P, T violating magneto-electro-optics

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Abstract. We study linear and bilinear magneto-electro-optical effects due to the propagation of light in centro-symmetric media in the presence of P, T violating interactions and external transverse and longitudinal electric and/or magnetic fields. We show that new magneto-electric optical effects appear. In particular, we show the existence of a Jones birefringence proportional to the square of the transverse field amplitude. All these effects are an unambiguous signature of the P, T violation, and a search for such new phenomena could also provide novel limits on electric dipole moment (EDM) of matter.

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1 Introduction

Charge conjugation (C) and parity (P) violation have been observed in nature in weak interactions and in K and B particles decay respectively. The violation of both CP and T induces an electric dipole moment (EDM) in ordinary matter particles such as neutrons and electrons [1]. The first search for such a phenomenon in neutrons is more than 50 years old [2]. Since then, several experiments on fermions, atoms and molecules have been carried on [1]. In particular, present accepted limits on electron and neutron EDM are respectively $1.6 \times 10^{-27}$ e.cm [3] and $6.3 \times 10^{-26}$ e.cm [4], and the limit for a permanent electric dipole moment of the $^{199}$Hg is $2.1 \times 10^{-28}$ e.cm [5].

Standard model CP violation predicts very low values for the neutron, proton and electron EDM, but CP violation also appears in new theories such as supersymmetry, giving rise to EDM values that can be tested in experiments [1].

CP violation is also expected in Quantum Chromodynamics. The fact that this violation has never been observed is called the strong CP problem, and a possible solution to this problem could be the existence of a new pseudoscalar boson known as the axion [6].

The role of the time reversal operator T, associated to time symmetry, in the determination of the properties of molecules in electric and magnetic fields is discussed in reference [7], in particular for the case of time-invariant enantiomorphic (true chiral) systems, i.e. systems that exist in two distinct enantiomeric states that are interconverted by parity P but not by time reversal T combined with any proper spatial rotation. Enantiomeric states are the distinguishable mirror-images of a physical system. Time-invariant enantiomorphous systems shows natural optical activity like sugar solutions. In general, chirality is always associated to P violation. Since a true chiral system do not violate T, by the CPT theorem we see that it must violate C. On other hand, the combination of P and T violations gives time-noninvariant enantiomorphic (false chiral) systems i.e. systems that again exist in two distinct enantiomeric states but which are interconverted by time reversal T as well as parity P (see also [8] and references within).

From the phenomenological point of view much attention has been paid to the fact that an electric field applied in the presence of a P, T violation creates a magnetization, and that a magnetic field creates an electrical polarization (see e.g. [9]). Propagation of light in the presence of a P, T violating interaction has been studied by several authors [10–12] to show that a rotation of the polarization plane of light occurs in presence of an electric field parallel to the light propagation vector (see also [13]).

In this letter we study linear and bilinear magneto-electro-optical effects due to the propagation of light in centro-symmetric media in the presence of P, T violating interactions and external transverse and longitudinal electric and/or magnetic fields. We show that new magneto-electric optical effects appear. In particular, we show the existence of a linear birefringence along axes which are at $\pm 45^\circ$ relative to the transverse magnetic field direction (Jones linear birefringence) proportional to the square of the field amplitude. We also recover the effect already predicted [10–12]. Our study uses mainly a method based on pictorial symmetry arguments introduced in 1980 by de

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Figueiredo and Raab [14]. A model calculation is also presented for a quantum vacuum. All these magneto-electro-optical effects are an unambiguous signature of the P, T violation, and a search for such new phenomena could also provide novel limits on EDM of matter.

2 Pictorial analysis

In 1980 de Figueiredo and Raab [14] have shown that pictorial symmetry arguments can be used to study light propagation. In particular this method has been used to prove the existence of new optical effects like the Jones birefringence [15]. In this approach the effect is studied by comparing schematic pictures representing a possible experiment and its subject to certain space and time transformations. In the following we will be especially concerned by P and T transformations of light polarization states (horizontal $\rightarrow$, vertical $\downarrow$, at $45^\circ$ $\rightarrow\downarrow$, at $-45^\circ$ $\rightarrow\downarrow$, circular states $\circ$ and $\land$), electric field $E$ and magnetic field $B$. These properties can be summarized as follows [14]:

- under $P$, as $\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow$, $\downarrow\rightarrow\downarrow\rightarrow\downarrow\rightarrow\downarrow$, $\circ\rightarrow\circ\rightarrow\circ\rightarrow\circ$, $\circ\rightarrow\circ\rightarrow\circ\rightarrow\circ$;
- under $T$, as $\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow\rightarrow$, $\downarrow\rightarrow\downarrow\rightarrow\downarrow\rightarrow\downarrow$, $\circ\rightarrow\circ\rightarrow\circ\rightarrow\circ$, $\circ\rightarrow\circ\rightarrow\circ\rightarrow\circ$.

Concerning the refractive index $n$, we write it as the sum of two terms: a zeroth order term $n_0$ invariant with respect to $P$ and $T$, and a term linear or bilinear with respect to the fields. Note that this second term is multiplied by a factor $(-1)$ under a $P$ or a $T$ transformation, to take into account that both $P$ and $T$ symmetries are violated and that $P^2$ and $T^2$ amount to no transformation.

2.1 Transverse magnetic or electric field

Let us start our study by a pictorial analysis of light propagation along the $z$-axis in a centro-symmetric medium with interactions that violate $P$ and $T$, where a magnetic field $B_0$ is applied along the $x$-axis (see Fig. 1). In the case of a $+45^\circ$ polarized light (a), the refractive index can be written as $n_+ = n_0 + c_+ B_0^2$, while in the case of a $-45^\circ$ polarized light (d), it becomes $n_- = n_0 + c_- B_0^2$. Since the interactions violate $T$, experiment (a) becomes (b) under time-inversion. If we rotate (b) of an angle $180^\circ$ about $y$-axis, we obtain (c) which is equivalent to (d) taking into account $T$-violation. We finally deduce that $c_+ = -c_-$ and $n_+ - n_- = 2c_+ B_0^2$. This is the optical signature of a Jones birefringence [15] proportional to $B_0^2$.

It is straightforward to show that our pictorial analysis gives the same result under space-inversion, and also that the same effect exists if one replaces the $B$ field with an $E$ field.

If one takes into consideration linear effects with respect to the transverse magnetic field $B$ instead of quadratic ones, one obtains under PT transformation that $c_+ = -c_-$ (see Fig. 2), that obviously means that $c_+ = 0$. Starting from experiment (d) of Figure 1, one also obtains that $c_- = 0$. One obtains the same result when replacing the $B$ field with an $E$ field. Therefore, no Jones birefringence effect linear with respect to the field can exist.

2.2 Longitudinal magnetic or electric field

If the field is longitudinal the optical eigenmodes [13] of light are the circular ones. In Figure 3 we show that a circular birefringence may exist in the case of a longitudinal electric field, since $c_+ = -c_-$. This is the optical effect treated in reference [12]. Using the same method, one can show that in the case of a longitudinal $B$ field there is no effect since $c_+ = c_- = 0$. In Figure 4 we also show that no quadratic effect exists.

2.3 Transverse electric and magnetic fields

Let us now look for bilinear effects proportional to $BE$. If $E$ and $B$ are parallel (see Fig. 5), one obtains that