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Electromagnetic momentum in frontiers of modern physics

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Abstract We review the role of the momentum of the electromagnetic (EM) fields $P_e$ in several areas of modern physics. $P_e$ represents the EM interaction in equations for matter and light waves propagation. As an application of wave propagation properties, a first order optical experiment which tests the speed of light in moving rarefied gases is presented. Within a classical context, the momentum $P_e$ appears also in proposed tests of EM interactions involving open currents and angular momentum conservation laws.

Moreover, $P_e$ is the link to the unitary vision of the quantum effects of the Aharonov-Bohm (AB) type and, for several of these effects, the strength of $P_e$ is evaluated. These effects provide a quantum approach to evaluate the limit of the photon mass $m_{ph}$. A new effect of the AB type, together with the scalar AB effect, provides the basis for table-top experiments which yield the limit $m_{ph} = 9.4 \times 10^{-52}g$, a value that improves the results achieved with recent classical and quantum approaches.

Keywords electromagnetic momentum, Aharonov-Bohm effect, magnetic model of light, Rowland experiment, photon mass

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

1 Introduction

Electromagnetic (EM) momentum is a classical physical quantity that appears in the standard description of the energy and momentum of EM fields, components of the EM tensor $\Theta^{\alpha\beta}$. We are considering here the interaction EM momentum $P_e$, a quantity that is attracting physicists’ attention as it arises in different scenarios of modern physics involving EM interactions. One of these scenarios is that of light propagation in slowly moving media [1-4]. Another is that of a unitary view of quantum nonlocal effects of the Aharonov-Bohm (AB) type [5-12]. More commonly, the interaction EM momentum $P_e$ appears as a nonvanishing quantity in EM experiments involving “open” or convection currents, while $P_e$ vanishes in the common EM experiments or interactions with closed currents or circuits [3, 4, 13, 14].

The main purpose of this article is to review the recent advances of physics involving the EM momentum $P_e$ and its role in the proposal of new tests or in making other advances, such as setting a new limit on the photon mass.

In the field of electromagnetism, a growing number of articles questioning the standard interpretation of special relativity have now appeared [15-25]. Some of the authors adhere to a point of view close to the historical works of Lorentz and Poincaré, who maintained the existence of a preferred frame. For example, Selleri [17, 18] has developed Bell’s idea [15, 16] and obtained a true Lorentzian theory, fully compatible with Einstein’s special relativity in its description of physical phenomena, but very different in interpretation and philosophy. Another Lorentzian theory, very close to Selleri’s formulation, was derived independently in Refs. [19-21].

It has been argued that these different formulations...
of Special Relativity are truly compatible only in vacuum, as differences may appear when light propagates in transparent moving media. Thus, Consoli and Costanzo [22–26], Cahill and Kitto [27, 28], and Guerra and de Abreu [19–21], point out that, for the experiments of the Michelson-Morley type, which are often said to have given a null-result, this is not the case and cite the famous work by Miller [29]. The claim of these authors is that the available data point towards a consistency of non-null results when the interferometer is operated in the “gas-mode”, corresponding to light propagating through a gas [22–26] (as in the case of air or helium, for instance, even in modern maser versions of optical tests [30–32]).

Moreover, tests that involve EM interactions in open currents or circuits have been reconsidered by Indorato and Masotto [33] who point out that these experiments are not completely reliable and may be inconclusive [3, 4]. Because of all this, physicists have recently proposed experiments about those predictions of the theory that have not been fully tested, or they have formulated untested assumptions that differ from the standard interpretation of Special Relativity [3, 4, 13, 14, 17–26].

The interesting point is that all the above-mentioned scenarios and polemical hypotheses are linked to the interaction EM momentum. Therefore, throughout this article we highlight the role of $P_\varepsilon$ in each one of these scenarios. In doing this we first link the wave equation for light propagation in moving media to the wave equation for matter waves in quantum effects of the AB type. This analogy leads to the proposal of new optical experiments which test the recent controversial hypothesis [22–26] of light propagation in rarefied moving media. Within classical electrodynamics we point out a new dedicated experiment that could feasibly test the nonconservation of the angular momentum of an isolated system in order to indirectly prove the reality of $P_\varepsilon$, a test that has never been performed and could settle the objections raised in Ref. [33].

Finally, we consider the unitary view of the effects of the AB type in terms of the interaction em momentum, with the aim of finding advanced applications to electrodynamics. This unitary view [10–12] has recently led to the discovery of a new quantum effect and the related table-top experiment that yields relevant improved values of the photon mass limit [72]. Using this quantum approach and by means of a table-top experiment that exploits the scalar AB effect, we determine the improved photon mass limit $m_\gamma = 10^{-52}$g, which is so far the best limit obtained by either a classical or quantum approach.

## 2 Untested aspects of electromagnetism

### 2.1 Wave equations for matter and light waves

To elucidate the role of EM momentum in modern physics, we start by considering the wave equations for matter and light waves and show how the interaction term $Q$ of these equations is related to $P_\varepsilon$ [36]. In general, with $T_{ik}$ the Maxwell stress-tensor, the covariant description of the em momentum leads to the four-vector em momentum $P_\varepsilon$ expressed as

$$ P_\varepsilon^a = -\gamma (v g + T_{ik}^M \beta^d) d^3 \sigma $$

$$ c P_\varepsilon^a = \gamma (u_{EM} - v \cdot g) d^3 \sigma $$

(1)

where $\beta = v/c$, and the em energy and momentum are evaluated in a special frame $K^{(0)}$ moving with velocity $v$ with respect to the laboratory frame. Here, $u_{EM}$ is the energy density and $S = gc$ is the energy flux or flow.

The analogy between the wave equation for light in moving media and that for charged matter waves has been pointed out by Hannay [1] and later addressed by Cook, Fearn and Milonni [2] 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 [5–9]. Generally, in quantum effects of the AB type [5–12] matter waves undergo an em interaction as if they were propagating in a flow of em origin that acts as a moving medium [10–12] and modifies the wave velocity. This analogy has led to the formulation of the so-called magnetic model of light propagation [1–4].

According to Fresnel [34], light waves propagating in a transparent, incompressible moving medium with uniform refraction index $n$, are dragged by the medium and develop an interference structure that depends on the velocity $u$ of the fluid ($u \ll c$). At the time of Fresnel the preferred inertial frame was that at rest with the so-called ether, which here may be taken to coincide with the laboratory frame. The speed achieved in the ether frame is

$$ v = \frac{c}{n} + \left(1 - \frac{1}{n^2}\right) u $$

(2)

as later corroborated by Fizeau [35]. Because of the formal analogy between the wave equation for light in slowly moving media and the Schrödinger equation for charged matter waves in the presence of the external vector potential $A$ (i.e., the magnetic Aharonov-Bohm effect), both equations contain a term that is generically referred to as the interaction momentum $Q$. Thus, the