The Intrinsic Electric Dipole Moment and the “Time-Space” Intrinsic Angular Momentum

Tomislav Ivezić
Rudjer Bošković Institute, P.O.B. 180, 10002 Zagreb, Croatia
ivezi@irb.hr

In this paper it is found that the spin four-tensor $S^{ab}$ can be decomposed into two 4-vectors, the usual “space-space” intrinsic angular momentum $S^a$ and a new one, the “time-space” intrinsic angular momentum $Z^a$, which are both equally well physical quantities. It is shown that an electric dipole moment (EDM) of a fundamental particle, as a four-dimensional geometric quantity, is determined by $Z^a$ and not, as generally accepted, by the spin $S$. Also it is proved that neither the $T$ inversion nor the $P$ inversion are good symmetries in the 4D spacetime. In our geometric approach only the world parity $W$, $x^a \rightarrow -x^a$, is well-defined in the 4D spacetime. The consequences for elementary particle theories and experiments that search for EDM are briefly discussed.

PACS: 03.65.Sq; 11.30.Er; 13.40.Em

Keywords: “Time-space” intrinsic angular momentum; EDM

1. Introduction

In this geometric approach it is considered that a physical reality is attributed to the four-dimensional (4D) geometric quantities and not, as usually accepted, to the 3D quantities. Using a general rule for the decomposition of a second rank antisymmetric tensor the spin four-tensor $S^{ab}$ is decomposed into two 4-vectors, the usual “space-space” intrinsic angular momentum $S^a$ and a new one, the “time-space” intrinsic angular momentum $Z^a$. It is shown that an electric dipole moment (EDM) of a fundamental particle, as a 4D geometric quantity, is determined by $Z^a$ and not by the spin $S$. (The vectors in the 3D space will be designated in bold-face.) Then it is explicitly shown that neither the $T$ inversion nor the $P$ inversion are good symmetries in the 4D spacetime. In our geometric approach only the world parity $W$, $x^a \rightarrow -x^a$, is well-defined in the 4D spacetime. Hence, in this approach, the existence of an EDM is not connected in any way with $T$ violation, or, under the assumption of CPT invariance, with CP violation.

2. 4D geometric approach

We shall deal with 4D geometric quantities that are defined without reference frames. They will be called 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) $m^a$, etc. In the following we shall rely on the results and the explanations from [1], see also references therein. As said in [1], according to [2], $F^{ab}$ can be taken as the primary quantity for the whole electromagnetism. $E^a$ and $B^a$ are then derived from $F^{ab}$ and the 4-velocity of the observers $v^a$: $F^{ab} = (1/c)(E^a v^b - E^b v^a) + \varepsilon^{abcd} v_c B_d$, whence $E^a = (1/c)F^{ab}v_b$ and $B^a = (1/c^2)\varepsilon^{abcd}F_{bc}v_d$, 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 $\{e_\mu\}$ in it is called the $e_0$-frame. (The standard basis $\{e_\mu; 0, 1, 2, 3\}$ consists of orthonormal 4-vectors with $e_0$ in the forward light cone. It corresponds to the specific system of coordinates with Einstein’s synchronization [3] of distant clocks and Cartesian space coordinates $x^i$.) In the $e_0$-frame $E^0 = B^0 = 0$ and $E^i = F^{i0}$, $B^i = (1/2c)\varepsilon^{ijk0}F_{jk}$. Therefore $E^a$ and $B^a$ can be called the “time-space” part and the “space-space” part, respectively, of $F^{ab}$. The reason for the quotation marks in “time-space” and “space-space” will be explained in Section 4.

In fact, as proved in, e.g., [4], any second rank antisymmetric tensor can be decomposed into two 4-vectors and a unit time-like 4-vector (the 4-velocity/c). This rule can be applied to $D^{ab}$. As shown in [1], $D^{ab}$ is the primary quantity for dipole moments. Then $d^a$ and $m^a$ are derived from $D^{ab}$ and the 4-velocity of the particle $u^a$

$$
D^{ab} = (1/c)(u^a d^b - u^b d^a) + (1/c^2)\varepsilon^{abcd} u_c m_d,
$$

$$
m^a = (1/2)\varepsilon^{abcd} d_{bc} u_d, \quad d^a = (1/c)D^{ba} u_b,
$$

(1)

with $d^a u_a = m^a u_a = 0$. Only in the particle’s rest frame (the $K'$ frame) and the $\{e'_\mu\}$ basis $d^0 = m^0 = 0$, $d^i = D^{i0}$, $m^i = (c/2)\varepsilon^{ijk0}D'_{jk}$. Therefore $d^a$ and $m^a$ can be called the “time-space” part and the “space-space” part, respectively, of $D^{ab}$.

In our geometric approach the interaction between $F^{ab}$ and $D^{ab}$ as 4D AQs can be written as the sum of two terms, [1],

$$
(1/2)F_{ab}D^{ba} = (1/c^3)[((E_a d^a) + (B_a m^a))(v_b d^b) - (E_a u^a)(v_b u^b) - (B_a u^a)(v_b m^b) + (1/c^3)\varepsilon^{abcd}(v_a E_b u_c m_d + c^2 d_a u_b v_c B_d)].
$$

(2)

As seen from the last two terms they naturally contain the interaction of $E^a$ with $m^a$, and $B^a$ with $d^a$, which are required for the explanations of the Aharonov-Casher effect and the Röntgen phase shift [1,5], and also of different methods of measuring EDMs, e.g., such one as in [6]. Moreover, there is no need for any transformation. We only need to choose the laboratory frame as our $e_0$-frame and then to represent the AQs $E^a$, $m^a$, and $B^a$, $d^a$ in that frame.

Furthermore, it is shown in [7] that the angular momentum four-tensor $M^{ab}$, $M^{ab} = x^a p^b - x^b p^a$ (i.e., in [7] the bivector $\bar{M} = x \wedge p$) 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 $v^a$)

$$
M^{ab} = (1/c)[(v^a K^b - v^b K^a) + \varepsilon^{abcd} L_{cd}],
$$

$$
L^a = (1/2c)\varepsilon^{abcd} M_{bc} v_d, \quad K^a = (1/c)M^{ba} v_b,
$$

(3)

2
3. “Time-space” intrinsic angular momentum and the intrinsic EDM

This consideration can be directly applied to the intrinsic angular momentum, the spin of an elementary particle. In the usual approaches, e.g., [9] Sec. 11.11 A., the relativistic generalization of the spin $S$ from a 3-vector in the particle’s rest frame is obtained in the following way: “The spin 4-vector $S^\alpha$ is the dual of the tensor $S^{\alpha\beta}$ in the sense that $S^\alpha = (1/2c)\varepsilon^{\alpha\beta\gamma\delta} u_\beta S_{\gamma\delta}$, where $u^\alpha$ is the particle’s 4-velocity.” The whole above discussion about $F^{ab}$, $D^{ab}$ and $M^{ab}$ implies a more general geometric formulation of the spin of an elementary particle. In our approach the primary quantity with the definite physical reality is the spin four-tensor $S^{ab}$, which can be decomposed into two 4-vectors, the usual “space-space” intrinsic angular momentum $S^a$ and the “time-space” intrinsic angular momentum $Z^a$

$$S^{ab} = (1/c)[(u^a Z^b - u^b Z^a)] + \varepsilon^{abcd} S_{cd} u_d,$$

$$S^a = (1/2c)\varepsilon^{abcd} S_{cd} u_d, \quad Z^a = (1/c)S^{ab} u_a,$$  \hspace{1cm} (4)

where $u^a = dx^a/d\tau$ is the 4-velocity of the particle and it holds that $S^a u_a = Z^a u_a = 0$; only three components of $S^a$ and $Z^a$ in any basis are independent. $S^a$ and $Z^a$ depend not only on $S^{ab}$ but on $u^a$ as well. Only in the particle’s rest frame, the $K'$ frame, and the $\{e'_{\mu}\}$ basis, $u^a = c\epsilon^a_0$ and $S^{0a} = Z^{0a} = 0$, with $L^\alpha v_\alpha = K^\alpha v_\alpha = 0$. $L^\alpha$ and $K^\alpha$ depend not only on $M^{ab}$ but also on $v^a$. Only in the $e_0$-frame $L^0 = K^0 = 0$ and $L^i = (1/2)\varepsilon^{ijk} M_{jk}$, $K^i = M^{0i}$. $L^i$ and $K^i$ correspond to the components of $\mathbf{L}$ and $\mathbf{K}$ that are introduced, e.g., in [8]. However Jackson [8], as all others, considers that only $\mathbf{L}$ is a physical quantity whose components transform according to Eq. (11) in [8], $L_x = L'_x$, $L_y = \gamma(L'_y - \beta K'_z)$, $L_z = \gamma(L'_z + \beta K'_y)$; the transformed components $L_i$ are expressed by the mixture of components $L_k$ and $K'_k$. The components of $\mathbf{B}$ (and of $\mathbf{E}$) are transformed in the same way, see [9] Eq. (11.148). It is recently [10] proved that the usual transformations of $\mathbf{E}$, $\mathbf{B}$, [9] Eq. (11.149), are not the Lorentz transformations (LT) (the boosts) but the “apparent” transformations (AT), which do not refer to the same 4D quantity and therefore they are not relativistically correct transformations. (For the term AT see [11].) Similarly it is proved in [7] (and [12]) that the transformations of $\mathbf{L}$, Eq. (11) in [8], and of all other 3D quantities, are also the AT and not the LT. In our approach, [7], a physical reality is attributed to the whole $M^{ab}$ or, equivalently, to the angular momentums $L^a$ and $K^a$, which together contain the same physical information as $M^{ab}$. Then, e.g., the AQ $L^a$ can be represented as $L^a = L'^e e_\mu = L'^\mu e_\mu$, where all primed quantities are the Lorentz transforms of the unprimed ones. The components $L^\mu$ 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), while the basis $e_\mu$ transforms by the inverse LT to $e'_\mu$ leaving the whole 4D AQ $L^a$ unchanged. Different representations (relatively moving observers and/or different bases) of $L^a$ represent the same 4D physical quantity $L^a$. All this holds for any 4D AQ, e.g., $E^a$, $B^a$, $d^a$, $m^a$, etc.
\[ S'^i = (1/2c)\varepsilon^{ijk} S'_j k, \quad Z'^i = S'^0i. \] The definition (4) essentially changes the usual understanding of the spin of an elementary particle. It 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 [13] it is asserted: “For an elementary particle, the only intrinsic direction is provided by the spin \( S \). Then its intrinsic \( \mu = \gamma S^a S^a \) and its intrinsic \( d = \delta Z^a \), where \( \delta S \) is a constant.” (In [13] the unprimed quantities are in the particle’s rest frame.) Thus both the MDM \( m' \) and the EDM \( d' \) (our notation) of an elementary particle are determined by the usual 3D spin \( S' \). In the usual approaches such result is expected because only the “space-space” intrinsic angular momentum is considered to be a well-defined physical quantity. However in our geometric approach a definite physical reality is attributed to \( S^{ab} \), or to \( S^a \) and \( Z^a \) taken together, see (4). The intrinsic direction in the 3D space is not important in the 4D spacetime since it does not correctly transform under the LT.

The whole above consideration suggests that the connection between dipole moments and the spin has to be formulated in terms of the corresponding 4D geometric quantities as

\[ m^a = \gamma S^a, \quad d^a = \delta Z^a, \]

where \( \gamma S \) and \( \delta Z \) are constants; \( \gamma S \) is known but \( \delta Z \) has to be determined from experiments. In the particle’s rest frame and the \( \{ e'_\mu \} \) basis, \( u^a = ce'_0 \) and \( d'^0 = m'^0 = 0, \quad d'^a = \delta Z'^a, \quad m'^i = \gamma S'^0 i. \) Thus in our approach 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 \( Z^a \). The relation (5) with 4D geometric quantities \( m^a, S^a, d^a \) and \( Z^a \) is a fundamentally new result that is not earlier mentioned in the literature. Obviously the elementary particle theories will need to change taking into account our relations (4) and (5).

4. T and P inversions and the world parity \( W \)

In elementary particle theories the existence of an EDM implies the violation of the time reversal \( T \) invariance. Under the assumption of CPT invariance a nonzero EDM would also signal CP violation. As said in [14]: “it is the \( T \) violation associated with EDMs that makes the experimental hunt interesting.” Let us briefly consider the connection between the EDM and the \( T \) invariance. Reversing time would reverse the spin direction but leave the EDM direction unchanged (the charge distribution does not change). Thus, with \( t \rightarrow -t \), \( S \rightarrow -S \), but \( d \rightarrow d \). However, as in [13], \( d \) is determined as \( d = dS/S \). Hence \( d \) must be parallel to the spin \( S \); it is considered that \( S \) is the only available vector in the rest frame of the particle. This leads that \( d \rightarrow -d \), i.e., \( d \rightarrow 0 \). As stated in [14]: “the alignment of spin and EDM is what leads to violations of \( T \) and \( P \).”

From the viewpoint of our geometric approach neither \( T \) inversion nor \( P \) inversion are well-defined in the 4D spacetime; they are not good symmetries.
For the position 4-vector as an AQ \( x^a \) only the world parity \( W \) (for the term see, e.g., [15]), according to which \( x^a \rightarrow -x^a \), is well-defined in the 4D spacetime. In general, the \( W \) inversion cannot be written as the product of \( T \) and \( P \) inversions. But this will be possible for the representations of \( W, T \) and \( P \) in the standard basis \( \{ e_\mu \} \). It is easy to see that, e.g., \( T \) inversion is not well-defined and that it depends, for example, on the chosen synchronization.

As explained, e.g., in [16], different systems of coordinates (including different synchronizations) are allowed in an inertial frame and they are all equivalent in the description of physical phenomena. Thus in [16] two very different, but completely equivalent synchronizations, Einstein’s synchronization and a drastically different, nonstandard, radio (“r”) synchronization, are exposed and exploited throughout the paper. The “r” synchronization is commonly used in everyday life and not Einstein’s synchronization. In the “r” synchronization there is an absolute simultaneity. As explained in [17]: “For if we turn on the radio and set our clock by the standard announcement ”...“at the sound of the last tone, it will be 12 o’clock,” then we have synchronized our clock with the studio clock according to the “r” synchronization. In order to treat different synchronizations, Einstein’s synchronization and a different synchronization (including different synchronizations) are allowed in an inertial frame and they are all equivalent synchronizations. Thus in [16] two very different, equivalent synchronizations, Einstein’s synchronization and a drastically different, nonstandard, radio (“r”) synchronization, are exposed and exploited throughout the paper.

For the position 4-vector as an AQ \( x^a \) only the world parity \( W \) (for the term see, e.g., [15]), according to which \( x^a \rightarrow -x^a \), is well-defined in the 4D spacetime. In general, the \( W \) inversion cannot be written as the product of \( T \) and \( P \) inversions. But this will be possible for the representations of \( W, T \) and \( P \) in the standard basis \( \{ e_\mu \} \). It is easy to see that, e.g., \( T \) inversion is not well-defined and that it depends, for example, on the chosen synchronization.

As explained, e.g., in [16], different systems of coordinates (including different synchronizations) are allowed in an inertial frame and they are all equivalent in the description of physical phenomena. Thus in [16] two very different, but completely equivalent synchronizations, Einstein’s synchronization and a drastically different, nonstandard, radio (“r”) synchronization, are exposed and exploited throughout the paper. The “r” synchronization is commonly used in everyday life and not Einstein’s synchronization. In the “r” synchronization there is an absolute simultaneity. As explained in [17]: “For if we turn on the radio and set our clock by the standard announcement ”...“at the sound of the last tone, it will be 12 o’clock,” then we have synchronized our clock with the studio clock according to the “r” synchronization. In order to treat different systems of coordinates on an equal footing we have presented, [16], the transformation matrix that connects Einstein’s system of coordinates with another system of coordinates in the same reference frame. Furthermore, in [16], we have derived such form of the LT which is independent of the chosen system of coordinates, including different synchronizations. The unit 4-vectors in the \( \{ e_\mu \} \) basis and the basis \( \{ r_\mu \} \) with the “r” synchronization , [16], are connected as \( r_0 = e_0, \ r_i = e_0 + e_i \). Hence, the components \( g_{\mu \nu, r} \) of the metric tensor \( g_{\mu \nu} \) are \( g_{0i, r} = 0 \), and all other components are \( = 1 \). Remember that in the \( \{ e_\mu \} \) basis \( g_{\mu \nu} = diag(1, -1, -1, -1) \). Then, according to [16], one can use \( g_{\mu \nu, r} \) to find the transformation matrix \( T^e_{\nu, r} \) which connects the \( \{ e_\mu \} \) basis and the \( \{ r_\mu \} \) basis; \( T^e_{\mu, r} = -T^0_{0, r} = 1 \), and all other elements of \( T^e_{\mu, r} \) are \( = 0 \). With such \( T^e_{\mu, r} \) one finds that the components of \( x^a \) are connected as \( x^0_r = x^0 - x^1 - x^2 - x^3 \), \( x^i_r = x^i \). It is clear that \( T \) inversion, \( t \rightarrow -t \), does not give that \( x^0_r \rightarrow -x^0_r \), which means that \( T \) inversion is not physical. In general the same holds for \( P \) inversion. However \( W \) inversion is properly defined since when \( x^a \rightarrow -x^a \) then necessarily \( x^0 \rightarrow -x^0 \). This is one of the reason why, contrary to the existing elementary particle theories, the \( T \) violation, i.e., the \( CP \) violation, cannot be connected in our approach with the existence of an intrinsic EDM. Furthermore, as already said, neither the direction of \( d \) nor the direction of the spin \( S \) have a well-defined meaning in the 4D spacetime. The only Lorentz invariant condition on the directions of \( d^a \) and \( S^a \) in the 4D spacetime is \( d^a u_a = S^a u_a = 0 \). This condition does not say that \( d \) has to be parallel to the spin \( S \). The above discussion additionally proves that our relations 5 are properly defined.

When an antisymmetric tensor (the components) \( A^{\mu \nu} \) (that tensor \( A^{\mu \nu} \) can be, e.g., \( F^{ab}, \ M^{ab}, \ S^{ab}, \ D^{ab}, \ldots \) ) is transformed by \( T^e_{\nu, r} \) to the \( \{ r_\mu \} \) basis then it is obtained that \( A^{10}_r = A^{10} - A^{12} - A^{13} \), which shows that the “time-space” components in the \( \{ r_\mu \} \) basis are expressed by the mixture of the “time-
space” components and the “space-space” components from the \( \{e_\mu\} \) basis, e.g., \( D_{r10}^{10} = -d^1 + (1/c)m^3 - (1/c)m^2 \). Thus only in the \( \{e_\mu\} \) basis it holds that \( E^i = F_r^{i0} \), \( d^i = D_r^{i0} \), \( Z^i = S_r^{i0} \), etc. This is the reason why we always put the quotation marks in the expressions “time-space” and “space-space.” In contrast to the usual covariant approach with coordinate dependent quantities all our relations (1), (2), (3), (4) and (5) are written in terms of 4D AQs, i.e., they are defined without reference frames.

5. Shortcomings in the EDM searches

The obtained results will significantly influence the interpretations of measurements of an EDM of a fundamental particle, e.g., \([6],[14],[18]\). In all experimental searches for a permanent electric dipole moment of particles the AT of \( E \) and \( B \) are frequently used and considered to be relativistically correct; i.e., that they are the LT of \( E \) and \( B \). Thus, in a recent new method of measuring electric dipole moments in storage rings \([6]\) the so-called motional electric field, our \( E' \), is considered to arise “according to a Lorentz transformation” from a vertical magnetic field \( B \) that exists in the laboratory frame; \( E' = \gamma c \beta \times B \). That field \( E' \) plays a decisive role in the mentioned new method of measuring EDMs. It is stated in \([6]\) that \( E' \) “can be much larger than any practical applied electric field.” and “Its action on the particle supplies the radial centripetal force.” Then, after introducing “g-2” frequency \( \omega_a \), due to the action of the magnetic field on the muon magnetic moment, they say: “If there is an EDM of magnitude \( d = \eta \hbar e/4mc \simeq \eta \times 4.7 \times 10^{-14} \) emc, there will be an additional precession angular frequency \( \omega_e = (\eta e/2m)\beta \times B \) about the direction of \( E' \), ... .” The new technique of measuring EDM in \([6]\) is to cancel \( \omega_a \) so that \( \omega_e \) can operate by itself. An important remark to such treatment is that the field \( E' \) is in the rest frame of the particle \( K' \) but the measurement of EDM is in the laboratory frame \( K \). Similarly happens in \([18]\) and many others in which ‘motional magnetic field’ \( B' = (\gamma/c)E \times \beta \) appears in the particle’s rest frame as a result of the AT of the \( E \) field from the laboratory. It is usually considered that \( (\gamma/c)E \times \beta \) field causes important systematic errors. Thus, it is stated, already in the abstract, in the first paper in \([18]\): “In order to achieve the target sensitivities it will be necessary to deal with the systematic error resulting from the interaction of the well-known \( \nu \times E \) field with magnetic field gradients ... . This interaction produces a frequency shift linear in the electric field, mimicking an EDM.” The same interpretation with the AT of \( E \) and \( B \) appears when the quantum phase of a moving dipole is considered, e.g., \([19]\). For example, when the Röntgen phase shift is considered then it is asserted in the second paper in \([19]\) that in “the particle rest frame the magnetic flux density \( B \) due to the magnetic line is perceived as an electric field” \( E' = \nu \times B \). Then that \( E' \) can interact with \( d' \) in \( K' \). In the usual approaches with the 3-vectors it is also possible to get the interaction between \( B \) and \( d \) in another way, which is more conforming to a description in \( K \). According to that way the magnetic field \( B \) in \( K \) interacts with the MDM \( m \) that is obtained from EDM \( d' \) by the AT for \( m \) and \( d' \): \( m = \gamma \nu \times d' \). (For the Aharonov-Casher effect that another way is
mentioned in [20].) However, as already said, the transformations of $E$ and $B$, and of $d$ and $m$, are not the LT but the AT, [10]. They have to be replaced by the LT of the corresponding 4D geometric quantities. Then, the LT transform $B^\mu$ from $K$ again to $B'^\mu$ in $K'$ and similarly $E^\mu$ from $K$ is transformed again to $E'^\mu$ in $K'$; there is no mixing of components. The same holds for the LT of $d^\mu$ and $m^\mu$. Thus, in our approach, there is no induced $E'$ as in [6] and [19], and there is no ‘motional magnetic field’ $B'$ as in [18] and [20], and there is no induced $d$ in $K$ as in [20]. As already said, it is seen from the last two terms in (2) that we have the direct interaction between the magnetic field $B^a$ and an EDM $d^a$, which is required for the explanation of measurements in [6]. In order to describe that interaction in $K$ we only need to choose the laboratory frame as our $c_0$-frame and then to represent the AQs $B^a$ and $d^a$ in that frame. For the phase shifts these questions are discussed in [1] and [5]. Accordingly, the experimentalists who search for an EDM, e.g., [6], [18], and, for example, those who observe the Aharonov-Casher phase shift [21], will need to reexamine the results of their measurements taking into account our relations (2), (4) and (5).

6. Conclusion

In conclusion, we believe that the new results (4) and (5) that are obtained in this paper, together with the expression (2) for the interaction term, [1], will greatly influence different branches of physics, particularly elementary particle theories and experiments, and also theories and experiments that treat different quantum phase shifts with dipoles. It is worth noting that the relations (3), (4) and (5) are generalized to the quantum case and the new commutation relations for the orbital and intrinsic angular momentums and for the dipole moments are introduced in [22].

References

[1] T. Ivezić, Phys. Rev. Lett. 98 (2007) 108901.
[2] T. Ivezić, Found. Phys. Lett. 18 (2005) 401.
[3] A. Einstein, Ann. Physik 17 (1905) 891, tr. by W. Perrett and G.B. Jeffery, in The Principle of Relativity, Dover, New York, 1952.
[4] M. Ludvigsen, General Relativity, A Geometric Approach, Cambridge University, Cambridge, 1999; S. Sonego and M.A. Abramowicz, J. Math. Phys. 39 (1998) 3158; P. Hillion, Phys. Rev. E 48 (1993) 3060.
[5] T. Ivezić, Phys. Rev. Lett. 98 (2007) 158901.
[6] F.J.M. Farley et al., Phys. Rev. Lett. 93 (2004) 052001.
[7] T. Ivezić, Found. Phys. 36 (2006) 1511.
[8] J. D. Jackson, Am. J. Phys. 72 (2004) 1484.
[9] J.D. Jackson, Classical Electrodynamics, 3rd ed., Wiley, New York, 1998.
[10] T. Ivezić, Found. Phys. 33 (2003) 1339; T. Ivezić, Found. Phys. Lett. 18 (2005) 301; T. Ivezić, Found. Phys. 35 (2005) 1585.
[11] F. Rohrlich, Nuovo Cimento B 45 (1966) 76.
[12] T. Ivezić, Found. Phys. 37 (2007) 747.
[13] J. Anandan, Phys. Rev. Lett. 85 (2000) 1354.
[14] N. Fortson, P. Sandars, and S. Barr, Physics Today, June 2003, page 33.
[15] V. Arunasalam, Found. Phys. Lett. 7 (1994) 515; Phys. Essays 10 (1997) 528.
[16] T. Ivezić, Found. Phys. 31 (2001) 1139.
[17] C. Leubner, K. Aufinger and P. Krumm, Eur. J. Phys. 13 (1992) 170.
[18] A.L. Barabanov, R. Golub, and S.K. Lamoreaux, Phys. Rev. A 74 (2006) 052115; C.A. Baker et al., Phys. Rev. Lett. 97 (2006) 131801; B.C. Regan, E.D. Commins, C.J. Schmidt, and D. DeMille, Phys. Rev. Lett. 88 (2002) 071805.
[19] M. Wilkens, Phys. Rev. Lett. 72 (1994) 5; S.A.R. Horsley and M. Babiker, Phys. Rev. Lett. 95 (2005) 010405.
[20] A. Zeilinger, R. Gähler, and M.A. Horne, Phys. Lett. A 154 (1991) 93.
[21] A. Cimmino, G.I. Opat, A.G. Klein, H. Kaiser, S.A. Werner, M. Arif, and R. Clothier, Phys. Rev. Lett. 63 (1989) 380; K. Sangster, E.A. Hinds, S.M. Barnett, E. Riis, and A.G. Sinclair, Phys. Rev. A 51 (1995) 1776.
[22] T. Ivezić, hep-th/0705.0744.