Accelerator experiments contradicting general relativity

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The deflection of gamma-rays in Earth's gravitational field is tested in laser Compton scattering at high energy accelerators. Within a formalism connecting the bending angle to the photon's momentum it follows that detected gamma-ray spectra are inconsistent with a deflection magnitude of 2.78 nrad, predicted by Einstein's gravity theory. Moreover, preliminary results for 13–28 GeV photons from two different laboratories show opposite – away from the Earth – deflection, amounting to 33.8–0.8 prad. I conclude that general relativity, which describes gravity at low energies precisely, break down at high energies.

PACS numbers: 04.80.Cc, 04.20.-q, 29.27.-a

Introduction.— Einstein's general relativity (GR) [1] is the currently established theory of gravitation and has been confirmed in all observations and experiments to date [2]. An essential validity check of GR is based on gravitational light bending. These deflection measurements, which were started by a spectacular observation of starlight deflection during a solar eclipse about a century ago [3], have been expanded to radio-waves and have become very precise [4]. The most accurate measurements are performed using the gravitational field of the Sun [5], as the bending increases with mass. The results prove that electromagnetic radiation, from radio to visible light frequencies, is bent according to GR and follows the curvature of space [6]. On a scale of less massive objects, the light bending strength of the planet Jupiter has also been tested and quantified [7]. For the Earth, however, a check of gravitational bending remains infeasible because of the smallness of the expected deflection, about 3 nrad (compared with more than 8 μrad for the Sun). The quoted numbers follow from the well-known expression $4GM/c^2R$ for the deflection angle [8], when light travels near a mass M with an impact parameter R (higher-order terms of deflection are neglected throughout the Letter). For a light ray grazing the Earth's surface, the total deflection angle is

$$\frac{4GM_\oplus}{c^2R_\oplus} \approx 2.78 \times 10^{-9}, \tag{1}$$

where G is the gravitational constant and c is the speed of light. The bending magnitude for light generated and measured in a laboratory is much smaller and is equal to

$$\frac{2GM_\oplus}{c^2R_\oplus}\frac{L}{\sqrt{L^2+R_\oplus^2}}, \tag{2}$$

where L is the length of light travel [9]. Thus, for a distance of 1m, this angle is only 2×10^{-16}rad and the light shifts by 0.2 femtometer, which is undetectably small, at least for a direct measurement. A way to overcome this problem is described in ref. [10], which is based on the idea of slowing light down to $v \approx 100$m/s, in order to substitute c in Eq.(2) by v and increase the bending magnitude.

In this Letter, I describe a laboratory method that probes gravitational bending of high-energy photon beams.

Gravity as a bending medium.— Within the method I use an idea that gravitation for light is equivalent to an optical medium. This idea was suggested by Einstein and was employed by many authors; see ref. [11] and references therein. Felice [11] has proved that a GR curved space described by Riemannian geometry is identical to the language of classical optics in a flat space medium. The author, however, has warned that the optical description may be mathematically more complicated, although it could be beneficial for solving certain problems. The deflection of high-energy photons is one such problem. In a recent paper [12], the authors further developed an optical approach and suggested the following refractive index for a spherically symmetric gravitational field:

$$n = \exp\Big(\frac{2GM}{c^2R}\Big), \tag{3}$$

which, for the Earth's weak field, reduce to

$$n_\oplus = 1 + \frac{2GM_\oplus}{c^2R_\oplus}. \tag{4}$$

The latter expression has also been derived by other authors [13–15] and is equivalent to Eqs.(1) and (2) when one applies optical tracking with such a refractive index. The main difference between the gravitational "medium" presented by Eq.(4) and any material medium is the bending independence on frequency of light or photon energy, which is a consequence of the gravity geometrical interpretation or the curved space-time concept. It will help us to test the gravitational bending since scattering or interaction angles decrease toward high energies; at some energy, the angle will approach the magnitude of refractivity given in the Eq.(4), interfering with the gravity.

The Compton process in a gravitational field.— A proper process to explore is high-energy Compton scattering, which is sensitive to tiny deviations of the refractive index from unity, as described in ref. [16]. Using energy-momentum conservation, when at $n \approx 1$ a photon scatters off an electron with energy $\mathcal{E}$, the Compton scattering kinematics is given by

$$\mathcal{E}x - \omega(1 + x + \gamma^2\theta^2) + 2\omega\Big(1 - \frac{\omega}{\mathcal{E}}\Big)\gamma^2(n-1) = 0, \quad (5)$$

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 electron, respectively. The initial photon's energy and angle are denoted by ω_0 and θ_0, while the refractive index n is in effect for the scattered photon with energy ω and angle θ; the angles are defined relative to the initial electron. This kinematic expression is identical to Eq.(8) from ref. [16] and is derived for small refractivity and high energies, i.e., the $\mathcal{O}((n-1)^2)$, $\mathcal{O}(\theta^3)$, and $\mathcal{O}(\gamma^{-3})$ terms are neglected. To determine the outgoing photon's energy, I solve Eq.(5) for ω and, to leading order of $(n-1)$, I obtain:

$$\omega = \frac{\mathcal{E}x}{1 + x + \gamma^2\theta^2}\Big(1 + \frac{2\gamma^2(n-1)(1+\gamma^2\theta^2)}{(1+x+\gamma^2\theta^2)^2}\Big). \quad (6)$$

Writing this formula for the maximal energy of the scattered photons (Compton edge, at $\theta = 0$) in the Earth's gravitational field, I obtain:

$$\omega_{max} = \frac{\mathcal{E}x}{1+x}\Big(1 + \frac{2\gamma^2(n_\oplus - 1)}{(1+x)^2}\Big), \quad (7)$$

where the Earth's light bending refractivity $n_\oplus - 1$ is amplified by γ^2, allowing one measure it by detecting the extremal energy of the scattered photons ω_{max}, or electrons $\mathcal{E} - \omega_{max}$. 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 electrons. The resulting dependencies for a free space ($n = 1$) and the Earth's gravity-induced refractivity are presented in Fig. 1. The plot shows considerable sensitivity, which grows toward high energies in a range available to accelerating laboratories.

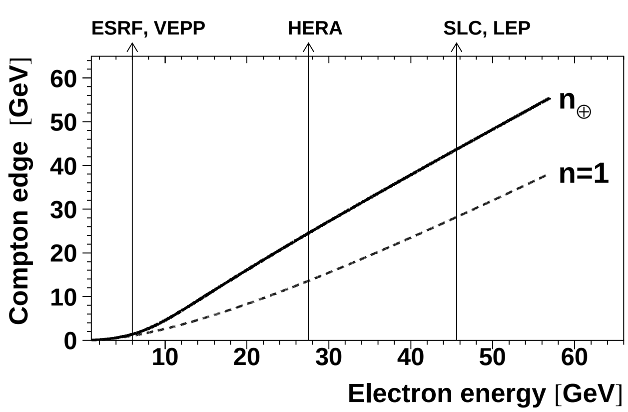

FIG. 1. Compton scattered photons' maximal energy (Compton edge) dependence on the initial electron energy for a head-on collision with 532nm laser light. Solid and dotted lines correspond to the refractive index of the gravitational field at the Earth's surface ($n_\oplus = 1 + 1.39 \times 10^{-9}$), and free space (n=1) respectively.

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 (ESRF and VEPP) have low sensitivity while the higher energy colliders (HERA, SLC, LEP) have a great potential for detecting the gravitational bending effect; see also Table I . Although all three machines are not operational anymore, one can analyze available data recorded by these accelerators where laser Compton setups were employed for polarimetry. Expected shifts of the maximal Compton energies are large and so prominent that they would not have been missed if this magnitude gravitational influence was present there. This is true for the HERA and SLC but not for the LEP Compton polarimeter, which has generated and registered many photons per machine pulse [17]. 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.

TABLE I. Sensitivity of different accelerators' Compton facilities to the Earth's gravitational field.

Accelerator	Electron energy GeV	Kinematic factor x	ω_{max} $n = 1$ GeV	ω_{max} $n = n_\oplus$ GeV	Shift by gravity GeV
ESRF, VEPP	6.0	0.21	1.05	1.39	0.34
HERA	26.5	0.98	13.1	23.4	10.3
SLC, LEP	45.6	1.62	28.2	43.7	15.5

Unlike the LEP, the SLC polarimeter has operated in multi-electron mode and has analyzed the energies of interacted electrons using a magnetic spectrometer [18]. The spectrometer converted energies to positions, which then were detected by an array of Cherenkov counters. The position-energy correspondence has been derived from the spectrometer magnetic field strength according to the following expression:

$$S_x = \frac{296.45\ GeV \cdot cm}{\mathcal{E}'} - 9.61\ cm\ , \quad (8)$$

where S_x is the position of the scattered electron with energy $\mathcal{E}' = \mathcal{E} - \omega$. The scaling factor is quoted from ref. [18] and the offset, which depends on the electron beam position at the laser-electron interaction point, corresponds to a calibration from ref. [19]. According to this relation, the SLC polarimeter's Compton edge electrons with 17.4 GeV energy will enter the detector at a position of 7.43cm. This is what has been measured with $200\mu m$ statistical accuracy by a kinematic endpoint scan and is presented in Fig. 3-9 of ref. [18]. Could it happen that these authors have measured the GR-supported value of 1.9 GeV (at $n = n_{\oplus}$ from table I) instead of 17.4 GeV? Eq. (8) tells us that the 1.9 GeV electrons will have a position of 146.4 cm at the detector location, inconsistent with what has been measured (7.43cm). Possible instrumental influence is limited to the initial electron beam position shift, less than 1 cm (to be contained in the accelerator's magnetic lattice [20]) and an estimated accuracy of the magnetic spectrometer, better than 2%. These factors add up to a maximum energy uncertainty or a possible offset of 1.4 GeV for the measured value of 17.4 GeV, reducing it to 16 GeV, which is still too high compared with the predicted value of 1.9 GeV. I therefor conclude that the SLC polarimeter data do not support GR gravitational bending.

At the HERA transverse polarimeter, Compton photons are registered by a calorimeter in single particle counting mode. A recorded Compton spectrum from ref.[21] is shown in Fig. 2 superimposed on a background Bremsstrahlung distribution. In contrast to the Compton

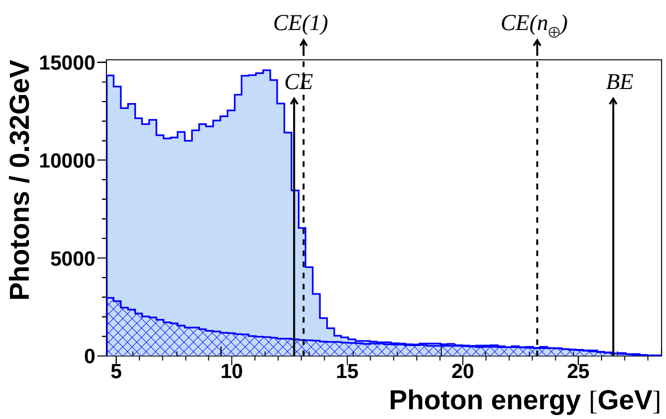

FIG. 2. HERA polarimeter Compton and Bremsstrahlung (hatched area) spectra. Vertical solid lines show measured positions of the Compton (CE) and Bremsstrahlung (BE) maximal energies. The dotted lines correspond to predicted Compton edge for free (CE(1)) and Earth's gravitational (CE($n_{\oplus}$)) space.

scattering, in the Bremsstrahlung process the momentum transfer is not fixed, and any small $n \neq 1$ effect is smeared out and becomes negligible [19]. Hence, following the analysis in ref. [19], I calibrate the energy scale according to the maximal Bremsstrahlung energy and show in Fig. 2 the free space- and GR-predicted Compton edge energies (from table I), relative to the Bremsstrahlung edge. Comparing a measured maximal Compton energy of 12.7 ± 0.1 GeV from ref. [19] with the GR expectation of 23.4 GeV reveals a huge difference that can not be explained by any one of the instrumental mis-measurement sources discussed in refs. [21] and [19] (or a total of these systematic uncertainties). Therefore, I have to conclude that the HERA Compton experiment rules out the GR prediction about gamma-ray bending.

From the SLC and HERA measurements and the derived or quoted numbers, it follows that both Compton facilities have a much higher sensitivity to the Earth's gravitational refractivity than that of the GR value in Eq. (4), $n_{\oplus} - 1 = 1.39 \times 10^{-9}$. Indeed, as reported in ref. [19], the anomalous refractivity equals $-(4.07 \pm 0.05) \times 10^{-13}$ for the SLC 16.3–28.3 GeV photons and $-(1.69 \pm 0.47) \times 10^{-11}$ for the HERA 12.7 GeV gamma-rays. At the time of the publication of ref. [19] and up until now, the source of this refractivity has remained unknown since possible contributions by a nonperfect machine vacuum, electromagnetic stray fields, or hypothetical vacuum polarizations [22–24] are negligibly small ($< 10^{-20}$). Now, in light of real gravitational field interpretations, the observed bending ability of the laboratory vacuum could be attributed to Earth's gravity as the most influental and likely source. Thus, combining the SLC and HERA results and multiplying by a factor of 2 to obtain the integral bending, one can state that 12.7–28.3 GeV gamma-rays are deflecting away from the Earth by 33.8–0.81×10^{-12}rad.

Conclusions.— In order to test the gravitational deflection of photons at the Earth, I first described GR light bending in equivalent, optical refractivity terms. Next, for the solution, I applied high-energy laser Compton scattering, which is extremely sensitive to any small refractivity due to its well-defined initial and final energy states and fixed momentum transfers. Finally, I explored available experimental records from the SLC and HERA Compton polarimeters, finding with high confidence that gamma-rays are not bending according to GR. The observed energy dependence of gravitational bending is incompatible with a curved space approach and invalidates GR or other alternative, purely geometrical, metric gravity theories described, for instance, in ref. [25].

The SLC and HERA data also revealed a much smaller, negative deflection or repulsion of the high-energy photons from the Earth. Such a change of refractivity sign from positive(attractive) at low energies to negative(repelling) at high energies is a known feature of photon interactions with ordinary matter [26]. This analogy could open new perspectives on quantum gravity, for which quantization of the GR geometrical gravitation is a major problem [27]. With the detected energy dependent photon scattering, gravity is exposing an attribute belonging to momentum transfer interactions, which the quantum approach can more conventionally handle. A possible connection of the observed effects to the Planck scale, where quantum gravity should materialize, has been discussed previously in ref. [16]. Nonetheless, despite its possible relation to the quantum regime, repelling gravity is something quite unusual and dedicated accelerator experiments are needed to check the preliminary SLC and HERA results on the negative refractivity.

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