Probing Positron Gravitation at HERA

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An equality of particle and antiparticle gravitational interactions holds in general relativity and is supported by indirect observations. Here I develop a method based on high energy Compton scattering 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 positron's 1.3(0.2)% weaker coupling to the gravitational field relative to an electron.

PACS numbers: 04.80.Cc, 14.60.Cd, 29.27.-a

INTRODUCTION

The weakness of gravitation makes it the least experimentally investigated interaction among the fundamental forces of nature. 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. Strictly speaking, general relativity deals only with masses and light, leaving gravitational interaction of particles, antiparticles, or photons to be established in quantum gravity theory [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 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.

Indirect observations of matter-antimatter gravitational asymmetry involve nuclei with different content of quark-antiquarks in the equivalence principle Eötvös type experiments [9, 10]. 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 [11]. Technical difficulties for charged antiparticle's gravitational coupling direct measurements turned physicists' attention to neutral antimatter tests [12–14] which may deliver conclusive results soon. The ongoing experiments, however, are still at low energy, and massive gravitons' interactions may remain unseen.

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 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 asymmetry for their gravitational interaction. Systematic effects and prospects for other tests will be discussed at the end.

GRAVITY INTRODUCED DISPERSION

In an earlier publication, high energy Compton scattering sensitivity has been shown to a Planck scale refractive and birefringent vacuum model [15]. Subsequently, I applied the same formalism to the Earth's gravity assuming the real gravitational field induced dispersion only for the Compton photons [16]. The dispersion, however, also affects the leptons involved in the scattering [17] in agreement with the equivalence principle. This makes the ref. [16] conclusions about the general relativity violation invalid [18].

Here I follow the formalism developed by Evans et al. [17] to find a massive particle's energy-momentum or dispersion relation in a static and isotropic gravitational field described by the Schwarzschild metric. Combining the Eq.(3) and Eq.(30) from the reference [17], for the Earth's weak field, one can derive a dispersion 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. [19] and references therein, or for a more recent reference, see ref. [20].

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 $G_p = -G$.

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

$$\mathcal{E}x - \omega(1 + x + \gamma^2\theta^2) + 4\omega\left(1 - \frac{\omega}{\mathcal{E}}\right)\gamma^2\frac{M_\oplus}{R_\oplus}\Delta G = 0, \quad (3)$$

where $x = 4\gamma\omega_0 \sin^2(\theta_0/2)/m$, with γ and m being the Lorentz factor and mass of the initial positron, respectively. The initial photon's energy and angle are denoted by ω_0 and θ_0, while the dispersion 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. To determine the outgoing photon's maximal energy, Eq.(3) is solved for ω at $\theta = 0$ with the following result:

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

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 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 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})

$$A = \frac{\omega^p_{max} - \omega^e_{max}}{\omega^p_{max} + \omega^e_{max}} \quad (5)$$

and use Eq.(3) to find the charge parity gravitational violation magnitude

$$\frac{\Delta G}{G} = \frac{2A(1 - A)(1 + x)^2}{(1 + A)(2Ax + A - 1)}\left(4\gamma^2\frac{GM_\oplus}{R_\oplus}\right)^{-1}. \quad (6)$$

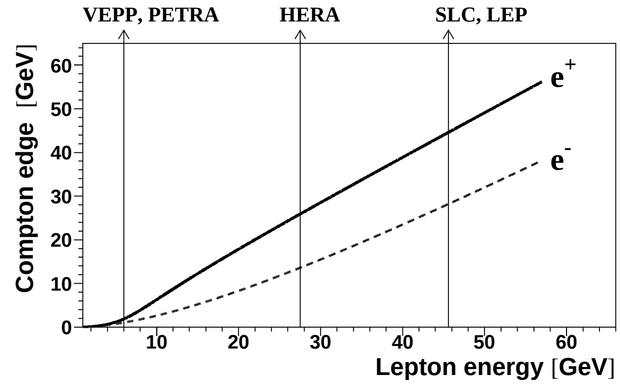

FIG. 1. The maximal energy of Compton scattered photons (Compton edge) and its dependence on the initial lepton energy for a head-on collision with 532nm laser light. Solid and dotted lines correspond to matter gravity (electron, G) and antimatter anti-gravity (positron, -G) respectively. Names of e^+e^- accelerators are printed at the upper part.

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 [21]. 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 [22]. However, at SLC only the electron beam was polarized, and positron data are missing. Hence, we turn to HERA, which have 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.[23], is shown in Fig. 2 superimposed on a background Bremsstrahlung distribution. In contrast to Compton scattering, in the Bremsstrahlung process the momentum transfer is not fixed, and any small dispersive effect is smeared out and becomes negligible [24]. Hence, following the analysis in ref. [24], 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

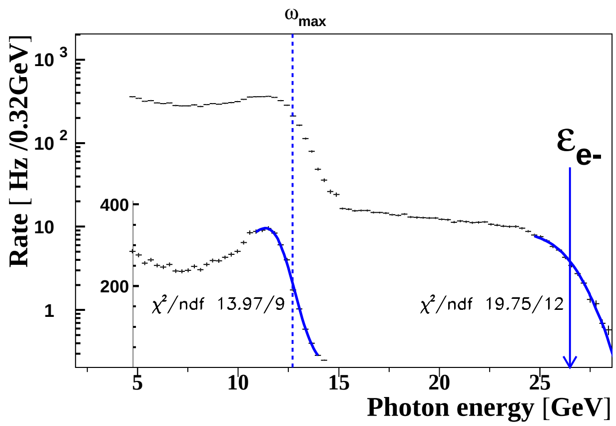

FIG. 2. HERA polarimeter Compton γ-spectrum produced by laser scattering on 26.5 GeV electrons, on top of background Bremsstrahlung with fit results. The inset displays the background subtracted Compton spectrum. Vertical lines show measured values of the Compton (ω_{max}) and Bremsstrahlung ($\mathcal{E}_{e-}$)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

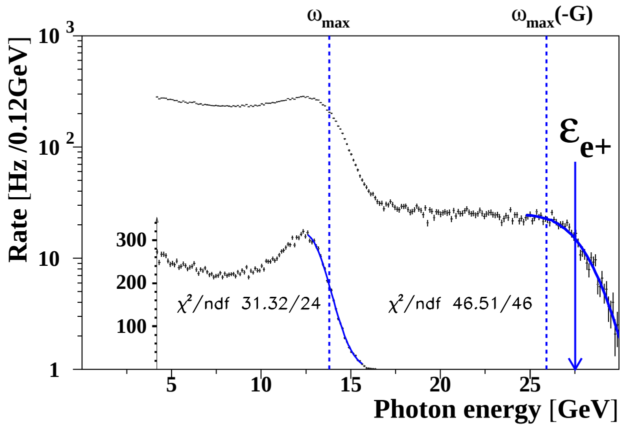

FIG. 3. A similar plot to Fig. 2 for positrons with energy 27.5 GeV. The Compton edge energy for anti-gravitating positrons is indicated by a vertical line $\omega_{max}(-G)$.

function,

$$F(E_\gamma) = N \int_0^{E_m} \frac{d\Sigma}{d\omega} \frac{1}{\sqrt{\omega}} \exp\left(\frac{-(\omega - E_\gamma)^2}{2\sigma_0^2 \omega} \right) d\omega, \quad (7)$$

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 $\omega^e_{max} = 12.70 \pm 0.02$ GeV. The fit results together with fit quality estimates are shown in Fig. 2. More details about the analysis and experimental setup can be found in the ref. [24].

The same analysis procedure is applied to a HERA polarimeter Compton spectrum that was generated with 27.5 GeV positrons and has been reproduced in Fig. 8 of ref. [25]. The resulting plots with fit quality outcomes are displayed in Fig. 3. Comparing the obtained Compton edge $\omega^p_{max} = 13.80 \pm 0.02$ GeV with the photons' maximal energy for the anti-gravitating positrons 25.9 GeV, derived from Eq.(4), one can conclude without any advanced systematic error analysis that anti-gravity for the positrons is ruled out.

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.(5). Hence, we omit systematic corrections or errors described in the refs. [23–25] and use only the quoted statistical errors for the ω^e_{max}, ω^p_{max} to obtain a positron-electron Compton edge asymmetry $A = 0.01297 \pm 0.00147$.

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 13.80 GeV for the electrons and positrons, respectively. These are the expected Compton edge values from Eq.(4) in the absence of gravitational anomaly, at $\Delta G = 0$. Normalization uncertainty associated with the laser and lepton beam energy spread is included in the asymmetry error.

Inserting the asymmetry into Eq.(6), we obtain a measured charge parity gravitational violation value

$$\frac{\Delta G}{G} = -0.0133 \pm 0.0015, \quad (8)$$

which differs from zero within a 9σ confidence. The obtained negative sign corresponds to a weaker gravitational coupling for the positrons relative to the electrons.

CONCLUSIONS

Applying a gravitational field-induced dispersion and assuming an equivalence principle violation in a general form $\Delta G/G$ for positrons, 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 $\Delta G/G$ 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 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 charge 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 could only be called 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 charge parity could reveal an interaction to massive or lower spin gravitons with a possible relation to dark matter or energy.

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* vahagn.gharibyan@desy.de; I thank B. Sobloher and S. Schmitt for providing details about the positron generated spectra, and R. Brinkmann for details about the electron measurement and the HERA. I'm thankful also to A. Buniatyan and K. Balewski for useful discussions.

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