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Spin resonance conditions for intrinsic and induced electric dipole moments of a spin-1 particle

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Abstract

We show that spin resonance caused by the tensor polarizability of a spin-1 particle rotating in a storage ring designed to measure the intrinsic electric dipole moment (EDM) is canceled on the average over time when conditions for the spin resonance caused by this EDM are precisely met. This solves the problem of a false EDM signal created by polarizability.

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1. Introduction

Competing designs for using storage rings to measure (in fact, to discover) electric dipole moments (EDM) of nuclei have recently been published [1–4]. If a nucleus spin $s > 1/2$, then, in addition to intrinsic magnetic and electric dipole moments, such a nucleus may possess an intrinsic quadrupole moment and induced magnetic and electric dipole moments. The induced electric dipole moment is caused by electric polarizability; its energy in the fields of the above mentioned designs can be much bigger than the energy of the assumed intrinsic EDM. The corresponding induced EDM can imitate an intrinsic EDM [5]. The immediate question arises whether the false signal produced by a big induced EDM can put a serious physical limit on the accuracy of the proposed measurements. The calculations presented in this Letter show that the false signal caused by a big induced EDM is canceled, on the average over time, under ideal experimental conditions. The reason is that the conditions for observing the intrinsic EDM and the induced EDM in the same storage ring are mutually incompatible. Here, we analyze these conditions in the case of the "resonance method" of EDM measurement in storage rings [3,4], where the frequency of the rest-frame electric field equals the frequency of spin rotations in the magnetic field. The presence of an intrinsic or induced EDM can be revealed by the same resonance frequency; however, different phases between spin and rest-frame electric field are needed to observe them optimally. Something similar can be said for the case of the non-resonant ("frozen spin") method [1,2], where a specially designed radial electric field cancels spin rotations in the magnetic field.

2. The intrinsic EDM

In classical field theory (see [6], for example) the electric dipole moment of a system of charges, observed at large distances relative to the system's size, is defined as $\vec{d} = \sum q_i \vec{r}_i$, where q_i is the charge and $\vec{r}_i$ the radius vector of the i-particle. Following

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Landau and Lifshitz, the origin of the coordinate system is placed "anywhere within the system of charges" [6]. If the system is located in an external electric field, $\vec{E}$, which slowly changes across the system, then the potential energy of the system is expanded into multipole energies, $H \equiv \sum q_i \phi(r_i) = Q\phi_0 + \vec{d}(\nabla\phi)_0 + \cdots$, where $Q = \sum q_i$, the total charge of the system; ϕ_0 is the "value of the potential at the origin", that is, anywhere within the system; $(\nabla\phi)_0 = -\vec{E}_0$, the electric field anywhere within the system; and $\vec{d}$ is the EDM of the full system as defined above.

Turning now to a quantum system like a proton, deuteron or molecule, it is clear that when its intrinsic microscopic EDM is observed by a macroscopic apparatus, the general expression for the EDM energy, $-\vec{d}\vec{E}$, remains unchanged if $\vec{E}$ is a slowly changing classical field. However, now vector $\vec{d}$ is not classical. In its rest frame it is oriented along the system's angular momentum, which is the system's spin operator,$\vec{s}$. The three components of $\vec{s}$ are three generators of rotation symmetry, so their commutation rules are the same for any s. As for the (still unknown) magnitude of d,

$$d = \frac{e\hbar}{mc}\eta s, \tag{1}$$

where, for deuterons, $\eta = 2 \times 10^{-15}$ if $d = 10^{-29}$ ecm.

Since an intrinsic EDM violates time reversal symmetry T and parity P, it can appear only when quantum field interactions violate those symmetries. In the deuteron case, the intrinsic EDM is assumed to be the sum of the proton and neutron EDMs plus theEDM from the nuclear forces violating CP (and hence T) symmetries [7]:

$$d_D = d_p + d_n + d_D^{\pi NN}. \tag{2}$$

The Standard Model (in which the P, C and PC symmetries are violated) predicts only very small intrinsic EDMs, for example, $\sim 10^{-31}$ ecm for deuterons. Beyond the Standard Model, particularly in the frame of supersymmetry, the predicted EDM values are several orders higher. The proposed accuracy of the deuteron intrinsic EDM measurement in a resonance EDM ring is 10^{-29} ecm [3,4] and 10^{-27} ecm in a frozen-spin ring [1,2].

3. The induced EDM

The induced EDM, a well-known physical phenomenon, does not violate P, C, and T symmetries and therefore is not directly relevant to the experiments proposed in [1–4]. However, as explained above, we need to understand whether the inevitable presence of the induced EDM limits the accuracy of such experiments. Let us denote the induced EDM by $\vec{d}^{\text{ind}}$ (reserving $\vec{d}$ for the intrinsic EDM). $\vec{d}^{\text{ind}}$ is not directed along the particle spin. The components of this vector are proportional to the components of the external electric field, $d_k^{\text{ind}} = \alpha_{kl} E_l$, α_{kl} is the polarizability tensor of the system placed in this field. Correspondingly, the induced energy of this system equals $\Delta H = -0.5\alpha_{kl} E_k E_l$, $\alpha_{kl} = \alpha_S \delta_{kl} + \alpha_T (s_k s_l + s_l s_k - 2\delta_{kl} s^2/3)$; α_S and α_T correspond to the so-called scalar and tensor polarizabilities; s_k is the k-component of the spin operator, $k = 1, 2$ and 3 corresponding to the longitudinal x, radial y, and vertical z coordinates in a storage ring. For the deuteron [8], $\alpha_S \approx 0.6\ \text{fm}^3$, $\alpha_T \approx 0.03\ \text{fm}^3$. Strictly speaking, these numerical values are correct provided that the deuteron's center of mass is not moved by the external electric fields. (Such movement would decrease the observed values of α_S, α_T.) This condition is met in an EDM storage ring, because the main rest-frame electric field is $\gamma[\vec{v} \times \vec{B}]$, which is directed radially while the particles move longitudinally. A longitudinal electric field of the synchrotron RF cavities exists, but is small compared with the radial $|\gamma[\vec{v} \times \vec{B}]|$. Thus, in our numerical estimates we can use the values given in [8].

Two unavoidable effects of polarizability are cause for concern. One is the shielding of the intrinsic EDM from the external electric field by the counter-field of the induced d_D^{ind}. As a result of that shielding, the observed value of the intrinsic EDM can change. Here we note only that electric shielding cannot be a big effect in nuclei since the main forces keeping particles together are big nuclear, not small Coulomb, forces. The second effect of concern—which is the subject of this Letter—is the appearance of additional torques applied to the spin, which means a change of the spin equations. The spin equations can be changed only by the spin-dependent part of the polarizability, that is, only by the term $-0.5\alpha_T(s_k s_l + s_l s_k)E_k E_l$ in the Hamiltonian.

4. The Hamiltonian

In any storage ring designed to measure the intrinsic EDM, the EDM manifests itself in a growth of vertical polarization. Our aim here is to find how spin-1 moves in the *vertical* plane. The problem is that this movement is caused not only by the intrinsic EDM generally described in [9], but also by the induced EDM, d^{ind}. We need to find the correct spin equations for the latter. This will be achieved in three steps. We will: (a) write the spin part of the Hamiltonian of the Schrödinger equation; (b) get the spin equations in the Heisenberg picture (thus avoiding the difficulty of solving the Schrödinger equation in the case of resonance in the presence of polarizability); and (c) calculate the quantum average of these spin equations for an arbitrary initial state of deuterons. Note that without d^{ind} (and also without the Stern–Gerlach and quadrupole interaction effects, not addressed here), the spin equations are linear. As a result, they are the same for the quantum spin-vector and classical polarization, and independent of the shape of the initial deuteron state. The induced d^{ind} makes spin equations non-linear, essentially quantum, and dependent on the initial state.