Charged Photons?
An Educated Guess of Properties

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We especulate on the dynamics of charged photons admitting a hypothetical non-neglible photon charge Q_γ, albeit our limited understanding of extragalactic magnetic fields and of the expansion of the universe lead to uncertainties on its bound. We found a wavelength for the charged photons proportional to $\sqrt{Q_\gamma/N_p}$, where N_p is their number density. The light waves frequencies being of the order of the cosmic rays ($> 10^{19}$ Hz).

Motivation

Electrodynamics phenomena, involving charged particles interacting by means of exchange of photons, depends upon the electrical neutrality and zero mass of photons [1]. Any measured bound placed on the photon is subject to uncertainty, but observations of photons that have traversed cosmological distances can still suggest novel physics phenomena. The immense distances over which photons travel may magnify small effects. A tiny change in how electromagnetic waves propagate after millions of Parsecs may give rise to a readily observable effect and from it an estimate for the bound of the photon charge Q_γ [2].

Our main focus in this brief essay is to pinpoint the ultimate frontier towards a fundamental physics approach of charged photon dynamics. It is worthwhile then to have precise bounds in order to identify the feasibility of such an approach.

Bounds Estimate

Placing bounds on an hypothetical charge has received less attention than constraining the photon's mass due to the lack of a fundamental theory describing charged photons. As discussed in [2], bounds on the photon mass haven been placed using dynamical stability conditions [3], observations of magneto-hydrodynamic waves [4] and tests with static fields [5] –although there seems to be unexpected model dependences [6].

Without any theory for the existence of a photon charge, one must rely on (direct or indirect) measurements of the effects of a photon charge and how photon propagation is affected. This search does not describe how static electromagnetic fields would be modified but concerns the "ultimate" nature of reality.

Searches on the effects of a photon charge include experiments on the variations in a photon's energy between a source and detector placed at different voltages, the deflection of photons by magnetic fields [7] and the associated time delays [8]. The most authoritative bound derived by these methods is 4×10^{-31} the elementary charge e. Bounds become actually two orders of magnitude smaller when positively and negatively charged photons are assumed to exist.

Constrains on the photon charge are also placed based on observations of photons that have travelled cosmological distances [9]. Since a non-zero photon charge could have disturbed the overall charge neutrality of the early universe, a bound of 10^{-35} e has been placed on the photon charge by measurements of the anisotropy of the cosmic microwave background [10]. Charged particles moving along different paths through a magnetic field take up different phases, and the observed coherence of photons from distant astrophysical sources allows to place bounds on Q_γ [11]. Considering quantum interference effects, a bound on the photon charge is set at 10^{-32} e when all photons carry the same charge, and 10^{-46} e if different photons have different charges [2].

Conjecture

We develop next some ideas on the theme. It is our hope to give clues and motive physisicts to develop theories admitting a non-zero photon charge, in order to study elementary particles motion over distance scales from the micro- to the macro-domains [12].

As pointed out in [11], if photons had a small electric charge Q_γ their path in a homogenous transverse magnetic field B would be curved, leading to a time delay Δt between photons of different frequencies ν from a source at distance ℓ. The quantum of energy for a photon $E = h\nu = 2\pi\nu$ emitted from this source takes approximately the time $t = \ell$ to reach our planet (using natural units $\hbar = c = 1$). And particles become delayed by

$$\frac{\Delta t}{t} = \frac{Q_\gamma^2 B^2 \ell^2}{6E^2} \quad . \tag{1}$$

If the entire dispersion is caused by the charge effect, then it is straightforward to derive the electromagnetic spectrum

$$\lambda_\gamma = \frac{Q_\gamma B}{E} \left(\frac{\ell^3}{6D} \right)^{1/2} \quad , \tag{2}$$

where D is a dispersion constant and the dispersion effect takes the form

$$\Delta t = \frac{D}{\nu^2} = D\left(\frac{\lambda}{c}\right)^2 = \frac{(2\pi)^2 D}{E^2} \quad . \tag{3}$$

This in practice is the base of astrophysical interferometry. Using B, D, ℓ data for the pulsar PSR 1937+21 data and $\alpha = e^2/4\pi$, the following bound is found [11]

$$\frac{Q_\gamma}{e} = \left(\frac{6\pi D}{\alpha B^2 \ell^3}\right)^{1/2} \sim 10^{-30} \quad . \tag{4}$$

On the other hand, in order to evaluate the different wavelengths λ_γ in Eq.(2), associated to the charged photon dynamics under discussion, it is necessary to give an estimate for the energy E of the electromagnetic waves.

Let us follow [2] and assume that the coupling of a single photon to the external electromagnetic field $A_{\rm ext}$ takes the form $L_{Q_\gamma} = -Q_\gamma v_\mu A^\mu_{\rm ext}$, with v^μ its four-velocity. This Lagrangian is essentially unique once one demands conventional Lorentz transformation properties and specifies that there exists the energy term $E = -Q_\gamma A^0_{\rm ext}$. Henceforth we search for a rough approximation for the external potential field.

It is known that photons in a plasma can adquire an equivalent charge q_p due to the electric force created by the photon pressure in a warm plasma [13, 14]. In these systems the electric field $\mathcal{E}_0$ of a electromagnetic wave satisfies

$$q_p^2 |\mathcal{E}_0|^2 = \left(\frac{\pi e}{\delta_D^2}\right) q_p N_p \quad , \tag{5}$$

where λ_D is a parameter, dependent on the temperature and plasma number density, and N_p is the number density of the photons.

To this end, the rough approximation $A^0_{\rm ext} \sim \mathcal{E}_0$ may be postulated based on the above results from the kinetic theory of induced electric charges of photons in a (unmagnetized) plasma. If one is allowed to do this, from Eqs.(2)-(5) we then get the remarkably simple form

$$\lambda_\gamma \sim \beta \left(\frac{Q_\gamma}{N_p}\right)^{1/2} \quad , \tag{6}$$

where the coefficient β depends on an analogous δ_D.

By considering the cosmic microwave background (CMB) radiation, the photon number density over cosmological scales is given by $n_p \sim (K_B T/\hbar c)^3$ where $K_B T$ is the thermal energy of a black body [10]. Considering a temperature of 2.726 K the CMB photon number density N_p is $\sim 400\ cm^{-3}$. Therefore a crude estimate for Eq.(6), using the bound in Eq.(4) and $\beta \sim 1$, yields high radiation frequencies: gamma and higher cosmic rays ($> 10^{19}\ Hz$).

Our limited understanding of extragalactic magnetic fields and of the expansion of the universe, lead to the greatest uncertainties for the photon charge bound [2]. This in turn add constrains on the proof of a fundamental physics approach based on the dynamics of charged light particles, since it would be necessary to measure both quantities N_P and Q_γ with precision –a forbidden challenge with the available technological means. In spite of the relevance of N_P to experiments and the foundations of quantum mechanics, no relativistically invariant positive definite expression for the photon number density exists so far [15]. To associate the photon charges in a unmagnetized plasma as done here is in addition heuristic. Hence, our Eq.(6) is an educated guess to provide an arena for discussion and exchange of ideas regarding eventual charged photons.

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