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Polarized Light Propagating in a Magnetic Field as a Probe of Millicharged Fermions

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Possible extensions of the standard model of elementary particle physics suggest the existence of particles with small, unquantized electric charge. Photon initiated pair production of millicharged fermions in an external magnetic field would manifest itself as a vacuum magnetic dichroism. We show that laser polarization experiments searching for this effect yield, in the mass range below 0.1 eV, much stronger constraints on millicharged fermions than previously considered laboratory searches. Vacuum magnetic birefringence originating from virtual pair production gives a slightly better constraint for masses between 0.1 eV and a few eV. We comment on the possibility that the vacuum magnetic dichroism observed by PVLAS arises from pair production of such millicharged fermions rather than from single production of axion-like particles. Such a scenario can be confirmed or firmly excluded by a search for invisible decays of orthopositronium with a sensitivity of about 10^{-9} in the corresponding branching fraction.

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The apparent quantization of the electric charges of all known elementary particles – i.e., the fact that they appear to be integer multiples of the electric charge of the d quark – is a long standing puzzle of fundamental interest. Strong experimental upper limits on the electric charge of neutrons, atoms, and molecules [1, 2, 3], $Q < \mathcal{O}(10^{-21})\, e$, with the magnitude of the electron electric charge e, as well as on the magnetic moments of the neutrinos [4], $\mu_\nu < \mathcal{O}(10^{-10})\, \mu_B$, with the Bohr magneton $\mu_B = e/2m_e$ and the electron mass m_e, strongly support the idea that charge quantization is a fundamental principle. However, the standard model of particle physics with three generations of quarks and leptons does not impose charge quantization [5]. One needs physics beyond the standard model in order to enforce it, as is demonstrated by Dirac's seminal argument for charge quantization based on the hypothetical existence of magnetic monopoles [6]. Whereas some extensions of the standard model, e.g. grand unified theories, provide mechanisms for enforcing charge quantization, other possible extensions suggest the existence of particles of small, unquantized charge $Q_\epsilon = \epsilon e$, with $\epsilon \ll 1$ [7, 8, 9, 10, 11].

There are a number of experimental and observational bounds on the fractional electric charge ϵ and on the mass m_ϵ of hypothetical millicharged particles, coming from laboratory experiments, astrophysics and cosmology [12, 13, 14, 15, 16, 17, 18] (for a recent review and further references, see Ref. [19]). In the sub-electron mass region, $m_\epsilon < m_e$, the best laboratory-based bounds on millicharged fermions, $\epsilon < \mathcal{O}(10^{-4})$, come from searches for the invisible decay of orthopositronium [20] and from a comparison [19] of Lamb-shift measurements [21, 22] with predictions of quantum electrodynamics (QED) (cf. Fig. 1). Stronger, albeit more model-dependent bounds arise through astrophysical and cosmological considerations. For example, stellar evolution constraints [25] yield a bound $\epsilon < \mathcal{O}(10^{-14})$, for $m_\epsilon < \mathcal{O}(10\ \mathrm{keV})$, whereas successful big bang nucleosynthesis leads to the restriction $\epsilon < \mathcal{O}(10^{-9})$, for $m_\epsilon < \mathcal{O}(1\ \mathrm{MeV})$.

In the present Letter, we want to investigate whether searches exploiting laser polarization experiments can give competitive constraints on millicharged fermions, most notably in comparison to other laboratory searches.

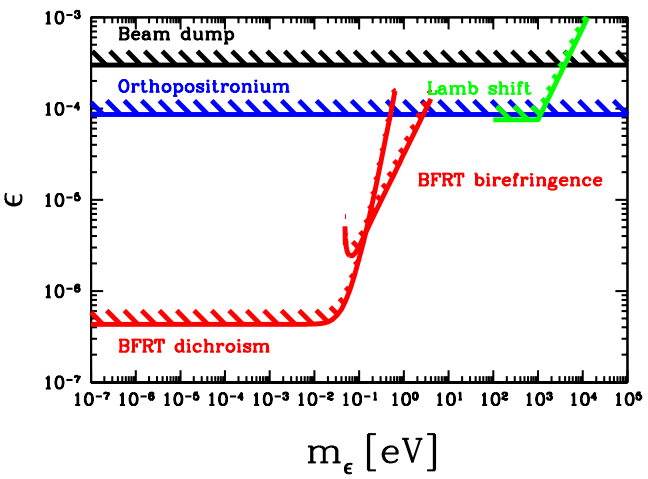

FIG. 1: Laboratory-based upper limits on the fractional electric charge $\epsilon = Q_\epsilon/e$ of a hypothetical millicharged fermion of mass m_ϵ. The "Beam dump" limit has been derived in Ref. [13] from a beam-dump search for new neutrino-like particles at SLAC [23, 24]. The "Orthopositronium" limit stems from a limit on the branching fraction of invisible orthopositronium decay [20]. The "Lamb shift" limit comes from a recent comparison [19] of Lamb shift measurements [21, 22] with QED predictions. The "BFRT dichroism/birefringence" limit arises from the upper limit on vacuum magnetic dichroism/birefringence placed by the laser polarization experiment BFRT [36] (see text).

It is theoretically well established in QED that photon-initiated electron-positron pair production, $\gamma \to e^+e^-$, in an external magnetic field [26, 27, 28, 29, 30, 31, 32, 33, 34, 35] manifests itself as a vacuum magnetic dichroism: the polarization vector of an initially linearly polarized photon beam with energy $\omega > 2m_e$ in general is rotated after passing a transverse magnetic field. However, because of its high threshold energy, this effect has not been detected in the laboratory yet. Recent past, present day, and near future instruments for the detection of vacuum magnetic birefringence and dichroism, such as BFRT [36], PVLAS [37], Q&A [38], BMV [39], and proposed experiments at CERN [40] and in Jena [41] exploit photon beams with energies $\omega = \mathcal{O}(\mathrm{eV})$. Correspondingly, they may be sensitive to vacuum magnetic dichroism induced by the production of fermion anti-fermion pairs with mass $2m_\epsilon < \omega = \mathcal{O}(\mathrm{eV})$. Similarly, they may also be sensitive to vacuum magnetic birefringence caused by the virtual production of these light millicharged particles, which induces ellipticity of the laser beam in the magnetic field.

Let us first consider dichroism. Let $\vec{k}$ be the momentum of the incoming photon, with $|\vec{k}| = \omega$, and let $\vec{B}$ be a static homogeneous magnetic field, which is perpendicular to $\vec{k}$, as it is the case in all of the above-mentioned polarization experiments. The photon-initiated production of a Dirac-type fermion anti-fermion pair, with electric charge $Q_\epsilon = \epsilon e$ and mass m_ϵ, at $\omega > 2m_\epsilon$, leads to a non-zero difference between the photon absorption coefficients $\kappa_{||}$ and $\kappa_\perp$, corresponding to photon polarizations parallel or perpendicular to $\vec{B}$. The fact that the absorption coefficients for the two polarizations, $||$ and $\perp$, are different directly leads to dichroism: for a linearly polarized photon beam, the angle θ between the initial polarization vector and the magnetic field will change to $\theta + \Delta\theta$ after passing a distance ℓ through the magnetic field, with

$$\cot(\theta + \Delta\theta) = \frac{E_{||}}{E_\perp} = \frac{E^0_{||}}{E^0_\perp} \exp\left(-\frac{1}{2}(\kappa_{||} - \kappa_\perp)\ell\right). \quad (1)$$

Here, $E_{||,\perp}$ are the electric field components of the laser parallel and perpendicular to the external magnetic field and the superscript "0" denotes initial values. For small rotation angle $\Delta\theta$, we have

$$\Delta\theta \simeq \frac{1}{4}(\kappa_{||} - \kappa_\perp)\ell \, \sin(2\theta). \quad (2)$$

Explicit expressions for the photon absorption coefficients $\kappa_{||,\perp}$ can be inferred from the literature on $\gamma \to e^+e^-$ in a homogeneous magnetic field [27, 28, 29, 30, 31, 32, 33, 34, 35]:

$$\begin{aligned} \kappa_{||,\perp}\ell &= \frac{1}{2}\epsilon^3 e\alpha \frac{B\ell}{m_\epsilon} T_{||,\perp}(\chi) \quad (3) \\ &= 1.09 \times 10^6 \, \epsilon^3 \left(\frac{\mathrm{eV}}{m_\epsilon}\right)\left(\frac{B}{\mathrm{T}}\right)\left(\frac{\ell}{\mathrm{m}}\right) T_{||,\perp}(\chi), \end{aligned}$$

where $\alpha = e^2/4\pi$ is the fine-structure constant. Here, $T_{||,\perp}(\chi)$ has the form of a parametric integral [33],

$$\begin{aligned} T_{||,\perp} &= \frac{4\sqrt{3}}{\pi\chi}\int_0^1 \mathrm{d}v \; K_{2/3}\left(\frac{4}{\chi}\frac{1}{1-v^2}\right) \\ &\qquad \times \frac{\left[\left(1-\frac{1}{3}v^2\right)_{||}, \left(\frac{1}{2}+\frac{1}{6}v^2\right)_\perp\right]}{(1-v^2)} \quad (4) \\ &= \begin{cases} \sqrt{\frac{3}{2}}\, \mathrm{e}^{-4/\chi} \; \left[\left(\frac{1}{2}\right)_{||}, \left(\frac{1}{4}\right)_\perp\right] & \text{for } \chi \ll 1 \\ \frac{2\pi}{\Gamma\left(\frac{1}{6}\right)\Gamma\left(\frac{13}{6}\right)}\chi^{-1/3}\left[(1)_{||}, \left(\frac{2}{3}\right)_\perp\right] & \text{for } \chi \gg 1 \end{cases}, \end{aligned}$$

the dimensionless parameter χ being defined as

$$\chi \equiv \frac{3}{2}\frac{\omega}{m_\epsilon}\frac{\epsilon e B}{m_\epsilon^2} = 88.6 \; \epsilon \; \frac{\omega}{m_\epsilon} \; \left(\frac{\mathrm{eV}}{m_\epsilon}\right)^2 \left(\frac{B}{\mathrm{T}}\right). \quad (5)$$

The above expression has been derived in leading order in an expansion for high frequency,

$$\frac{\omega}{2m_\epsilon} \gg 1, \quad (6)$$

and of high number of allowed Landau levels of the millicharged particles,

$$N_{\mathrm{Landau}} = \frac{1}{24}\left(\frac{\omega^2}{\epsilon \, eB}\right)^2 \gg 1. \quad (7a)$$

Let us remark that expression (4) was originally derived in Ref. [33] in the more restrictive high-frequency $\omega/2m_\epsilon \gg 1$ and weak-field limit $\epsilon \, eB/m_\epsilon^2 \ll 1$, in agreement with the results of Refs. [27, 28, 29, 30, 31]. These in turn agree with the result of Ref. [34] which are obtained with the conditions (6) and (7a). Intuitively, we can understand the nature of this approximation as follows. Expression (4) is a rather smooth function of the frequency ω. However, from the discrete nature of the Landau levels we would rather expect absorption peaks. Yet, if the peaks are very dense we cannot resolve them and we have to average over a small frequency interval $\Delta\omega$, yielding the smooth function (4). Averaging is allowed if we have a large number of peaks $\Delta N_{\mathrm{peaks}}$ in the interval $\Delta\omega$,

$$\begin{aligned} \Delta N_{\mathrm{peaks}} &= \frac{1}{2}\Delta N_{\mathrm{Landau}} = \frac{1}{12}\left(\frac{\omega^2}{\epsilon \, eB}\right)^2 \frac{\Delta\omega}{\omega} \gg 1 \quad (7b) \\ &\Leftrightarrow \epsilon \ll 4.89 \times 10^{-3} \left(\frac{\omega}{\mathrm{eV}}\right)^2 \left(\frac{\mathrm{T}}{B}\right)\left(\frac{\Delta\omega}{\omega}\right)^{\frac{1}{2}}. \end{aligned}$$

This expression agrees with (7a) up to a factor of $\Delta\omega/(2\omega)$ which takes the uncertainty in the frequency into account. In the above-mentioned laser polarization experiments, a cavity is used to reflect the laser beam back and forth, thereby enhancing the signal. In that

case, the frequency uncertainty is $\Delta\omega/\omega \sim 1/N_r$, where N_r is the number of reflections in the cavity.

At present, the most stringent bound on vacuum magnetic dichroism comes from the BFRT laser polarization experiment [36]. A linearly polarized laser beam ($\omega = 2.41$ eV) was sent along the magnetic field of two superconducting dipole magnets ($B = 2$ T), which were placed in an optical cavity with $N_r = 254$ reflections, such that the optical path length was $\ell = N_r \times 8.8$ m $\simeq 2235$ m. An upper limit on the absolute value of the rotation,

$$|\Delta\theta| < 6 \times 10^{-10} \qquad (95\,\%\ \text{confidence level}), \tag{8}$$

was obtained. This can be turned into an upper limit on ϵ, as a function of m_ϵ, by exploiting the predictions (1)-(4) for $\Delta\theta$ from photon-initiated pair production of millicharged fermions in an external magnetic field. The resulting limit is displayed in Fig. 1 and labelled as "BFRT dichroism". Clearly, for small masses, $m_\epsilon \lesssim 0.1$ eV, this represents currently the best laboratory limit on millicharged fermions.

Let us now turn to birefringence. The propagation speed of the laser photons is slightly changed in the magnetic field owing to the coupling to virtual charged pairs. The corresponding refractive indices $n_{||,\perp}$ differ for the two polarization modes, causing a phase difference between the two modes,

$$\Delta\phi = \omega\ell(n_{||} - n_\perp). \tag{9}$$

This induces an ellipticity ψ of the outgoing beam,

$$|\psi| = \frac{\omega\ell}{2}|(n_{||} - n_\perp)\sin(2\theta)| \qquad \text{for } \psi \ll 1. \tag{10}$$

Virtual production can occur even below threshold $\omega < 2m_\epsilon$. Therefore, we consider both high and low frequencies. As long as (7b) is satisfied one has [42]

$$n_{||,\perp} = 1 - \frac{\epsilon^2\alpha}{4\pi}\left(\frac{\epsilon\, eB}{m_\epsilon^2}\right)^2 I_{||,\perp}(\chi), \tag{11}$$

with

$$I_{||,\perp}(\chi) = 2^{\frac{1}{3}}\left(\frac{3}{\chi}\right)^{\frac{4}{3}}\int_0^1 \mathrm{d}v\, \frac{\left[\left(1-\frac{v^2}{3}\right)_{||}, \left(\frac{1}{2}+\frac{v^2}{6}\right)_\perp\right]}{(1-v^2)^{\frac{1}{3}}} \times \tilde{e}_0'\left[-\left(\tfrac{6}{\chi}\tfrac{1}{1-v^2}\right)^{\frac{2}{3}}\right] \tag{12}$$

$$= \begin{cases} -\frac{1}{45}\left[(14)_{||}, (8)_\perp\right] & \text{for } \chi \ll 1 \\ \frac{9}{7}\frac{\pi^{\frac{1}{2}}2^{\frac{1}{3}}\left(\Gamma\left(\frac{2}{3}\right)\right)^2}{\Gamma\left(\frac{1}{6}\right)}\chi^{-4/3}\left[(3)_{||}, (2)_\perp\right] & \text{for } \chi \gg 1 \end{cases}.$$

Here, $\tilde{e}_0$ is the generalized Airy function,

$$\tilde{e}_0(t) = \int_0^\infty \mathrm{d}x\, \sin\left(tx - \frac{x^3}{3}\right), \tag{13}$$

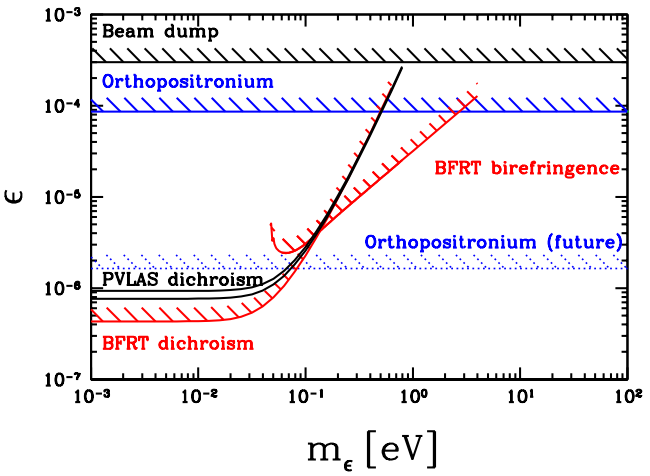

FIG. 2: Laboratory-based upper limits on the fractional electric charge $\epsilon = Q_\epsilon/e$ of a hypothetical millicharged fermion of mass m_ϵ (same as in Fig. 1). The parameter values between the two lines labelled "PVLAS dichroism" correspond to the preferred 95 % confidence region if the PVLAS rotation is interpreted as orginating from pair production of millicharged fermions. The dashed limit labelled "Orthopositronium (future)" corresponds to the projected 95 % exclusion limit obtainable through a search for invisible orthopositronium decay with a sensitivity of 10^{-9} in the corresponding branching ratio.

and $\tilde{e}_0'(t) = \mathrm{d}\tilde{e}_0(t)/\mathrm{d}t$. Using the parameters for the BFRT birefringence measurement, $\omega = 2.41$ eV, $B = 2$ T, $N_r = 34$, and $\ell = N_r \times 8.8$ m, their upper limit on the ellipticity,

$$|\psi| < 2 \times 10^{-9} \quad (95\%\ \text{confidence level}), \tag{14}$$

leads to the limit depicted in Fig. 1, which is the currently best laboratory limit in the range 0.1 eV $\lesssim m_\epsilon \lesssim 3$ eV. Let us finally remark that all our limits remain valid for $m_\epsilon \gtrsim 10^{-2}$ eV, even if we impose the more strict validity constraint $\epsilon eB/m_\epsilon^2 \ll 1$ for Eqs. (4) and (12). For a check of the quantitative convergence of the underlying expansion for $m_\epsilon \lesssim 10^{-2}$ eV, a next-to-leading order calculation may ultimately be needed.

Recently, the PVLAS collaboration reported the observation of an optical rotation generated in vacuum by a magnetic field [37],

$$|\Delta\theta|/N_r = (3.9 \pm 0.5) \times 10^{-12}. \tag{15}$$

The experimental parameters in their setup were $\omega = 1.17$ eV, $B = 5$ T, $N_r = 4.4 \times 10^4$, and $\ell = N_r \times 1$ m. If interpreted in terms of pair production of millicharged fermions, we obtain the preferred 95 % confidence region lying between the two black lines labelled "PVLAS dichroism" in Fig. 2. Apparently, at two standard deviations, this is in conflict with the limit from BFRT. Nevertheless, the PVLAS result is very close to the boundary

of the excluded region for masses $\mathcal{O}(0.1\,\mathrm{eV})$, and therefore the pair-production interpretation still represents a remote alternative to the standard, axion-like-particle (ALP) interpretation of the PVLAS result [43, 44]. For both interpretations, there are problems with the astrophysical bounds [25] which are difficult to avoid for ALPs [45, 46, 47, 48]. It remains to be seen whether pair production provides easier ways to evade them. A promising way to test the parameter region around $m_\epsilon \sim 0.1$ eV, $\epsilon \sim 3 \times 10^{-6}$, opens up in the near future, when the sensitivity of searches for the invisible decay of orthopositronium reach the 10^{-9} level in the corresponding branching ratio [49] (cf. Fig. 2). Also, a PVLAS birefringence measurement can be expected to explore the interesting region around $m_\epsilon \sim 0.1$ eV; a positive signal would fix both parameters ϵ and m_ϵ of hypothetical millicharged particles by reading off the intersection point of the dichroism and birefringence curves.

In summary, polarization measurements of laser beams traversing intense magnetic fields provide a very sensitive probe of light millicharged fermions in the laboratory. In the sub-eV range, already the limits inferred from the pioneering BFRT experiment are more than two orders of magnitude better than other laboratory based limits.

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