Experimental hint for gravitational CP violation

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An equality of particle and antiparticle gravitational interactions holds in general relativity and is supported by indirect observations. Gravity dependence on rotation or spin direction is experimentally constrained only at low energies. Here a method based on high energy Compton scattering is developed to measure the gravitational interaction of accelerated charged particles. Within that formalism the Compton spectra measured at HERA rule out the positron's anti-gravity and hint for a gravitational CP violation around 13 GeV energies, at a maximal level of $1.3 \pm 0.2\%$ for the charge and $0.68 \pm 0.09\%$ for the space parity. A stronger gravitational coupling to left helicity electrons relative to right helicity positrons is detected.

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INTRODUCTION

The weakness of gravitation at sub-atomic scales makes it the least experimentally investigated interaction among the fundamental forces of nature. Any test with a single carrier of the gravitational force, hypothetical graviton, is unfeasible whereas in the electroweak or strong interactions experimental results with a photon, W, Z boson or a gluon are readily available at sufficiently high energies. The weak gravity combined with a rarity and vulnerability of antiparticles drives any attempt of testing the antimatter gravitation to its technical limits. Einstein's general relativity [1], the currently accepted theory of gravitation, does not distinguish between particles and antiparticles or their properties such as spin or helicity. The general relativity is based on universality of gravity and equivalence principle, and, there is no alternative theory available to predict or describe violations of these principles in a consistent way. Departures from perfect spin or particle-antiparticle symmetry are allowed in some quantum gravitation scenarios [2]. Hence, observations of antiparticle gravitation could serve as an experimental input for quantum gravity [3]. Additional motivations for such investigation are the still unexplained matter-dominant universe [4] and the connection of antimatter's possible anti-gravity [5] to the accelerated expansion of the universe [6]. One can also think about a possible particle-antiparticle gravitational asymmetry and helicity dependence from an analogy to electroweak interactions, where a photon's massive partners, W and Z bosons, are considered responsible for space and charge parity violations [7]. Thus, possible massive or lower spin gravitons could introduce similar violations [8] that may remain hidden at low energies and will become detectable at high energies.

Another possibility to incorporate asymmetric space or charge gravitational interactions is a modification of vacuum properties described within the Standard Model Extension (SME) [9] by Lorentz violating terms in Lagrangian. Such action based approach is further developed for anomalous antimatter gravity in [10].

Indirect observations of matter-antimatter gravitational asymmetry involve nuclei with different content of quark-antiquarks in the equivalence principle Eötvös type experiments [11, 12]. Using CPT conservation the observed stringent limits for the equivalence principle violating matter could be expanded to a limit below 10^{-7} for the matter-antimatter low energy gravitational asymmetry [13]. Hughes and Holzscheiter have set limits on the matter-antimatter gravitational differencies from an equality of particle-antiparticle cyclotron frequencies [14]. As the source of gravitation, however, they have used the potential of the local supercluster while for the Earth's potential the derived restrictions are completely lifted. Technical difficulties for charged antiparticle's gravitational coupling direct measurements turned physicists' attention to neutral antimatter tests [15–17] which may deliver conclusive results soon. The ongoing experiments, however, are still at low energy, and massive gravitons' interactions may remain unseen.

Spin dependent gravitation (for a review see [18]) motivated by Lorentz violation [19], torsion gravity [20], exchange of pseudoscalar bosons [21] or few other hypothesis has been constrained by low energy spin-polarized experiments, such as the test with polarized torsion pendulum [22]. Here also the high energy could reveal gravitation's preference for a helicity which is hidden at low energies.

In this Letter I will demonstrate an extreme sensitivity of a high energy process - laser Compton scattering - to an antiparticle's hypothetical anti-gravity and gravitational charge and space parity violation. Next, applying the developed formalism to the existing data of the HERA Compton polarimeter, I will compare the γ-spectra generated by electrons and positrons to measure the charge and spin asymmetry for their gravitational interaction. Systematic effects and prospects for other tests will be discussed at the end.

GRAVITY INTRODUCED REFRACTION

In an earlier publication, high energy Compton scattering sensitivity has been shown to a Planck scale dispersive and birefringent vacuum model [23]. Subsequently, I applied the same formalism to the Earth's gravity assuming the real gravitational field induced refractivity only for the Compton photons [24]. The refraction, however, also affects the leptons involved in the scattering [25] in agreement with the equivalence principle. This makes the ref. [24] conclusions about the general relativity violation invalid [26].

Here I follow the formalism developed by Evans et al. [25] to find a massive particle's energy-momentum or refraction relation in a static and isotropic gravitational field described by the Schwarzschild metric. Combining the Eq.(3) and Eq.(30) from the reference [25], for the Earth's weak field, one can derive a refraction relation

$$\frac{P}{\mathcal{E}} = \beta + \frac{2GM_{\oplus}}{R_{\oplus}}, \tag{1}$$

where G is the gravitational constant and $\mathcal{E}, P, \beta$ are energy, momentum, velocity of the particle ($c = 1$ is assumed throughout the Letter). This relation is also valid for massless particles. Indeed, at $\beta = 1$ it describes the photon refraction in a gravitational field in a form derived by many authors; see ref. [27] and references therein, or for a more recent reference, see ref. [28]. In Eq.(1) the $M_{\oplus}$ and $R_{\oplus}$ are the Earth's mass and the mean radius respectively so, that the second term is a scaled gravitational potential of the Earth. Choice of such potential is required for describing processes in a laboratory reference frame attached to the Earth and, there is no need to consider gravitational potentials imposed by the Sun, Galaxy or the Universe. For instance, the Eq.(1) alone is sufficient to derive gravitational light deflection trajectory relative to the (Earth) laboratory while adding the Sun's or the Galaxy's potential will describe the light trajectory relative to the Sun or to the Galaxy respectively.

To allow departure from the equivalence principle let us retain the interaction strength G for matter particles and use a different strength G_p for antimatter leptons to write Eq.(1) for positrons in the following form

$$\frac{P}{\mathcal{E}} = \beta + \frac{2GM_{\oplus}}{R_{\oplus}}\left(1 + \frac{\Delta G}{G}\right), \tag{2}$$

with $\Delta G = G_p - G$. For an anti-gravitating positron $G_p = -G$.

In a similar manner, within the spin affected gravitation, we can assign an interaction constant G_- to particles possessing a negative(left) helicity and modify the Eq.(1) to include a helicity dependent term $\Delta G_- = G_- - G$

$$\frac{P}{\mathcal{E}} = \beta + \frac{2GM_{\oplus}}{R_{\oplus}}\left(1 + \frac{\Delta G_-}{G}\right), \tag{3}$$

with the G assigned to unpolarized (helicity=0) particles.

Anomalous dispersion or refraction relations similar to the Eq.(2) or Eq.(3) are often applied for vacuum, within the context of action based Lorentz violation [29, 30]. Such models have an advantage to access modified dynamic properties (cross-sections) of considered processes though stringent observational and experimental limits, in particular from a Compton scattering test [32], exist for Lorentz violating vacuum [31].

Here we limit ourselves exceptionally with kinematics in a real gravitational field to investigate how the hypothetical refractions by Eq.(2) and Eq.(3) are affecting the high energy laser Compton process.

THE COMPTON PROCESS AFFECTED BY GRAVITY

Using energy-momentum conservation with Eq.(1) and Eq.(2), when in the Earth's gravitational field a photon scatters off a positron with energy $\mathcal{E}$, the Compton scattering kinematics is given by

$$\mathcal{E}x - \omega(1 + x + \gamma^2\theta^2) - 4\omega\left(1 - \frac{\omega}{\mathcal{E}}\right)\gamma^2\frac{M_{\oplus}}{R_{\oplus}}\Delta G = 0, \tag{4}$$

where $x = 4\gamma\omega_0 \sin^2(\theta_0/2)/m$, with m and $\gamma = \mathcal{E}/m$ being the mass and Lorentz factor of the initial positron, respectively. The initial photon's energy and angle are denoted by ω_0 and θ_0, while the refraction of Eq.(1) is in effect for the scattered photon with energy ω and angle θ; the angles are defined relative to the initial positron. This kinematic expression is derived for weak gravity and high energies, i.e., the $\mathcal{O}((GM_{\oplus}/R_{\oplus})^2)$, $\mathcal{O}(\theta^3)$, and $\mathcal{O}(\gamma^{-3})$ terms are neglected. In this approximation the refraction effect of Eq.(1) for the initial laser photon is negligible. For the initial and scattered positrons the refraction of Eq.(2) is applied. To determine the outgoing photon's maximal energy, Eq.(4) is solved for ω at $\theta = 0$ with the following result:

$$\omega_{max} = \mathcal{E}\ \frac{b + q - \sqrt{b^2 + q(q - 2b + 4)}}{2\,q}, \tag{5}$$

where $b = 1 + x$ and $q = 2\gamma^2 M_{\oplus}\Delta G/R_{\oplus}$. Thus, in high energy Compton scattering the factor ΔG is amplified by γ^2, allowing one to measure it by detecting the extreme energy of the scattered photons ω_{max}, or positrons $\mathcal{E} - \omega_{max}$ (Compton edge).

In order to estimate the method's sensitivity, I calculate the Compton edge from the Eq.(5) for an incident photon energy 2.32 eV (the widely popular green laser) at different energies of the accelerator leptons. The resulting dependencies for a matter (electron) gravity and antimatter (positron) anti-gravity are presented in Fig. 1. The plot shows considerable sensitivity, which grows toward high energies in a range available to accelerating

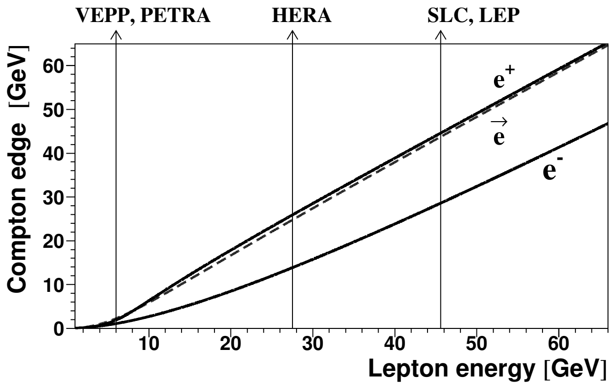

FIG. 1. The maximal energy of Compton scattered photons (Compton edge) and its dependence on the initial lepton energy for a head-on collision with 532nm laser light. Solid lines correspond to matter gravity (e^-, electron, G) and antimatter anti-gravity (e^+, positron, $-G$). The dotted line corresponds to a negative helicity secondary lepton sterile to gravity ($\vec{e}$, $G_- = 0$). Names of e^+e^- accelerators are printed at the upper part.

laboratories. For handling measurement's systematic errors, from an experimental point of view, it is more precise to measure a relative asymmetry rather than absolute Compton edge energy. Therefore, we form an asymmetry of Compton edges measured on positrons (ω^p_{max}) and electrons (ω^e_{max})

$$A = \frac{\omega^p_{max} - \omega^e_{max}}{\omega^p_{max} + \omega^e_{max}} \qquad (6)$$

and use Eq.(4) to find the charge parity gravitational violation magnitude

$$\frac{\Delta G}{G} = \frac{2A(1-A)(1+x)^2}{(1+A)(2Ax+A-1)}\left(4\gamma^2\frac{GM_\oplus}{R_\oplus}\right)^{-1}. \qquad (7)$$

For evaluating a sensitivity of the laser Compton process to the spin dependent Earth's gravitation let's investigate a left helicity photon scattering on an unpolarized (helicity=0) lepton. According to helicity conservation the scattered photon and lepton at the Compton edge energies will retain the helicity of the initial photon [33]. Hence we apply the helicity modified refraction relation of Eq.(3) to the initial and final photons as well as to the scattered lepton, reserving the refraction of Eq.(1) for the initial lepton. This modifications will bring the Eq.(5), Eq.(7) for the charge parity case to

$$\omega^-_{max} = \mathcal{E}\ \frac{x_-}{1+x_-}, \qquad (8)$$

with $x_- = x + 2\gamma^2 M_\oplus \Delta G_-/R_\oplus$, and, with a measured asymmetry
$A_- = (\omega^-_{max} - \omega^0_{max})/(\omega^-_{max} + \omega^0_{max})$, to

$$\frac{\Delta G_-}{G} = -\frac{A_- x(1+x)}{2A_- x + A_- - 1}\left(2\gamma^2\frac{GM_\oplus}{R_\oplus}\right)^{-1}, \qquad (9)$$

for the space parity case. Energy dependence of Eq.(8), if the gravity attracts only right helicity particles, is plotted on the Fig. 1. From the plot and formulas we can conclude that Compton process sensitivity to the gravitational space parity violation is sufficient for introducing a Compton edge sizable shift in a scenario of the Earth's helicity dependent gravitational field.

EXPERIMENTAL RESULTS

The high-energy accelerators where laser Compton facilities have been operated for years, are listed on the upper energy scale of Fig. 1. As can be seen from the plot, 6 GeV storage rings have low sensitivity while the higher energy colliders (HERA, SLC, LEP) have a great potential for detecting gravity related energy shifts. This is true for the HERA and SLC Compton polarimeters but not for the LEP polarimeter, which has generated and registered many photons per machine pulse [34]. In this multi-photon regime, any shift of the Compton edge is convoluted with the laser-electron luminosity and can-not be disentangled and measured separately. Unlike the LEP, the SLC polarimeter operated in multi-electron mode and analyzed the energies of interacted leptons using a magnetic spectrometer [35]. However, at SLC only the electron beam was polarized, and positron data are missing. Hence, we turn to HERA, which has recorded Compton measurements for both the electrons and the positrons. At the HERA transverse polarimeter Compton photons are registered by a calorimeter in single particle counting mode. A recorded Compton spectrum produced by 514.5nm laser scattering on 26.5 *GeV* electrons, from ref.[36], is shown in Fig. 2 superimposed on a

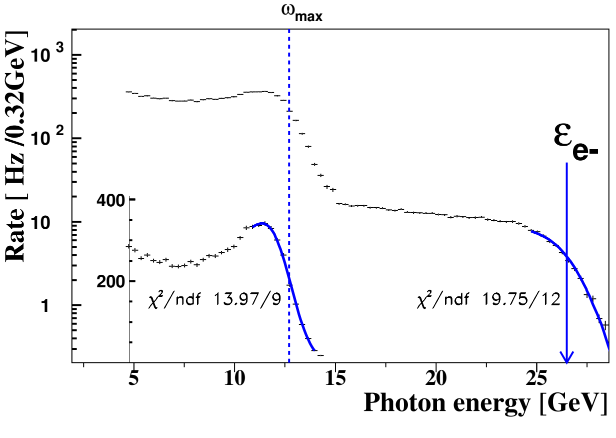

FIG. 2. HERA polarimeter Compton γ-spectrum produced by laser scattering on 26.5 *GeV* electrons, on top of background Bremsstrahlung with fit results. The inset displays the background subtracted Compton spectrum. Vertical lines show measured values of the Compton (ω_{max}) and Bremsstrahlung ($\mathcal{E}_{e-}$) maximal energies.

background Bremsstrahlung distribution. In contrast to Compton scattering, in the Bremsstrahlung process the momentum transfer is not fixed, and any small refractive effect is smeared out and becomes negligible [37]. Hence, following the analysis in ref. [37], I calibrate the energy scale according to the maximal Bremsstrahlung energy which is found by fitting a convolution of parent energy distribution $d\Sigma/d\omega$ with the detector response gaussian function,

$$F(E_\gamma) = N \int_0^{E_m} \frac{d\Sigma}{d\omega} \frac{1}{\sqrt{\omega}} \exp\left(\frac{-(\omega - E_\gamma)^2}{2\sigma_0^2 \omega} \right) d\omega, \quad (10)$$

to the Bremsstrahlung spectrum. σ_0 and E_γ in the fitting function denote the calorimeter resolution and detected photon's energy respectively while the normalizing factor N and maximal energy E_m are free fitting parameters. The same fitting function with the Bremsstrahlung parent distribution replaced by the Compton scattering differential cross-section $d\Sigma_C/d\omega$ is applied to the background subtracted spectrum to find the Compton edge at $\omega_{max}^{e0} = 12.70 \pm 0.02$ GeV. Here the upper indexes denote (scattered) lepton type, helicity and the 0 stands for a spectrum summed over the laser left and right helicities. The fit results together with fit quality estimates are shown in Fig. 2. The absolute value of the Compton edge is calculated from 3 measurements – Bremsstrahlung and Compton edges B_{max} and C_{max} in ADC units, and electron beam energy E_{beam} in GeV – by a formula $\omega_{max} = E_{beam} C_{max}/B_{max}$. More details about the analysis and experimental setup can be found in the ref. [37].

The same analysis procedure is applied to a HERA polarimeter Compton spectrum that was generated with left helicity photons scattered on 27.5 *GeV* positrons and has been reproduced in Fig. 8 of ref. [38]. As it mentioned above, left helicity laser photons are generating the same (negative) helicity scattered positrons at the Compton edge (ω_{max}^{p-}). The resulting plots with fit quality outcomes are displayed in Fig. 3. Comparing the obtained Compton edge $\omega_{max}^{p-} = 13.80 \pm 0.02$ GeV with the photons' maximal energy for the anti-gravitating positrons 25.9 GeV, derived from Eq.(5), one can conclude without any advanced systematic error analysis that anti-gravity for the positrons is ruled out.

Using only the quoted statistical errors for the ω_{max}^{e0}, ω_{max}^{p-} we obtain a positron-electron and negatve-zero helicity Compton edge asymmetry $A_{ep0-} = 0.01297 \pm 0.0013$. In order to account for the different energies of accelerated electrons and positrons 26.5 and 27.5 GeV, the measured maximal energies in the asymmetry calculation have been normalized to 13.10 and 13.87 GeV for the electrons and positrons, respectively. These are the expected Compton edge values from Eq.(5) or Eq.(8) in the absence of gravitational anomaly, at $\Delta G = 0$ or $\Delta G_- = 0$ respectively.

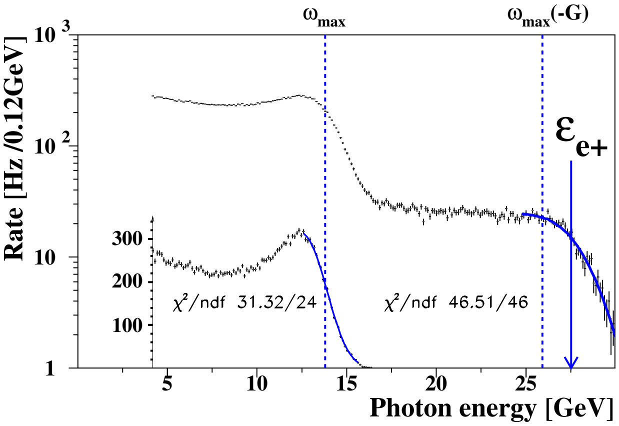

FIG. 3. A similar plot to Fig. 2 for positrons with energy 27.5 *GeV*. The Compton edge energy for anti-gravitating positrons is indicated by a vertical line $\omega_{max}(-G)$.

Since the spectra for electrons and positrons are detected with the same experimental setup, i.e. with the same laser, geometry and detector, both measurements will experience the same systematic influences that will cancel out or reduce greatly in the asymmetry of Eq.(6). Hence, we omit systematic corrections with associated errors applied to polarization or energy measurements (as described in the refs. [36–38]), in order to analyze instrumental errors specific to the detected asymmetry which we rewrite in a more convenient form:

$$A_{ep0-} = \frac{\eta_p x_e(1 + x_p) - \eta_e x_p(1 + x_e)}{\eta_p x_e(1 + x_p) + \eta_e x_p(1 + x_e)}, \quad (11)$$

where $\eta = C_{max}/B_{max}$ is a ratio of the measured Compton and Bremsstrahlung edges, x is the kinematic factor with indexes e and p denoting the measurement with electrons and positrons respectively. Uncertainty of the factor $x_{e,p} = 4\mathcal{E}_{e,p}\omega_0 \sin^2(\theta_0/2)/m^2$ is dominated by the lepton beam energy spread while contribution of the other constituents is negligible: $\sigma(\omega_0)/\omega_0 \approx 10^{-5}$, $\sigma(m)/m \approx 3 \cdot 10^{-7}$, $\Delta(\theta_0) \approx 2\ mrad \Rightarrow \Delta \sin^2(\theta_0/2) \approx 3 \cdot 10^{-6}$. Therefore, HERA leptons' energy spread $\sigma(\mathcal{E})/\mathcal{E} \approx 10^{-3}$ will introduce a systematic uncertainty 0.054% to the measured asymmetry. Since the electron and positron measurements are considerably separated in time, one of important potential sources for a false asymmetry could be detector aging and degraded performance. This assumption could be checked by measuring the calorimeter resolution from the spectra edges' slops - the same energy resolution $\sigma_0 = 0.24$ for both spectra indicates the same, non-degraded, response of the calorimeter. A major energy correction factor, detector non-linearity, applied to each measured Compton edge will largely cancel in the asymmetry. However, assuming a possible change of detector's linearity we apply a non-linearity correction (as described in ref. [37]) which will scale the ratio

$\eta \to \eta(1+f\mathcal{E}(1-\eta))$ with a factor $f = 0.001GeV^{-1}$. Limiting the possible change of non-linearity factor to 10%, from error propagation in the Eq.(11), we derive an associated conservative systematic uncertainty of 0.096% for the asymmetry which is affected negligibly by the correction. Other minor instrumental false asymmetry sources are electronic pedestal offsets, estimated to be $\pm 4MeV$ with $\approx 0.03\%$ contribution to asymmetry and luminosity dependent pile-up photons. The latter amounts to 0.02 and 0.0015 photons/bunch for the electrons and positrons respectively, and, in our case, will tend to reduce any true asymmetry so, it can't be responsible for the observed effect. An ignorable, about the order of m, contribution to electron-positron asymmetry is coming from Bremsstrahlung edge charge dependence. With a quadratic sum of the estimated systematic and statistical errors the measured asymmetry and its error become

$$A_{ep0-} = 1.293 \pm 0.169\%, \tag{12}$$

which differs from zero within more than 7σ confidence.

Separate contributions of the gravitational charge and space parity violations can't be derived from this asymmetry alone. Instead one can assume space P parity conservation and calculate maximally possible electron-positron charge C parity violation by inserting the observed asymmetry into Eq.(7):

$$\frac{\Delta G}{G} = -1.32 \pm 0.17\%. \tag{13}$$

In a similar way, within a perfect C parity conservation one will have maximal P parity violation magnitude using Eq.(9):

$$\frac{\Delta G_-}{G} = 0.68 \pm 0.093\%. \tag{14}$$

In a general case of C&P violation the C and P symmetries are violated to lesser degrees. Obtained signs of violations correspond to a stronger gravitational coupling for the left helicity electrons relative to the right helicity positrons.

The resulting numbers are derived assuming a massive, limited-range interaction carrier and using Earth's potential $GM_\oplus/R_\oplus = 6.9 \cdot 10^{-10}$. In case the gravitational CP symmetry is violated by a massless particle one should consider the local supercluster's potential $3 \cdot 10^{-5}$ which is the largest potential at the Earth's surface [14]. Putting this potential in Eq.(7) and Eq.(9) one obtains $(-3.0 \pm 0.4) \cdot 10^{-7}$ and $(1.6 \pm 0.2) \cdot 10^{-7}$ for the C and P violations in Eq.(13) and Eq.(14) respectively.

CONCLUSIONS

Applying a gravitational field-induced refraction and assuming an equivalence principle violation in a general form $\Delta G/G$ for positrons and $\Delta G_-/G$ for helicty, an outstanding sensitivity has been demonstrated for the high energy Compton scattering to such gravitational anomaly. Within the developed formalism, the HERA Compton polarimeter's recorded spectra with electrons and positrons strongly disfavor the positron's anti-gravity and show a significant deviation of the $\Delta G/G$ or $\Delta G_-/G$ from zero. The last claim is based on a detected 1.3% energy asymmetry, which is a large number compared to the laser and lepton beam energy relative uncertainty of 10^{-5} and 10^{-3}, respectively. The remaining source of a possible systematic energy error is the detector that is greatly eliminated from final result by using the asymmetry instead of absolute energy measurements. However, additional uncorrelated systematic errors may impair the outcome and, claiming a definite observation of CP parity violation at high energy gravitational interactions would require the following:

– a thorough analysis of many Compton spectra accumulated and recorded by the HERA during its running period;

– elimination of possible electroweak sources that can mimic such result;

– experimental verification at other accelerators.

In the absence of these, the measured electron-positron asymmetry can only be considered as a hint for the gravitational symmetry breaking and an invitation for further studies. New experiments, however, will require future e^-e^+ machines with sufficiently high γ or a precise setup on the currently running 6 GeV accelerator PETRA-III with the highest positron energy available. Anyway, it is worth the efforts since high energy violation of the equivalence principle and gravitational CP parity could reveal an interaction to massive or lower spin gravitons with a possible relation to dark matter or energy.

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