Problems with the Rotating-Torsion-Balance Limit on the Photon Mass

Recently, Luo *et al.* [1] improved an ingenious method of Lakes [2] to detect a possible small photon mass μ. In the Proca ($\mu = \text{const}$) formulation, nonzero μ fixes the Lorentz gauge for electrodynamics, and thus makes unique the vector potential $\mathbf{A}$ at any point due to specified sources. The $\mu^2 A^2$ Proca term in the Lagrangian implies a torque on a loop of magnetic flux from the ambient magnetic vector potential $\mathbf{A}_{\mathrm{amb}}$, analogous to the torque on a loop of electric current from an ambient magnetic field. The torque $\boldsymbol{\tau} = \boldsymbol{\nu} \times \mu^2 \mathbf{A}_{\mathrm{amb}}$ acts on $\boldsymbol{\nu}$, the "vector-potential dipole moment" of the flux loop. As one knows $\boldsymbol{\nu}$, measuring or limiting $\boldsymbol{\tau}$ yields $(\mu^2 \mathbf{A}_{\mathrm{amb}})$. Determining $\mathbf{A}_{\mathrm{amb}}$ then places a value on μ. A typical value of $\mathbf{A}_{\mathrm{amb}}$ can be very large, $A \sim |\langle \mathbf{B} \rangle| L$, with L the size of a region with $\mathbf{B} \sim \text{const}$.

Lakes [2] already noted a source of statistical error—at any particular location within a large region of approximately uniform $\mathbf{B}$ (whose exact boundaries are poorly specified), one knows neither the direction nor the magnitude of $\mathbf{A}_{\mathrm{amb}}$. Lakes looked for diurnal variation in the torque on his toroidal magnet. So, for $\mathbf{A}$ closely aligned with the rotation axis of the Earth, he would have been insensitive to μ. The new improvement [1] was rotating the axis of the magnet, allowing detection of all projections of $\mathbf{A}$, and a 100 times greater signal sensitivity. This reduced the purely statistical uncertainty for the Lakes method by roughly a factor $\sqrt{2}$. The works in Refs [1,2] do not account for this uncertainty in the quoted limits.

Though original and potentially promising for the future, these works [1,2] neither provide the best available limit on $\mu^2 A$ nor a reliable limit at all on μ.

(1) For specified sources, the Proca equation in vacuum implies exponential Yukawa damping of the magnetic vector potential and field on the scale of the reduced photon Compton wavelength $\bar{\lambda}_C = 1/\mu$. However, in the presence of plasma a static magnetic field may take exactly the form it would have in $\mu = 0$ magnetohydrodynamics, *provided* [3,4] the plasma supports a current $\mathbf{J}$ that exactly cancels the "pseudocurrent" $-\mu^2 \mathbf{A}/\mu_0$ induced by the photon mass. Thus, if we place a limit on plasma currents everywhere in a region larger than some putative value of $1/\mu$, we place the same limit on $\mu^2 A$.

(2) Using the above, we can obtain a stronger limit. For the largest available A (coming from a typical $\mathbf{B}$ over the dimensions of clusters such as Coma [5,6]), we require a limit on the intergalactic plasma current, obtainable from the same astrophysical data used in [1,2] to estimate A. The mean electron density is $\leq 0.01\ \mathrm{cm}^{-3}$ [6]. The electron temperature is about 5 keV (higher in places) [6], yielding a (more than generous) velocity bound on the order of $0.1c$. This allows a current density $< 5 \times 10^{-8}\ \mathrm{A/m^2}$, roughly a factor of 200 smaller than the pseudocurrent allowed by the result of Luo *et al.* [1]. This current density limit of course applies everywhere, including all places where A has its typical size. The resulting limit for $\hbar\mu/c$ is about 10^{-52} g, or $\bar{\lambda}_C > 4 \times 10^9$ km, almost 30 AU. Uncertainty about the degree of inhomogeneity in the Coma or even in our local galactic cluster makes it hard to quote a definite result, but it is unlikely to be worse than the claim of [1].

(3) Of course, anywhere the plasma density becomes unusually small, including any large vacancies in the plasma allowed by our ignorance about inhomogeneity [6], the vacuum exponential decay applies. If we happened to be in such a vacancy then A at our location could be arbitrarily small, and, hence, the laboratory limit on $\mu^2 A$ would give no constraint on μ.

(4) Although the torque method cannot yet yield a solid limit on μ, surely the true limit is smaller than that from the best direct observations, but we have no clear idea by how much. The best direct limit we know comes from Ryutov [7] (who used a generous upper bound on the $\mu^2 A^2$ energy of the solar wind magnetic field), $\mu < 10^{-49}$ g or $\bar{\lambda}_C = 3 \times$!0^6 km, about five solar radii [8].

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