Amplification of a ($P+T$)-odd optical activity

L. M. Barkov, M. S. Zolotarev, and D. A. Melik-Pashaev
Institute of Nuclear Physics, Siberian Branch of the Academy of Sciences of the USSR

(Submitted 31 May 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 3, 134–136 (10 August 1988)

Nonlinear-spectroscopy effects which lead to an amplification of an induced optical activity of atoms and molecules as a result of interactions which violate spatial and temporal invariance are discussed.

Nondegenerate quantum systems, in particular, systems of elementary particles, atoms, and molecules, can have an electric dipole moment only if both spatial and temporal invariance are violated (see, for example, the review by Ramsey[1]). Numerous experiments carried out to search for electric dipole moments have so far yielded only upper limits of their values.[1,2] Since most of these experiments are approaching their limits of capability, further progress in this field will apparently have to await the development of new methods. As was pointed out by Sushkov and Flambaum,[3] one possibility for searching for an electric dipole moment of a molecule or atom is to measure the induced optical activity in a longitudinal electric field. Such an activity is an analog of the Faraday effect: an induced optical activity in a longitudinal magnetic field.

An electric dipole moment can be induced in molecules (or atoms) by a T-odd electron-nucleon interaction, the electric dipole moment of an electron, the electric dipole moments of nucleons, and also T-odd nuclear forces (Ref. 2, for example).

Let us discuss the relationship between the electric dipole moment of a molecule and that of an electron. When a molecule is placed in a external electric field, the T-odd shift of the energy levels is proportional to dE_i, where d is the electric dipole moment of the electron, and E_i is the effective intramolecular field. If the molecule is completely polarized by an external electric field, E_i is given in order of magnitude by[4]

$$(Ze/a^2)\cdot(Z^2\alpha^2)\ .$$

Here Z is the charge of the nucleus, a is the first Bohr radius, and α is the fine-structure constant. The factor $Z^2\alpha^2$ characterizes the square velocity of the electron. It appears because according to Schiff's theorem[5] the average field acting on an electron would be completely screened in the nonrelativistic limit. Diatomic molecules which consist of different atoms and which are in electronic states with a projection $\Omega\neq 0$ onto the total angular momentum of the electron have a large polarizability because of the proximity of levels of opposite parity (Ω-doubling). In most cases, external electric fields of a few tens of kilovolts per centimeter would be sufficient to completely polarize molecules. The fields E_i for certain heavy molecules reach 10^{12} V/cm. In other words, a significant amplification of an effective electric field[6] means that the electric dipole moments of the molecules are many orders of magnitude greater than that of an electron. It should be noted here that, in contrast with experiments on P-odd interactions,[2] measurements of the ($P+T$)-odd optical activity can be carried out on

ordinary E1 transitions; it is sufficient that the condition $\Omega \neq 0$ hold in at least one of the states: the upper or lower.[4] We might also note that although there is no regular mechanism for an amplification of the electric dipole moment in atoms as the result of a proximity of rotational states of opposite parity, there are several atoms which by chance have nearly degenerate levels of opposite parity. Among these atoms are lanthanides[7] and also actinides (U, Pu). Such atoms are also possible subjects for the experiments which we are discussing here.

Let us estimte the magnitude of the optical activty. Making use of the analogy with Faraday rotation (Ref. 2, for example), we find the following for a resonant transition:

$$\varphi \sim (dE_i/h\Gamma)\, L/L_O \,. \tag{1}$$

Here Γ is the width of the transition, L is the thickness of the molecular layer through which the light passes, and L_0 is the absorption length.

The magnitude of the induced optical activity is inversely proportional to the linewidth [see (1)]. Nonlinear-spectroscopy methods make it possible to narrow the effective widths to values ~ 10 kHz, while the typical width in the linear case would be $\Gamma \sim 1$ GHz (the Doppler width). At the present limit on the electric dipole moment of an electron,[8] $d \leqslant 10^{-24}|e|$ cm, these widths would correspond to a polarization-plane rotation angle $\varphi \sim 10^{-2}$ rad under optimum conditions. At the polarimetric sensitivity currently available, it would thus become possible to push back the limit on the electric dipole moment of the electron and on T-odd interactions associated with the spin of an electron by some seven or eight orders of magnitude. Furthermore, it would become possible to improve the limit on the electric dipole moments of nucleons, other T-odd electron-nucleon, nucleon-nucleon, and quark-quark interactions by several orders of magitude (Refs. 2, 9, and 10, for example).

To illustrate the amplification of an induced optical activity, we consider the example of a nonlinear Faraday effect. (A nonlinear magnetooptic activity has been the subject of several experimental and theoretical studies.[11-18]) With a laser beam of adequate power, the magnetooptic activity near a resonant transition is quite different from that in the linear case, both in the shape of the frequency dependence and in magnitude. Nonlinear effects are seen most clearly in the behavior of the angle through which the polarization plane is rotated as a function of the magnetic field. Figure 1 shows a plot of this sort which we obtained for the 570.7-nm transition of a samarium atom (Sm152), $4f^6 6s^2\ ^7F_1 \rightarrow 4f^6 6s\ 6p^7F_0$. Samarium vapor was produced by heating a metallic sample in a beryllium oxide cell. The cell was evacuated and did not contain a buffer gas. The optical thickness of the column of samarium vapor did not exceed a single unsaturated-absorption length. External magnetic fields were weakened by a shield. As the light source we used a single-frequency cw tunable dye laser. Under the experimental conditions, the laser power was 5 μW, and the beam diameter on the order of a millimeter. The cell holding the vapor was placed between a polarizer and an analyzer, whose axes made an angle of 45° with respect to each other. The beam was separated into two components with orthogonal polarizations at the analyzer. The difference in the intensities of these components served as a measure of the angle through which the polarization plane was rotated.

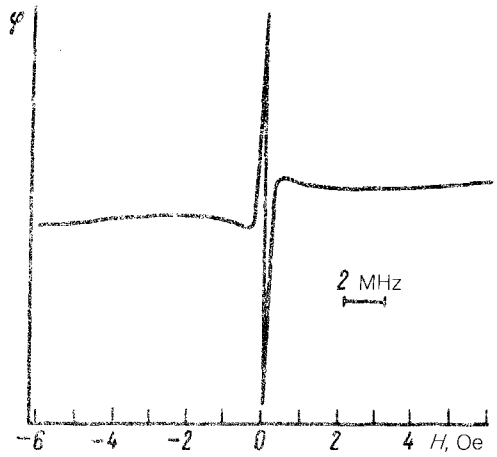

FIG. 1.

It can be seen from Fig. 1 that there are peaks of opposite signs in the plot of the polarization-plane rotation angle versus the magnetic field. These peaks correspond to the values $g\mu H \approx 60$ kHz and 1 mHz ($g = 1.5$). The appearance of narrow peaks can be explained in terms of coherence effects.[13] Here the effective width is determined by the relaxation time of the coherence of the Zeeman components of the lower state. In our case, this effective width is determined by the transit time of the atoms through the laser beam. The appearance of wider peaks is associated with the formation of Bennett structures on the velocity distribution of the particles. In this case the effective width is determined by the width of the Bennett structure, i.e., by the sum of the homogeneous width of the transition and the width of the laser output line. The rise in the Faraday rotation in high magnetic fields is a consequence of the ordinary linear effect.

In weak fields, the nonlinear Faraday rotation is four orders of magnitude greater than the linear rotation (in magnitude). We would expect that an increase in the size of the laser beam would result in a decrease in the effect of widths, which would make it possible to achieve a greater amplification of the induced optical activity.

This amplification of Faraday rotation may be regarded as a demonstration that it is possible to use nonlinear-spectroscopy methods to amplify a $(P + T)$-odd optical activity.

We wish to thank O. P. Sushkov and V. V. Flambaum for stimulating discussions.

[1]N. F. Ramsey, Annu. Rev. Nucl. Part. Sci. **32**, 211 (1982).
[2]I. B. Khriplovich, Parity Breaking in Atomic Phenomena, Nauka, Moscow, 1988.
[3]O. P. Sushkov and V. V. Flambaum, Zh. Eksp. Teor. Fiz. **74**, 1208 (1978) [Sov. Phys. JETP **47**, 634 (1978)].
[4]V. V. Flambaum, Doctoral Dissertation, Institute of Nuclear Physics, Novosibirsk, 1987.
[5]L. I. Schiff, Phys. Rev. **132**, 2194 (1963).
[6]P. G. H. Sandars, Phys. Rev. Lett. **19**, 1396 (1967).
[7]V. A. Dzuba, V. V. Flambaum, and I. B. Khriplovich, Z. Phys. **D1**, 243 (1986).
[8]N. J. Fortson, Opt. Soc. Am. **4**, 38 (1987).

[9]O. P. Sushkov, V. V. Flambaum, and I. B. Khriplovich, Zh. Eksp. Teor. Fiz. **87**, 1521 (1984) [Sov. Phys. JETP **60**, 873 (1984)].
[10]V. M. Khatsimovsky, I. B. Khriplovich, and A. S. Yelkhovsky, Modern Developments in Nuclear Physics (ed. O. P. Sushkov), Singapore: World Scientific, 1988.
[11]W. Gawlik *et al.*, Opt. Commun. **12**, 400 (1974).
[12]A. M. Badalyan *et al.*, Kvant. Elektron. (Moscow) **11**, 1802 (1984) [Sov. J. Quantum Electron. **14**, 1206 (1984)].
[13]S. Giraud-Cotton, V. P. Kaftandjian, and L. Klein, Phys. Rev. **A 32**, 2211; 2223 (1985).
[14]W. Lange, K. H. Drake, and J. Mlynek, in: Proceedings of the Fourteenth International Quantum Electronics Conference, San Francisco, California, June 9–13, 1986. Technical digest, p. 34.
[15]O. É. Buevich *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 322 (1987) [JETP Lett. **44**, 414 (1986)].
[16]S. V. Fomichev, Preprint IAÉ-4431/12, I. V. Kurchatov Institute of Atomic Energy, Moscow, 1987.
[17]I. O. J. Davies, P. E. G. Baird, and J. L. Nicol, J. Phys. **B20**, 5371 (1987).
[18]F. Schuller, M. J. D. McPherson, and D. N. Stacey, Physica **147C**, 321 (1987).

Translated by Dave Parsons