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Experimental perspectives in (low-energy) photon-photon scattering

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Abstract. The possibility of photon-photon scattering is a striking difference between classical and quantum electrodynamics. This genuinely quantum feature is made possible by the fluctuations of charged fields, and it makes quantum vacuum a nonlinear optical medium. Photon-photon scattering is thus a delicate probe into the structure of quantum electrodynamics and any departure from the expected behavior would be a powerful signal of "new physics". To date this process has never been observed – except as a radiative correction to other processes – and several experiments are trying to detect it at very low energy, in the scattering of real photons in powerful light beams off the virtual photons of intense magnetic fields. Here we briefly review the experimental state-of-the-art, with special emphasis on the PVLAS experiment, and we describe a new proposal to observe photon-photon scattering in the range 1 – 2 MeV.

1. Introduction

Classical electrodynamics is a linear theory, the superposition principle plays an important and ubiquitous role in all its applications, and it usually comes as a surprise when one first learns that this is not so in quantum electrodynamics, although the departure from linearity is exceedingly small. The nonlinearity is associated with the quantum fluctuations of charged fermion fields, and therefore with the very nature of quantum vacuum, and a detailed examination of its nature leads to a wealth of interesting and deep results. Figure 1 shows the lowest-order Feynman diagram for photon-photon interaction: there is no tree-level diagram, and only an even number of photon vertices is allowed around the loop, because of Furry's theorem. This was studied early in the development of quantum field theory, and its nonlinear nature was first captured in the low-energy Lagrangian density correction $\mathcal{L}_{\rm EH}$ introduced by Euler and Heisenberg [1] and by Weisskopf [2] (EHW) – written here in standard S.I. units:

$$\mathcal{L}_{\rm EH} = \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\mathbf{E}}{c}\cdot\mathbf{B}\right)^2\right], \qquad (1)$$

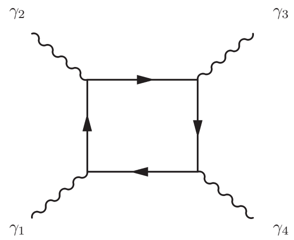

Figure 1. The lowest order Feynman diagram for photon-photon scattering.

where the A_e coefficient is defined by

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2 \lambda\!\!\!^{-}{}_e^3}{m_e c^2} = 1.32 \cdot 10^{-24}\ \mathrm{T}^{-2}. \tag{2}$$

The two quadratic terms in parentheses in eq. (1) correspond to the invariants $\mathcal{F} = F_{\mu\nu}F^{\mu\nu}$ and to $\mathcal{G} = \epsilon_{\mu\nu\sigma\tau}F^{\mu\nu}F^{\sigma\tau}$, so that the EHW Lagrangian is a linear combination of the squares of the admissible next-to-lowest-order invariants. As far as the linear terms are concerned, the lowest order, classical Lagrangian is indeed proportional to $\mathcal{F}$, while $\mathcal{G}$ is forbidden by parity conservation. A careful study of the generic Lagrangian density where the coefficients of the linear combination are free to vary leads to a rich low-energy phenomenology [3, 4], and using the optical theorem we can connect the observed vacuum birefringence with the photon-photon scattering amplitude, and finally with the photon-photon cross section [5, 6].

2. The PVLAS experiment

Although the EHW Lagrangian has been known for a long time – the original calculations date back to 1936 – the effects produced by the nonlinear correction are exceedingly small with near-visible photons, and the first experimental proposal was put forward by Emilio Zavattini and collaborators only at the end of the 1970's [7]. The experiment aims at measuring the scattering of photons from a laser source off the virtual photons of an intense, static, uniform dipolar magnetic field. The direction of the magnetic field lies in a plane perpendicular to the laser beam direction, and it influences the laser beam polarization, much as a uniaxial birefringent optical medium would do. It can be shown [8] that with an external field B_{ext} the difference between the refractive indexes for beam polarization parallel and perpendicular to the field is

$$\Delta n^{(EHW)} = n_{||}^{(EHW)} - n_{\perp}^{(EHW)} = 3A_e B_{ext}^2, \tag{3}$$

so that linearly-polarized light propagating in the field region acquires a small ellipticity, which depends on the A_e coefficient, the result of the QED calculation. Even with strong magnetic fields, this difference is extremely small: a 2.5 T magnet (roughly the saturation field of iron) gives $\Delta n^{(EHW)} \approx 10^{-23}$. This means that even tiny phase changes $\Delta\phi$ require very long path lengths $L = \lambda\Delta\phi/2\pi\Delta n^{(EHW)}$. Long path lengths are commonly obtained by folding the light path: in PVLAS this is done by means of a high-finesse Fabry-Perot cavity. In addition, we must also remember that photodetectors are only sensitive to intensity, and therefore in a crossed-polarizer arrangement the transmitted intensity changes by a factor $1 - \cos\Delta\phi \approx \Delta\phi^2$, and apparently we have to revise our estimates to make the path much longer. However, this can be corrected by modulating the effect, so that at the modulation frequency it becomes proportional to the derivative of the cosine and therefore proportional to $\Delta\phi$. This is usually achieved by pulsing or rotating the magnetic field, either electrically, as in the LAS experiment

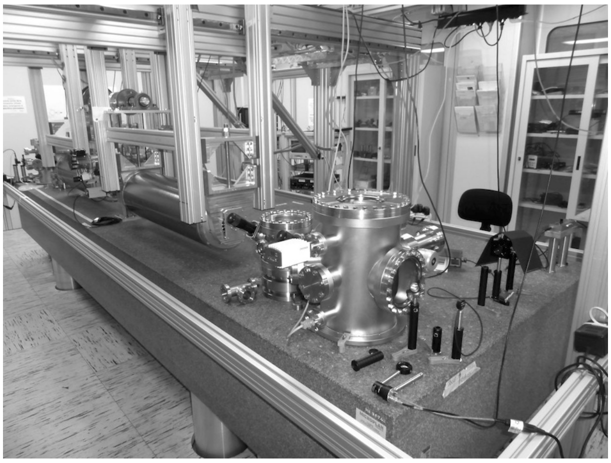

Figure 2. The new PVLAS experimental setup in Ferrara (Italy). The optical table sits in a clean room and has both passive and active noise damping. The magnetic field region is defined by two 1 m-long 2.5 T permanent magnets (dark gray cylinders on the left). The laser beam is produced by a 1 W Nd-YAG infrared laser (hidden by the support structure), it is linearly polarized at the far end of the table, and its ellipticity is modulated by a PEM. The outgoing beam is detected at the near end. The structure above the optical table is used to support the magnets and the motor that rotates them: these parts are mechanically isolated from the optics.

[9, 10], or mechanically, as in PVLAS [8]. The light intensity is detected by a photodiode and the amplitude of the spectral line at twice the modulation frequency carries the physical information [8]. Unfortunately, it is not possible to modulate the magnetic field faster than a few Hz: thus the spectral line at the modulation frequency is drowned in the low-frequency $1/f$ noise peak. This can be fixed, by further modulating the initial polarization at a frequency of a few kHz – for instance by means of a photo elastic modulator (PEM) as in PVLAS – and thus moving the physical signal to higher frequency, far from the $1/f$ noise peak due to mechanical vibrations and to electronic noise. The final sensitivity of the experiment is determined by the noise level close to the PEM modulation frequency, and the latest tests performed with the new PVLAS apparatus yield a noise figure for the measured ellipticity close to 3×10^{-7} radians/$\sqrt{\text{Hz}}$. Further improvements shall be needed to bring this down to the level of 10^{-8} radians/$\sqrt{\text{Hz}}$, required to successfully carry out a measurement in about a month of data taking time. More details can be found in the original proposal [7], and in recent papers, such as [8]. At the moment the PVLAS collaboration is setting up a new improved apparatus (see figure 2). The first tests are encouraging, and the collaboration hopes to collect data by the end of 2013. PVLAS is one of several competing experiments: two of them (OSQAR [11] and Q&A [12]) use the same basic technique, BMV [13] utilizes a strong, pulsed magnetic field, to take advantage of the quadratic dependence of the effect on field intensity – see eq. (3) – while an experiment at ELI could utilize the very high beam intensity [14]. Differences and comparisons among experiments can be found in the ref. [8].

3. Higher-energy experiments

Even though the birefringence of vacuum has not yet been observed, it is already possible to estimate an upper limit to the photon-photon scattering cross section in the 1 eV region, and in PVLAS we find [8] $\sigma_{\gamma\gamma} < 1.2 \times 10^{-32} \mu$b with 1064 nm photons. The fast growth $\sigma_u \propto (\hbar\omega)^6$ at energies below ~ 0.7 MeV (see figure 3), brings the total cross section to nearly 2 μb at the

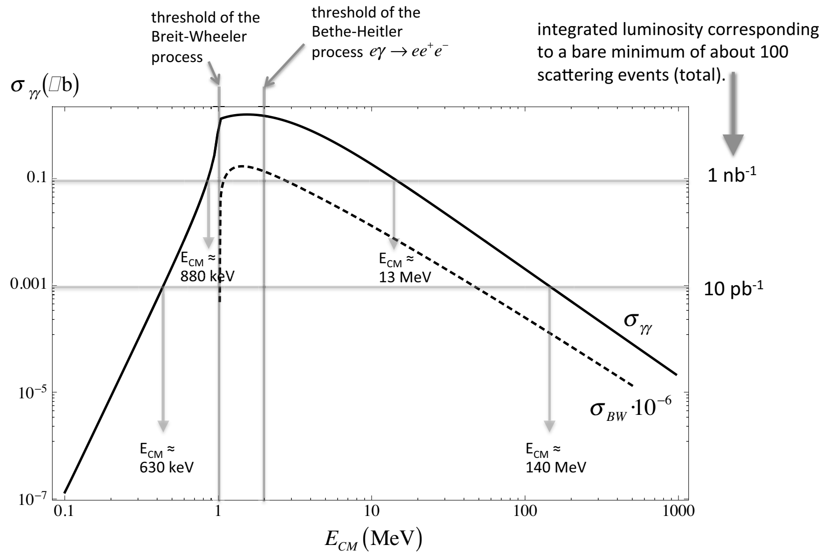

Figure 3. Unpolarized photon-photon cross section $\sigma_{\gamma\gamma}$ vs. CM energy, from the electronic contribution to the fermion loop of figure 1. The initial fast growth brings the cross section to about 2 μb close to the peak. σ_{BW} is the cross section of the background Breit-Wheeler process.

peak, and it is possible to contemplate a different experimental setup with colliding gamma rays [4, 15]: a photon-photon collider facility with center of mass energy around 1-2 MeV could soon make this true, if the IRIDE project – now in the preliminary Technical Design Report phase – shall be a approved as wished and construction shall start in a new laboratory near Rome [16].

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