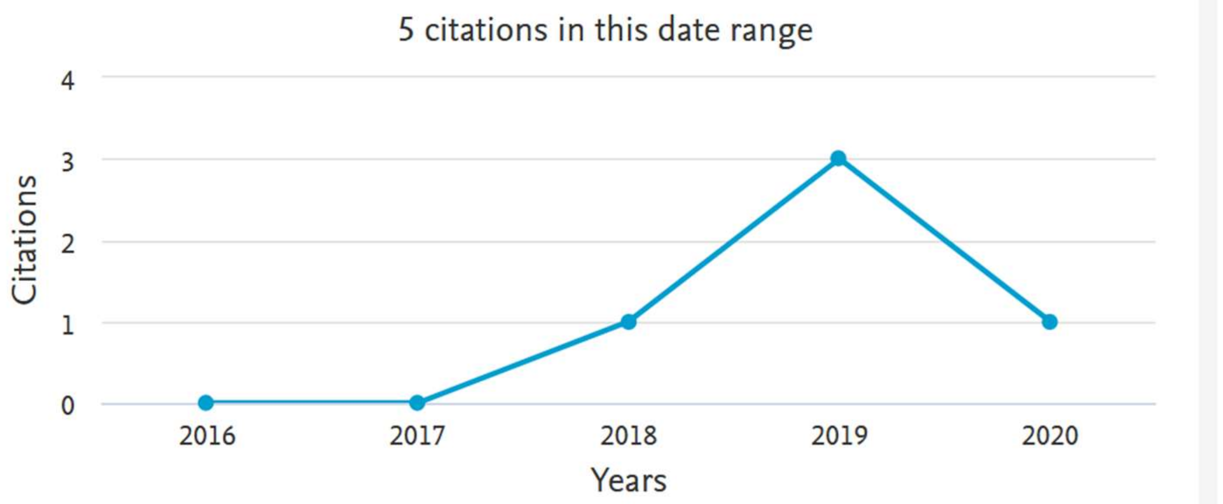
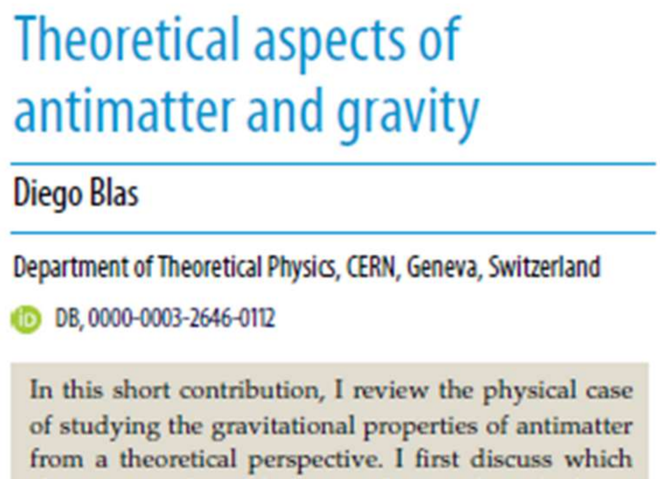


Image source: Scopus

Paper Impact

- Antigravity-theory review articles
  - *Theoretical aspects of antimatter and gravity*, Diego Blas
  - *Tests of discrete symmetries*, M. S. Sozzi
- “Extended Space Model”
  - Proposed by Dmitry Tsipenyuk


Theoretical aspects of antimatter and gravity

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In this short contribution, I review the physical case of studying the gravitational properties of antimatter from a theoretical perspective. I first discuss which

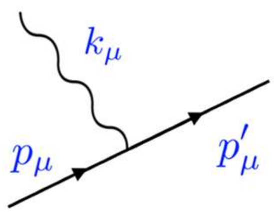
Future Outlook

- At the moment, there is considerable interest in the possibility that Lorentz and CPT may not be exact symmetries of nature (eg. Hořava–Lifshitz gravity).
- If this is so, then there should be weak signatures of this effect in the effective theories governing low-energy phenomena.
- WEP violation would constitute one such signature but there may be others.

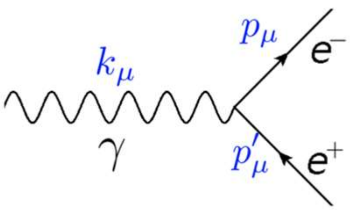
Future Outlook

doi:10.1088/1742-6596/761/1/012035

- There is a low-energy effective theory, known as the standard model extension (SME) which contains all possible Lorentz and CPT violating corrections to the standard model and general relativity.
- SME allows for many interactions that are prohibited in SM.



Vacuum Cherenkov radiation



Photon Decay

Future Outlook

- The version of SME considered by Kalaydzhyan contains only a single independent lorentz violating parameter (the anomalous redshift) which causes anti-matter to couple to gravity non-universally.
- Experimentally placing bounds on these lorentz violating parameters would provide more robust tests of Lorentz and CPT invariance and could potentially lead to new physics.

Conclusion

- Despite its long history, the gravitational properties of antimatter have not been well tested.
- Long-term variation in synchrotron energy losses constrains Weak Equivalence Principle violations.
- Kalaydzhyan’s paper establishes an upper bound of 0.13% on the deviation of the inertial and gravitational masses of the positron.