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Search for a preferred frame of the photon

Jacek Ciborowski[*]
Department of Physics, University of Warsaw, Pasteura 5, PL-02-093 Warsaw, Poland

Jakub Rembieliński[†]
Department of Theoretical Physics, University of Łódź, Pomorska 149/153, PL-90-236 Łódź, Poland

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Polarization of photons is the key physical quantity in measurements of quantum spin correlations. According to a variant of quantum and classical electrodynamics formulated by us on the grounds of a hypothesis of existence of a preferred frame of reference (PF) a modification of the Malus law is expected if photonic states are frame dependent. A search for a quantum PF of the photon has been conducted by way of dedicated measurements of optical rotation using a high-precision commercial polarimeter. The data yield an upper limit of the PF velocity with respect to the Earth of 3.0 km/s at the time of the measurements, allowing us to reject the hypothesis that the cosmic microwave background radiation frame might be a PF for the photon.

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The concept of a preferred frame (PF) has appeared already decades ago in the context of specific research topics like, e.g., quantization of gravity or searches for violation of the Lorentz symmetry (predicted in theories beyond the standard physics). It has also been mentioned in relation to quantum mechanics (QM), particularly in connection to special relativity (Dirac [1,2], de Broglie–Bohm [3,4], Bell [5], Gisin *et al.* [6]). In particular, it has been known for several decades that there is a specific tension between QM and relativity in the context of quantum spin correlations. In experiments on this subject, polarization of photons is measured using respective polarizers oriented at predefined angles by two spacelike-separated observers. The tension regards for instance the instantaneous collapse of a nonlocal quantum state under a measurement performed by one of them. Such a phenomenon cannot be described in a Lorentz-covariant way within Einstein's relativity. Even a particular test of nonlocal quantum spin correlations, involving observers in a relative motion, has been performed using entangled photons [7] too. There is no credible explanation of the "spooky action at a distance" [8] to date. The measurements presented in this paper constitute a step towards a deeper insight into the intersection of QM and relativity, the concept of a PF being a way to approach this issue, in particular in regard to the polarization of photons.

A rigorous implementation of the idea of a PF at the classical level has been given by one of us in [9]. In this formalism the preferred frame is distinguished via the mechanism of spontaneous symmetry breaking of the synchronization group [10] in consequence of which the relativity principle is broken but the Lorentz covariance is preserved. The resulting PF special relativity is equivalent to the standard one in the kinematical sector of massive and massless particles. Since this formalism does not contain indications regarding the preferred frame it is natural to consider an intriguing candidate—a reference frame in which the cosmic microwave background radiation (CMBR) is isotropic. The velocity of the CMBR frame (in units of c) with respect to the Earth amounts to $V = 0.001\,23$ (368 km/s) in the direction $l = (263.85 \pm 0.10)^\circ$ and $b = (48.25 \pm 0.04)^\circ$ in terms of galactic coordinates (Leo constellation).

The existence of a hypothetical PF could also manifest at the quantum level. A Lorentz-covariant quantum mechanics with a preferred frame was formulated by one of us [11]. A promising area of research for the preferred frame lies in particular within the sector of nonlocal phenomena, like Einstein-Podolsky-Rosen correlations [12].

Recently we have undertaken efforts to clarify whether a hypothetical PF could show up in phenomena involving polarization of light. For this purpose we have developed a quantum description of photonic states [13] and formulated free quantum and classical electrodynamics [14], both on the grounds of this hypothesis. We exploited the Wigner-Mackey induction procedure to obtain the one-particle space of photonic states in this context. If $u^\mu = (u^0, \boldsymbol{V})$ and $k^\mu = (k^0, \boldsymbol{k})$ denote the timelike four-velocity of the PF as seen by a given inertial observer and the photon four-momentum, respectively, the hypothesis can be nontrivially realized only if monochromatic photonic states are frame dependent, i.e., are parametrized not only by k^μ (as in the standard case) but also by u^μ: $|k, u, \lambda\rangle$, where $\lambda = \pm 1$ is the photon helicity. It has been demonstrated that a modification of the Malus law at the quantum and classical levels can be predicted in this case. The effect can be illustrated as follows. Consider in one reference frame a source emitting a beam of linearly, vertically polarized light which passes through a polarizer (analyzer) perpendicular to the wave vector, $\boldsymbol{k}$, as depicted in Fig. 1. It has been shown in the aforementioned paper [14] that when the axis of the analyzer, initially aligned with the polarization vector of the light ray, is rotated by an angle δ about the beam direction, the Wigner phase ϕ is

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[*] cib@fuw.edu.pl

[†] jaremb@uni.lodz.pl

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given by

$$\phi(\delta, \chi, V) = 2 \arctan \frac{\sqrt{1-V^2} + [(1-\sqrt{1-V^2})\cos\chi - V]\cos\chi}{(1 - V\cos\chi)\cot(\delta/2) + [(1-\sqrt{1-V^2})\cos\chi - V]\sin\chi}, \tag{1}$$

where V is the length of the velocity vector $\boldsymbol{V}$ of the preferred frame with respect to the observer (in units of c) and χ is the angle between the vectors $\boldsymbol{k}$ and $\boldsymbol{V}$. If the axis of the analyzer is found in the initial configuration (oriented vertically), the intensity of light measured in the downstream detector is at maximum and equals I_0. However, if the polarizer axis is rotated by an angle δ about the $\boldsymbol{k}$ direction, the intensity of light is a function of the phase $\phi(\delta, \chi, V)$ in the PF scenario

$$I(\delta, \chi, V) = I_0 \cos^2 \phi(\delta, \chi, V) \tag{2}$$

and not of the angle δ alone, as would be in the standard case, $\propto I_0 \cos^2 \delta$. Moreover, the condition for vanishing intensity of light, $\phi(\delta, \chi, V) = \pi/2$, would be satisfied by values of δ in general different than $\pi/2$ for $V \neq 0$. Assuming the CMBR frame for the PF, the predicted difference can range up to about a few hundredths of a degree of arc, depending on the season as well as location and hour of the measurement on Earth. Seeing that an elementary macroscopic phenomenon makes a tool to test the PF scenario for light, it is tempting to test (1) and (2) in a simple experiment. Thus the aim of the present project was to measure the PF velocity with respect to Earth (or determining its upper limit) by searching for deviations from the Malus law in terms of directions on the celestial sphere. For simplicity, we have limited our studies to the case of one PF candidate—the CMBR frame. The subject of this research refers to the historical experiments of Michelson and Morley in 1887 [15,16] whose aim was to search for a relative motion of the Earth and the luminiferous aether—a hypothetical medium in which, according to the past ideas, light was supposed to propagate. Obviously, the present-day concept of PF, although reminiscent, should not be identified with the historical idea of the luminiferous aether.

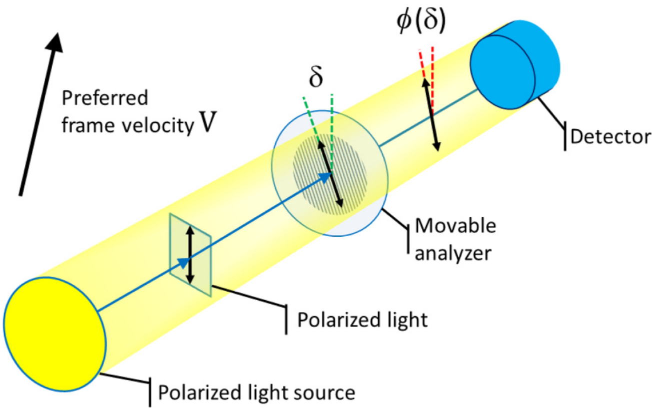

FIG. 1. Schematic presentation of a polarization experiment, involving the source and the detector at rest, to search for departures from the classical Malus law according to the PF electrodynamics, presented in this paper. Rotation of the analyzer slit by an angle δ (passive transformation) results in a change of intensity of light according to (2).

A high-precision commercial polarimeter was the apparatus of choice. The principle of operation of such instrument meets the basic requirements imposed by (1) and (2), as can be seen in Fig. 1. The measurements were done using the model AUTOPOL III S2 (APIII) of Rudolph Research Analytical [17], which has a resolution of 0.0003° in the range of the intended measurements (<1°) and is sufficiently accurate to detect the predicted effects, if present. A polarized, wavelength-selected (589 nm) light beam emitted from the source is propagated in the air (optically nonactive medium) through a distance of about 20 cm along the instrument axis (in typical applications it would be through the sample under study) to reach the movable polarizer (analyzer) and the detector placed behind it. In the APIII polarimeter the angle of optical rotation is measured by making use of the Malus law. The principle of measuring optical rotation with the APIII is based on rotating the analyzer by such an angle for which the intensity of light measured in the detector reaches minimum (and the value of 90° is subtracted from the result for display). Thus measurements for typical applications consist of two steps: (i) finding an internal reference value for the angle of rotation with an empty sample chamber for which the intensity of light in the detector is at minimum ("zeroing" the measuring device); (ii) subsequent measurement, i.e., rotating the analyzer to find a new position of zero intensity in the detector (e.g., with the sample cartridge inserted). In the case of the present search measurement, we made use of a similar procedure: (i) zeroing in the initial spatial orientation and (ii) measuring optical rotation after having changed the spatial orientation of the instrument axis. According to (2), if $V \neq 0$ then one would expect a nonzero result for optical rotation.

The following experimental methodology was adopted. The polarimeter was manipulated on a horizontal tabletop in a room with the ambient temperature stabilized to within ±0.1 °C. Denoting the azimuthal angle in the local horizontal coordinates by α, the instrument was oriented towards the N direction ($\alpha = 0^\circ$) and after performing "zero" a series of 30 measurements at 10-s intervals was completed. Additional studies have shown that the averaged values of multiple zero measurements were Gaussian-distributed with a dispersion even smaller than the resolution quoted by the manufacturer. After rotating the body of the instrument to reach one of the remaining cardinal directions $\alpha = 90^\circ$, 270°, or180° (E, W, or S, respectively), another series of 30 measurements was recorded in the new position. A difference of averaged values of optical rotation for the two series, $\Delta\phi_A(\alpha, t_c) = \langle \phi(\alpha, t_c) \rangle - \langle \phi(0, t_c) \rangle$, where t_c denotes the central time of the measurement, made the experimental result for the difference of phases for the two spatial configurations. Since the total measuring time of less than 10 min was needed to complete both steps, variations of the ambient temperature had a negligible effect on the result. Influence of the geomagnetic field on the APIII performance in the context of rotations was studied separately and no modification of measured values of

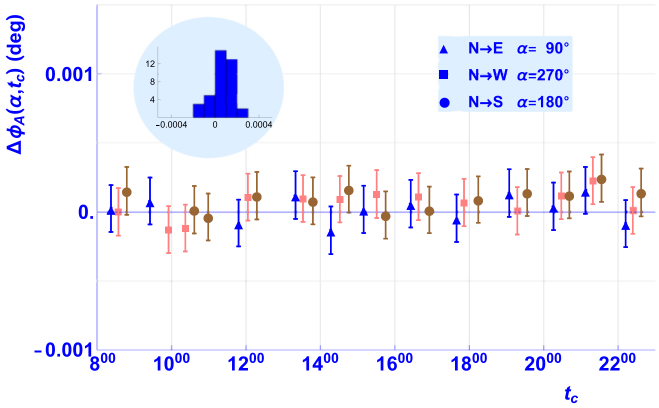

FIG. 2. Phase shift, $\Delta\phi_A$, relative to the N direction, as function of the time of the day (hour), t_c, for azimuthal rotations N → E ($\alpha = 90^\circ$), N → W ($\alpha = 270^\circ$), and N → S ($\alpha = 180^\circ$), where α is the azimuthal angle. Error bars denote statistical and systematic uncertainties added in quadrature. Inset: distribution of $\Delta\phi_A$ for all measurements.

optical rotation has been observed in an external magnetic field of comparable intensity. A separate study has shown that a systematic uncertainty associated with the movement of the polarimeter did not exceed $0.000\,15^\circ$. The total systematic uncertainty amounted to 0.0002°. The results of 38 series of measurements randomly distributed over a one-month period (February–March 2017), altogether covering about 16 h of the day, are shown in Fig. 2 as a function of the time of the day, t_c.

No evidence is seen for any time-dependent effect whose amplitude would exceed, in view of the experimental uncertainties, a few ten-thousandths of a degree—a magnitude falling far below that predicted theoretically according to (1), assuming the CMBR frame for the PF. These measurements can be compared to the theoretical prediction (1) in order to determine an upper limit on the PF velocity relative to the Earth; the angle χ can be expressed in terms of the azimuthal angle α in the local horizontal coordinates and the hour of the measurement, t_c, for a given geographical location and date. Assuming the velocity vector $\boldsymbol{V}$ aligned with the Earth-CMBR frame direction at the time of measurements and taking into account the total systematic uncertainty, one yields a limit of $V < 3.0$ km/s (10^{-5} c) at 95% c.l. We have checked that if different directions were assumed, the order of magnitude of such a result would remain the same; thus we had spared the effort of sampling the entire celestial sphere to determine limits corresponding to various directions as that would not have altered the conclusions that follow.

According to our working hypothesis [14] we conclude that the CMBR frame cannot act as the cosmological PF for photons. Thus the monochromatic photonic states are to high accuracy frame independent, i.e., can be parametrized only by momentum and helicity, $|k,\lambda\rangle$. Strictly speaking, one cannot *a priori* exclude a case of a local PF associated with the Earth (not even with the Solar System since the value $V < 3.0$ km/s falls significantly below the orbital velocity of the Earth), however it would be difficult to reconcile an idea of such a local PF with the geometrical nature of the expected effect. The above result for photons does not preclude the existence of a PF in nature as well as other phenomena in which the existence of a PF could make an appearance. The measurements reported in this paper have been performed using a polarimeter of resolution appropriate for the range of values expected from theoretical predictions (1), assuming the CMBR frame for the PF. Using a commercial polarimeter of higher resolution would allow one to decrease the value of the upper limit, however would not alter the above conclusions regarding the CMBR frame.

An additional remark is also due in the historical perspective. The measurement of interference by Michelson and Morley involved unpolarized light rays propagating along closed paths in their interferometer. Their null result is also in agreement with predictions of the PF special relativity [9] for those experimental conditions. Our present measurement can be recognized as matching that of Michelson and Morley with polarization of light, and not velocity, being the quantity under study. As a curiosity, the small value obtained for the upper limit of the velocity of the PF with respect to the Earth can be also confronted with their conclusion "...if there be any relative motion between the Earth and the luminiferous ether, it must be small ..." [16]. By undertaking this research, we have complemented the ideas which were guiding Michelson and Morley 130 years ago.

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