Electromagnetic momentum, quantum effects and photon mass

G Spavieri, J Ayazo, J Erazo, J Quintero, A Sánchez, and M Rodríguez*

Centro de Física Fundamental y PFF, Universidad de Los Andes

Mérida, 5101 Venezuela (spavieri@ula.ve)

** Departamento de Física, FACYT,*

Universidad de Carabobo, Valencia, 2001-Venezuela

Resumen

El momento electromagnético $\mathbf{P}_e$ aparece en las ecuaciones para la propagación de ondas de luz y materia. Sus propiedades conducen a una nueva prueba de la velocidad de la luz en gases enrarecidos en movimiento, mientras que un experimento que involucra los efectos cuánticos del tipo Aharonov-Bohm conduce al siguiente límite para la masa del fotón $m_{ph} \simeq 10^{-52}$ g.

Abstract

The electromagnetic momentum $\mathbf{P}_e$ appears in equations for matter and light waves propagation. Its properties lead to a new test of the speed of light in moving rarefied gases, while a table-top experiment involving quantum effects of the Aharonov-Bohm type yields the photon mass limit $m_{ph} \simeq 10^{-52}$ g.

PACS: 03.30.+p, 03.65.Ta, 01.55.+b, 42.15.-i

The main purpose of this article is to point out recent advances of physics involving the electromagnetic (em) momentum of fields $\mathbf{P}_e$ and its role in the proposal of new tests or in obtaining relevant achievements, such as new limits for the photon mass.

1- *Light propagation in moving media and quantum nonlocal effects of the Aharonov-Bohm type.*

The analogy between the wave equation for light in moving media and that for charged matter waves has been pointed out by Cook, Fearn, and Milonni (Cook et al., 1995) who have suggested that light propagation at a fluid vortex is analogous to the Aharonov-Bohm (AB) effect, where charged matter waves (electrons) encircle a localized magnetic flux (Aharonov and Bohm, 1959; Spavieri, 1999a, b). In quantum effects of the AB type matter waves undergo an em interaction as if they were propagating in a flow of em origin that acts as a moving medium and modifies the wave velocity. This analogy has led to the formulation of the so-called magnetic model of light propagation (Cook et al., 1995; Spavieri and Gillies, 2007). Both effects are described by the same wave equation

$$(-i\nabla - \mathbf{Q})^2\Psi = p^2\Psi$$

where $\mathbf{Q}$ is related to the em momentum $\mathbf{P}_e$, $\mathbf{Q} = \pm\mathbf{P}_e = \left(\frac{1}{4\pi c}\right)\int \mathbf{E}\times\mathbf{B}d^3x'$. This equation describes matter waves if the momentum p is that of a material particle, while, if p is taken to be the momentum $\hbar k$ of light (in units of $\hbar = 1$), it describes light waves. For the magnetic AB effect one finds $\mathbf{Q} = (e/c)\mathbf{A}$ while for light in slowly moving media $\mathbf{Q} = -\frac{\omega}{c^2}(n^2 - 1)\mathbf{v}$ (Spavieri and Gillies, 2007; Spavieri, 2006a, b), which is the Fresnel-Fizeau momentum.

Within the light propagation scenario, Consoli and Costanzo (Consoli and Costanzo, 2004, 2007), and Guerra and de Abreu (Guerra and Abreu, 2004), after a re-analysis of the optical experiments of the Michelson-Morley type, claim that the available data point towards a consistency of non-null results when light in the arms of the interferometer propagates in a rarefied gas, like the cases of air at normal pressure and temperature. To test this assumption, we have derived possible modifications of the form of the present Fresnel-Fizeau momentum when the moving medium is composed of rarefied gas. Introducing the ratio of rarefied/nonrarefied gas volumes V_i/V (Spavieri, 2006a, b) the effective Fresnel-Fizeau term is now $e_f\mathbf{Q} = (V_i/V)\mathbf{Q}$ and the velocity of light reads $\mathbf{c}_n = (c/n)(\mathbf{c}/c) + e_f(1 - 1/n^2)\mathbf{v}$.

The main consequence is that ether drift experiments of the order v/c become meaningful again and thus an experiment which is a variant of the Mascart and Jamin experiment of 1874 has been proposed (Spavieri et al, 2008). Here, instead than in water, light propagates in rarefied gas. The result is that this optical experiment, in passing from second order (including tests by Jaseja et al. using He-Ne masers) to first order, improves the range of detectability of *v* by a factor 3×10^{2}, i.e., detects with the same interferometer speeds 3×10^{2} smaller (Spavieri et al, 2008).

2- Effects of the Aharonov-Bohm type and the photon mass

The possibility that the photon possesses a finite mass and its physical implications have been discussed theoretically and investigated experimentally by several researchers (Williams et al, 1971; Davis et al, 1975; Luo et al, 2003; Boulware and Deser, 1989). Originally, the finite photon mass m_γ (in centimeters^{-1}) has been related to the range of validity of the Coulomb law (Williams et al, 1971). If $m_\gamma \neq 0$ this law is modified by the Yukawa potential $U(r) = e^{-m_\gamma r}/r$, with $m_\gamma^{-1} = \hbar/m_{ph}c = \lambda_C/2\pi$ where m_{ph} is expressed in grams and λ_c is the Compton wavelength of the photon. There are direct and indirect tests for the photon mass and, among the classical tests, we mention the results of: (Williams et al, 1971), (Davis et al, 1975), yielding the range of the photon rest mass $m_\gamma^{-1} > 3 \times 10^{9}\,cm$, and (Luo et al, 2003), yielding the range $m_\gamma^{-1} > 1.66 \times 10^{13}\,cm$ (or $m_{ph} \simeq 10^{-51}\,\text{g}$). Within a quantum approach, the possibility that any effects due to m_{ph} become manifest has been discussed by Boulware and Deser (BD) (Boulware and Deser, 1989) in considering the solenoid of the AB effect. Proca's equation $\partial_\nu F^{\mu\nu} + m_\gamma^2 A^\mu = J_\mu$ yields the magnetic field $\mathbf{B} = \mathbf{B}_0 + \hat{\mathbf{k}} m_\gamma^2 \Pi(\rho)$ and, because of the extra mass-dependent term, BD obtained a nontrivial limit on the range of the transverse photon from a table-top experiment yielding $m_\gamma^{-1} > 1.4 \times 10^{7}\,cm$.

After the AB effect, other quantum effects of this type have been developed involving particles with various em properties (Spavieri, 1999a, b, 2006a, b; Sangster et al, 1993; Dowling et al, 1999). The impact of some of these new effects on the photon mass has been studied by Spavieri and Rodriguez (SR). Exploiting the mentioned recent techniques (Spavieri, 1999a, b, 2006a, b; Sangster et al, 1993; Dowling et al, 1999), SR use an effect involving a coherent superposition of beams of particles with opposite charge state $\pm q$ (Spavieri, 2006a, b) and obtain the photon mass limit $m_{ph} \simeq 10^{-51}$ g (Spavieri and Rodriguez, 2007), which greatly improves the result of BD.

Having exploited previously the magnetic AB effect, we consider now the scalar AB effect. In this effect charged particles interact with a uniform external scalar potential V. The standard phase φ_s acquired during the time of interaction is $\varphi_s = (1/\hbar)\int eV(t)dt$. In the actual experiment a conducting cylinder of radius R is set at the potential V during a time τ while electrons travel inside it. In agreement with the results of Ref. (Neyenhuis et al, 2007) and for the simple case of a beam traveling inside the cylinder for a short time interval τ, we derive the phase shift

$$\Delta\varphi_s = -\frac{em_\gamma^2}{4}(\rho^2 - R^2)V\frac{\tau}{\hbar}$$

Interferometric experiments may be performed with a precision of up to 10^{-4}, therefore, following the approaches of BD and SR we set $\Delta\varphi_s = \varepsilon$, $\varepsilon = 10^{-4}$ and obtain

$$m_\gamma^{-1} = \frac{R}{2}\sqrt{\frac{\pi V\tau}{\varepsilon(h/2e)}}$$

With reasonable and standard values for the parameters in the above equation we easily get the improved photon mass limit $m_{ph} \simeq 10^{-52}$ g . Indeed, the strength of the coupling $e\mathbf{A}/c$ of the AB magnetic phase is smaller than that of the coupling eV of the AB scalar phase. Thus, better results are expected in an approach with the scalar AB effect. Moreover, we hope to show elsewhere that by means of the techniques of (Spavieri, 1999a, b, 2006a, b); (Sangster et al, 1993); (Dowling et al, 1999) and (Spavieri and Rodriguez, 2007), much better values of m_{ph} can be reached, confirming that quantum approaches may well compete with classical ones.

This work was supported in part by the CDCHT (Project C-1413-06-05-A), ULA, Mérida, Venezuela.

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