The interaction of the electric and magnetic dipole moments of a particle with the electromagnetic field is investigated in an approach that deals with four-dimensional (4D) geometric quantities. The new commutation relations for the 4D orbital and intrinsic angular momentums and also for the 4D dipole moments are introduced. The expectation value of the quantum 4-force, which holds in any frame, is worked out in terms of them. In contrast to it the whole calculation in [1] (J. Anandan, Phys. Rev. Lett. 85, 1354 (2000)) has been made only in the rest frame of the dipole. It is proved that, e.g., the expression for the 3D force $f_S$ in [1] is not relativistically correct and that the quantum 4-force is not zero in the experiments proposed in [1]. This means that the phase shifts that could be observed in such experiments are not topological phase shifts.

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1. Introduction

In a recent paper [1] Anandan has presented a covariant treatment of the interaction of the electric and magnetic dipole moments of a particle with the electromagnetic field. In [2] some objections to such treatment have been raised. A geometric approach to special relativity is considered in [2] in which a physical reality is attributed to the four-dimensional (4D) geometric quantities and not, as usually accepted, to the 3D quantities. The same approach and the results from [2], and [3], will be used in this paper. Instead of the interaction term, Eq. (5) in [1], much more general expression has been derived in [2], with tensors as 4D geometric quantities. In [1] Anandan also calculated the expectation value of the quantum force operator for two models: the dipole which is made of two particles with charges $q$, $-q$ and an elementary particle with its intrinsic magnetic and electric dipole moments. The whole calculation is made only in the rest frame of the dipole. Here, a more general expression for the force from [1] (for the second model), which holds in any frame, will be presented using the geometric approach. The 4-force is calculated by means of the new commutation relations for the orbital (1) and intrinsic angular momentum 4-vectors and also for the dipole moments (2). This force is compared with the force $f_S$, Eq. (26) in [1]. It is found that $f_S$ from [1] is not relativistically correct and that, contrary
to the assertion from [1], the quantum 4-force is not zero in the experiments proposed in [1].

2. 4D geometric approach

In the same way as in [2], [3] and [4], the 4D geometric quantities, that are defined without reference frames, i.e., the absolute quantities (AQs), e.g., the 4-vectors of the electric and magnetic fields \(E^a\) and \(B^a\), the electromagnetic field tensor \(F^{ab}\), the dipole moment tensor \(D^{ab}\), the 4-vectors of the electric dipole moment (EDM) \(d^a\) and the magnetic dipole moment (MDM) \(m^a\), the spin four-tensor \(S^{ab}\), etc. will be employed here. Also, we shall deal with the representations of the AQs in the standard basis. Note that usually, including [1], only one velocity is defined without reference frames, i.e., the absolute quantities \(\{E^a, B^a\}\), and the 4-vectors of the electric and magnetic fields \(E^a\) and \(B^a\), etc. will be employed here. Note that for the comparison with experiments we only need to choose the laboratory frame as our \(e_0\)-frame and then to represent the AQs \(E^a, m^a\) and \(B^a\) in that frame.

3. The quantum phase shift

Let us start quoting some results from [2], which are used in [3] and [4] as well. First, \(F^{ab}\), as the primary quantity for the whole electromagnetism, can be decomposed into \(E^a, B^a\) and the 4-velocity \(v^a\) of the observers who measure fields; \(F^{ab} = (1/c)(E^a v^b - E^b v^a) + \epsilon^{abcd} v_d B_d\), whence \(E^a, B^a\) are derived as \(E^a = (1/c) F^{ab} v_b\) and \(B^a = (1/2c^2) \epsilon^{abcd} F_{bc} v_d\), with \(E^a v_a = B^a v_a = 0\). The frame of “fiducial” observers, in which the observers who measure \(E^a, B^a\) are at rest with the standard basis \(\{e_μ\}\) in it is called the \(e_0\)-frame. In the \(e_0\)-frame \(E^0 = B^0 = 0\) and \(E^i = F^{0i}, B^i = (1/2c) \epsilon^{ij0k} F_{jk}\). The similar relations hold for \(D^{ab}\), \(d^a\) and \(m^a\), and the 4-velocity of the particle \(u^a\), \(u^a = dx^a/dτ\). Then \(D^{ab} = (1/c)(u^b/\epsilon_d - u^d/\epsilon_b) + (1/c^2) \epsilon^{abcd} u_d m_d\), \(m^a = (1/2) \epsilon^{abcd} D_{bc} u_d\), \(d^a = (1/c) D^{0a} u_0\), with \(d^a u_a = m^a u_a = 0\). Only in the particle’s rest frame (the \(K'\) frame) and the \(\{e'_μ\}\) basis \(d'^0 = m'^0 = 0\), \(d'^i = D'^{0i}\), \(m'^i = (c/2) \epsilon^{ij0k} D'_{jk}\). Observe that in [1] only one velocity \(u^a\) is used both for the determination of \(d^a, m^a\) from \(D^{ab}\) and the determination of \(E^a, B^a\) from \(F^{ab}\). (Actually in [1] only components are considered and the decompositions of \(F^{ab}\) and \(D^{ab}\) are never used.) This is objected in [2], where different 4-velocities \(v^a\) and \(u^a\) are introduced. The Eqs. (7) and (6) from [1] become \((1/2) F_{ab} D^{ba} = (1/c) D_{ab} u^a + (1/c^2) M_{ab} u^a = a^a u_b\), where \(a_b = (1/c) D_b + (1/c^2) M_b\), and \(D_b = d^a F_{ab}, M_b = m^a F_{ab} = (1/2) m^a \epsilon^{abcd} F_{cd}\). Hence Eq. (5) from [1] becomes more complicated.

\[
(1/2) F_{ab} D^{ba} = \text{written as the sum of two terms (}1/c^2\)[(E_a d^a + (B_a m^a))(\epsilon_b u^b)\] - (E_b u^b)(\epsilon_a d^a) - (B_b u^b)(\epsilon_a m^a)\] and \((1/c^3)[\epsilon^{abcd} (u_a E_b u_c m_d + c^2 d_a u_b u_c B_d)]\).

As seen from the second term it naturally contains the interaction of \(E^a\) with \(m^a\), and \(B^a\) with \(d^a\). Such interactions are required for the explanations of the Aharonov-Casher effect and the Röntgen phase shift, as shown in [2,4], and also of different methods of measuring EDMs, e.g., [7], which is considered in [3]. Note that for the comparison with experiments we only need to choose the laboratory frame as our \(e_0\)-frame and then to represent the AQs \(E^a, m^a\) and \(B^a\) in that frame.

2
The quantum phase shift that the particle experiences due to the field is given by Eqs. (9), (10) and (11) in [1], but with our $a_\mu$:

$$a_\mu = (1/c)d^n F_{\nu\mu} + (1/2c^2)m' \varepsilon_{\nu\mu\rho\lambda} F^{\rho\lambda}. \quad (1)$$

As said in [1] $d$ and $m$, and therefore $a_\mu$ are now operators which need not commute. ($E_\nu$ and $B_\nu$ are not operators; they are not quantized fields.) In [1] $a_\mu$ is given by Eq. (16). The components $a_0$ and $a_i$ in Eq. (16) in [1] are written in terms of $E$, $B$, $d$ and $m$ and it is stated that Eq. (16) is a low energy approximation. (The vectors in the 3D space will be designated in bold-face.) Our $a_\mu$ is obtained inserting the decomposition of $F^{\mu\nu}$ ($F^{\mu\nu} = (1/c)(E^\mu E^\nu - E^\nu E^\mu) + \varepsilon^{\mu\nu\rho\lambda} B_\rho B_\lambda$) into $a_\mu$ and it differs in several important respects relative to $a_\mu$ from [1]. First, we always deal with 4D quantities and not with the 3D vectors. Furthermore, we do not need to make a low energy approximation. The comparison with [1] can be made writing our $a_\mu$ in the $e_0$-frame. There, $v^\mu = (c, 0, 0, 0)$ and $E^0 = B^0 = 0$. Hence

$$a_0 = (-1/c)(d^0 E^1 + m^0 B^1),$$
$$a_i = (1/c)(d^0 E^i + m^0 B^i) + \varepsilon^{0ijk} d^j B^k - (1/c^2)\varepsilon^{0ijk} m^j E^k; \quad (2)$$

the metric is diag(1, -1, -1, -1), $\varepsilon^{0123} = 1$ and the components of the 3D vectors correspond to the components of the 4D vectors with upper indices.

Since the experiments are made in the laboratory frame (the $K$ frame) we shall choose that $K$ is our $e_0$-frame. As already said, in [1] only the particle’s 4-velocity is considered and all 3D vectors are written in $K'$, the particle’s rest frame. Hence, only when $K'$ is the $e_0$-frame then Eq. (16) from [1] is recovered, but with the components of the 4D quantities. However that case is physically unrealizable since in the experiments the observers do not “seat” on the particle. As seen from [2] this ambiguity of the theory from [1] is simply avoided in our formulation with two 4D geometric velocities $v^a$ and $u^a$. Furthermore, as explained in [8], [9] and [2], the transformations of $E$ and $B$ (e.g., [10] Eq. (11.149)), and also of $d$ and $m$, are all the “apparent” transformations (AT) of the 3D vectors and not the Lorentz transformations (LT). The AT do not refer to the same 4D quantity and, [8], [9] and [2], they are not relativistically correct transformations. Therefore, contrary to the assertion from [1], Eq. (16) cannot be transformed in a relativistically correct way to the laboratory frame. For our $a_\mu$ it will hold that $a^b = a^a e_\mu = a^{\mu'} e'_\mu$, as for all other 4D geometric quantities; it is the same quantity for relatively moving observers in $K$ and $K'$. Observe that all primed quantities are the Lorentz transforms of the unprimed ones. On the other hand such relation does not hold for the quantities from [1], e.g., $a^{\mu'}$ Eq. (16), $f'$ Eq. (25) and $f'_S$ Eq. (26), since all 3D vectors transform by the AT and not by the LT.

4. The quantum 4-force, I

In [1] the 4-force (in fact, the components in the $\{e_\mu\}$ basis) is defined by Eq. (12), which we write as $f^\mu \equiv m_\xi = \langle \psi | G^\mu_\nu | \psi \rangle \xi$, where $\xi^\mu$ denotes the
expectation value of the components of the 4-position operator, the dot denotes the derivation over the proper time of the particle, and $G_{\mu\nu} = \partial_{\mu}a_\nu - \partial_{\nu}a_\mu - (i/\hbar)\langle a_\mu, a_\nu \rangle$, Eq. (11) in [1]. In our calculation the 4-force, as a geometric quantity, will be written as $f^\mu e_\mu = \langle \psi \mid G^\mu_\nu \mid \psi \rangle u^\nu e_\mu$, where, from now on, the expectation value $\xi$ is denoted as $u^\nu$. In [1], the forces $f'$ Eq. (25) and $f'_S$ Eq. (26) are determined in the rest frame of the particle (i.e., the dipole) where $f'^0 = 0$ (in our notation all quantities in Eqs. (25) and (26) are the primed quantities). There, in [1], it is argued “The force in an arbitrary inertial frame may be obtained by Lorentz transforming the above $f^\mu$ (Eq. (25), our remark) to this frame.” But, as discussed above, this statement is not true since the transformations of 3D quantities from Eqs. (25) and (26) are the AT and not the LT. Therefore we shall derive the expression for $f'_S e_\mu$ for an elementary particle that holds in any inertial frame.

When deriving $f_S$, Eq. (26) in [1], it is asserted: “For an elementary particle, the only intrinsic direction is provided by the spin $S$. Then its intrinsic $\mu = \gamma SS$ and its intrinsic $d = \delta_S S$, where $\delta_S$ is a constant.” (In [1], as already said, the unprimed quantities are in the particle’s rest frame $K'$.) Thus both the 3D MDM $m'$ and the 3D EDM $d'$ (our notation) of an elementary particle are determined by the usual 3D spin $S'$. Then, only the commutation relation for the components of the 3D spin operator $\langle [S^i, S^j] = \mathfrak{d} \varepsilon^{ijk} S_k \rangle$ are used in the calculation of the commutator $[a_i, a_0]$, i.e., the commutators of $m'$, $d'$ with $m'$, $d'$.

Recently, [9] and [3], it is shown that the angular momentum four-tensor $M^{ab}, M^{ab} = x^a p^b - x^b p^a$, can be decomposed into the “space-space” angular momentum of the particle $L^a$ and the “time-space” angular momentum $K^a$ (both with respect to the observer with velocity $u^\nu$). In [3] a similar consideration is applied to the intrinsic angular momentum, the spin of an elementary particle. The primary quantity with the definite physical reality is considered to be the spin four-tensor $S^{ab}$, which is decomposed into two 4-vectors, the usual “space-space” intrinsic angular momentum $S^a$ and the “time-space” intrinsic angular momentum $Z^a$, see [3]. Thus, [3] introduces a new “time-space” spin $Z^a$, which is a physical quantity in the same measure as it is the usual “space-space” spin $S^a$. In all usual approaches only $L$ is considered to be a well-defined physical quantity, whose components transform according to the AT, see, e.g., Eq. (11) in [11], $L_x = L'_x, L_y = \gamma (L'_y - \beta K'_y), L_z = \gamma (L'_z + \beta K'_y)$; the transformed components $L_i$ are expressed by the mixture of components $L'_i$ and $K'_i$. (These transformations are the same as are the AT for the components of $B$, e.g., [10] Eq. (11.148), since $L$ correspond to $-B$ and $K$ correspond to $-E$.) In our geometric approach a physical reality is attributed to the whole $M^{ab} (S^{ab})$ or, equivalently, to the angular momentums $L^a (S^a)$ and $K^a (Z^a)$, which contain the same physical information as $M^{ab} (S^{ab})$ only when they are taken together. The components $L^\mu$, or $K^\mu$, transform by the LT again to the components $L'^\mu (L'^0 = \gamma (L^0 - \beta L^1), L'^1 = \gamma (L^1 - \beta L^0)), L'^{2,3} = L^{2,3}$, for the boost in the $x^1$ - direction), and the same holds for $S'^\mu$, or $Z'^\mu$. Furthermore, in [3], an essentially new connection between dipole moments and the spin is for-
mulated in terms of the corresponding 4D geometric quantities as \( m^a = \gamma_S S^a \), \( d^a = \delta_Z Z^a \), where \( \gamma_S \) and \( \delta_Z \) are constants. In the particle’s rest frame and the \( \{e^i_\mu\} \) basis \( d^0 = m^0 = 0 \), \( d^i = \delta_Z Z^i \), \( m^i = \gamma_S S^i \). Thus, [3], the intrinsic MDM \( m^a \) of an elementary particle is determined by the “space-space” intrinsic angular momentum \( S^a \), while the intrinsic EDM \( d^a \) is determined by the “time-space” intrinsic angular momentum \( Z^a \).

5. New commutation relations

Hence, in the calculation of the commutator \([a_\mu, a_\nu]\) the usual commutation relations will be generalized taking into account the results from [3]. From the Lie algebra of the Poincaré group we know that \([M^{\mu\nu}, M^{\rho\sigma}] = -i\hbar(-g^{\mu\rho}M^{\nu\sigma} + g^{\mu\sigma}M^{\nu\rho} - g^{\nu\rho}M^{\mu\sigma} - g^{\nu\sigma}M^{\mu\rho})\). Then, one has to take into account the decomposition of the components \( M^{\mu\nu} \) into \( L^\mu \) and \( K^\mu \) (they are now operators), \( M^{\mu\nu} = (1/c)[\ell(\mu K^\nu - v^\mu K^\nu) + \varepsilon^{\mu
u\rho\sigma}L_\rho v_\sigma] \), where, for a macroscopic observer, \( v^\nu \) can be taken as the classical velocity of the observer (the components), i.e., not the operator. This leads to the new commutation relations

\[
[L^\mu, L^\nu] = (i\hbar/c)\varepsilon^{\mu\alpha\beta}\ell_\alpha v_\beta, \quad [K^\mu, K^\nu] = (-i\hbar/c)\varepsilon^{\mu\alpha\beta}K_\alpha v_\beta, \\
[L^\mu, K^\nu] = (i\hbar/c)\varepsilon^{\mu\alpha\beta}L_\alpha v_\beta, \quad (3)
\]

which, in the \( e_0 \)-frame, where \( L^0 = K^0 = 0 \), reduce to the usual commutators for the components of \( L \) and \( K \) (as operators), see, e.g., [12] Eqs. (2.4.18) - (2.4.20).

The same commutators as in (3) hold for the intrinsic angular momentums (the components) \( S^\mu \) and \( Z^\mu \); \( S^\mu \) replaces \( L^\mu \), \( Z^\mu \) replaces \( K^\mu \) and the velocity of the particle (the components) \( v^\mu \), i.e., the expectation value \( \xi \), replaces the velocity of the observer \( v^\mu \),

\[
[S^\mu, S^\nu] = (i\hbar/c)\varepsilon^{\mu\alpha\beta}S_\alpha u_\beta, \quad [Z^\mu, Z^\nu] = (-i\hbar/c)\varepsilon^{\mu\alpha\beta}Z_\alpha u_\beta, \\
[S^\mu, Z^\nu] = (i\hbar/c)\varepsilon^{\mu\alpha\beta}S_\alpha u_\beta. \quad (4)
\]

Note that in [1] only the commutators \([L_i, L_j]\) and \([S_i, S_j]\) appear. Taking into account the relations \( m^\mu = \gamma_S S^\mu \) and \( d^\mu = \delta_Z Z^\mu \) one can express the commutation relations for \( m^\mu \) and \( d^\mu \) in terms of those for \( S^\mu \) and \( Z^\mu \)

\[
[m^\mu, m^\nu] = \gamma_S^2 [S^\mu, S^\nu], \quad [d^\mu, d^\nu] = \delta_Z^2 [Z^\mu, Z^\nu], \quad [m^\mu, d^\nu] = \gamma_S \delta_Z [S^\mu, Z^\nu]. \quad (5)
\]

6. The quantum 4-force, II

Then, the 4-force (components) \( f_5^\mu \) can be calculated using (5) and (4). The obtained expressions for \( f_5^\mu \) are much more general but also much more complicated than those in [1]. First we consider the terms which come from \( \partial_\mu a_\nu - \partial_\nu a_\mu \) in \( G_{\mu\nu} \). This term
\[
(1/c) \langle \psi | \partial_{\mu}[d^\alpha(E_\alpha v_\mu - E_\mu v_\alpha)] - \partial_{\nu}[d^\alpha(E_\alpha v_\mu - E_\mu v_\alpha)] | \psi \rangle u^\nu g^{\lambda\mu} e_\lambda
\]
in \( f_2^0 e_\lambda \) will correspond to \( \nabla'(d' \cdot B') \) in \( f_2^0 \) (our notation), Eq. (26) in [1], when \( K' \) is taken to be the \( e_0 \)-frame, i.e., when \( u^\mu = v^\mu = (c, 0, 0, 0) \). Similarly the term which will correspond to \( \nabla'(m' \cdot B') \) in \( f_2^0 \) is obtained from the above quoted term replacing \( d^\alpha, E^\alpha \) with \( m^\alpha, B^\alpha \). The other two terms in \( \partial_{\mu} a_\nu - \partial_{\nu} a_\mu \) are \((1/c)\{\partial_{\mu} [e_{\alpha\sigma\rho} d^\alpha v^\sigma B^\rho] - \mu \leftrightarrow \nu \} \) and \((1/2e^3)\{\partial_{\mu} [e_{\alpha\sigma\rho} m^\alpha (E^\sigma v^\rho - E^\rho v^\sigma)] - \mu \leftrightarrow \nu \} \) which, when \( K' \) is the \( e_0 \)-frame, correspond to the third and the fourth term, respectively, in Eq. (26) in [1].

The commutator \([a_\mu, a_\nu] \) will give the additional sixteen terms in our \( f_2^0 e_\lambda \), which are easily determined using [5] and the commutation relations for \( S^\mu \) and \( Z^\mu \). In the case when \( K' \) is the \( e_0 \)-frame then only four terms remain. From the following part \(- (i/\hbar) [a_\mu, a_\nu] \) of \( G_{\mu\nu} \) we find the general expressions for the mentioned four terms. The two terms are: \((-\gamma_S/2c^5)\varepsilon_{\alpha\sigma\rho}e^{\alpha\beta\gamma\delta}(E^\sigma v^\rho - E^\rho v^\sigma)(B_\alpha v_\beta - B_\beta v_\alpha)u_\gamma u_\delta \), and \((-\gamma_S/c^6)\varepsilon_{\alpha\sigma\rho}e^{\alpha\beta\gamma\delta}(E_\sigma E^\rho - E_\rho E^\sigma)(B_\alpha v_\beta - B_\beta v_\alpha)\partial_\gamma \partial_\delta \). They determine two terms in \( f_2^0 e_\lambda \), which correspond to \(-\gamma_S/c^2 \langle m' \cdot B' \rangle \times E' \) and \(-\gamma_S/c^2 \langle d' \times E' \rangle \times E' \), respectively, in \( f_2^0 \). The other two terms are: \((-\gamma_S/c^5)\varepsilon_{\alpha\sigma\rho}e^{\alpha\beta\gamma\delta}(B_\alpha v_\beta - B_\beta v_\alpha)B^\rho v^\sigma u_\gamma u_\delta \), and \((-\gamma_S/6c^6)\varepsilon_{\alpha\sigma\rho}e^{\alpha\beta\gamma\delta}(E_\alpha v_\beta - E_\beta v_\alpha)B^\rho \partial_\gamma \partial_\delta \). They would correspond to \(-\gamma_S \langle d' \times B' \rangle \times B' \) and \(-\gamma_S/6 \langle d' \times E' \rangle \times B' \). Such terms do not exist in \( f_2^0 \). In the first experiment it is taken that the interfering particles have magnetic moment, but no electric charge and zero or negligible electric dipole moment, as in a neutron interferometer. The entire interferometer is subject to a homogeneous
and time independent electric field $E$ that is parallel to a pair of arms of the interferometer. From the expression for $G_{\mu\nu}$ and $f_{\lambda}^S$, Eq. (26) in [1], it is visible that both quantities are zero in the considered experiment, as argued in [1]. However, here, in contrast to [1], this experiment will be examined directly in $K$, i.e., $K$ is chosen to be the $e_0$-frame. First, when $B^\mu = d^\mu = 0$ then there are only two terms in $G_{\mu\nu}$ and consequently in $f_{\lambda}^Se_{\lambda}$, which are different from zero. (Remember that $f_{\lambda}^Se_{\lambda}$ is formed taking the expectation value of $G_{\mu\nu}$ and multiplying it by $u_\nu g_{\lambda\mu}e_\lambda$.) The general forms of these terms (for $G_{\mu\nu}$) are: 

$$ \left( \frac{\delta^2}{c^5} \gamma_S \right) \varepsilon^{\alpha\beta\gamma\delta} \varepsilon_{\mu\nu\rho\sigma} (E^\mu E^\nu - E^\rho E^\sigma) (E^\sigma E^\rho - E^\sigma E^\rho) m_{\gamma\delta}.$$ 

In $K$ it holds that $v^\mu = (c, 0, 0, 0)$ and hence $E^0 = 0$. Inserting these values into the quoted terms one can see that $f_{\lambda}^Se_0 \neq 0$ (from the first term) and $f_{\lambda}^Se_i \neq 0$ (from both terms). For the lack of space these expressions will not be written. The same would happen for the dual experiment that is proposed in [1]. This consideration proves our assertion from the beginning of this paragraph. This means that the phase shifts in these experiments are not due to force-free interaction of the dipole, i.e., they are not topological phase shifts. The same would happen for the Aharonov-Casher and the Röntgen phase shifts; the only difference is that for them the fields are not homogeneous. It is interesting to note, as shown in [4], that even the classical 4-force $(1/2)D^{ab}\partial_c F_{ab}$ is not zero in the case of the Aharonov-Casher and the Röntgen effects. Also, it is worth noting that the first model from [1] can be treated in a similar way using the commutation relations for the 4D quantities. The results from [1] are already used in several papers, e.g., [13]. Our discussion applies in the same measure to their results.

8. Conclusions

In conclusion, here it is revealed that a unified and fully relativistic treatment of the interaction from [1] can be achieved when in all steps of the calculation only the 4D geometric quantities are used and not the 3D quantities. It is expected that the obtained commutation relations for the angular momentums [2], and the analogous ones for the intrinsic angular momentums [4], and those for the dipole moments [5], will greatly influence the existing quantum field theories. Finally, the result that the quantum 4-force $f_{\lambda}^Se_{\lambda}$ for the second model from [1] (and similarly $f_{\lambda}^Se_{\lambda}$ for the first model) is different from zero will significantly change the usual explanations of the quantum phase shifts in, e.g., the neutron interferometry, the Aharonov-Casher and the Röntgen effects.

References

[1] J. Anandan, Phys. Rev. Lett. 85 (2000) 1354.
[2] T. Ivezić, Phys. Rev. Lett. 98 (2007) 108901.
[3] T. Ivezić, physics/0703139.
[4] T. Ivezić, Phys. Rev. Lett. 98 (2007) 158901.
[5] A. Einstein, Ann. Physik 17 (1905) 891, tr. by W. Perrett and G.B. Jeffery, in The Principle of Relativity, Dover, New York, 1952.
[6] T. Ivezić, Found. Phys. Lett. 18 (2005) 401.
[7] F.J.M. Farley et al., Phys. Rev. Lett. 93 (2004) 052001.
[8] T. Ivezić, Found. Phys. 33 (2003) 1339; T. Ivezić, Found. Phys. Lett. 18 (2005) 301; T. Ivezić, Found. Phys. 35 (2005) 1585.
[9] T. Ivezić, Found. Phys. 36 (2006) 1511.
[10] J.D. Jackson, Classical Electrodynamics, 3rd ed. Wiley, New York, 1998.
[11] J. D. Jackson, Am. J. Phys. 72 (2004) 1484.
[12] S. Weinberg, The Quantum Theory of Fields, Volume I, Foundations, Cambridge University, Cambridge, 1999.
[13] C. Furtado and C. A. de Lima Ribeiro, Phys. Rev. A 69 (2004) 064104.