Feasibility of observing parity nonconservation in atomic transitions

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The possibility is discussed of observing parity nonconservation in optical transitions by determining the rotation of the plane of polarization in heavy-metal vapors. The rotation angle can reach 10^{-5} rad/m at a pressure of 100 mm.

The feasibility in principle of observing a weak interaction of an electron with a proton or a neutron by observing parity nonconservation in atomic transition was pointed out many years ago by Zel'dovich[1] and has since been discussed many times by the theoreticians[2–5] (see also[6–9]). Particularly noteworthy among these articles is that of Bouchiat[3] where it is shown that the parity-nonconservation effects in heavy atoms are enhanced to such a degree that their experimental observation is at the borderline of the feasible. However, a concrete estimate of the degree or circular polarization of photons in the $6s_{1/2}$—$7s_{1/2}$ transition in cesium, given in[3], seems to be too high (see[5]), so that the corresponding experiment is more difficult than would be expected from Bouchiat's estimates.

In this article I wish to call attention to a sufficiently realistic possibility of observing parity nonconservation in atomic transitions by measuring the rotation of the polarization plane of light in vapors of heavy metals. The fact that parity nonconservation leads to the appearance of optical activity was first noted in[1].

The refractive indices for right- and left-polarized photons having a frequency ω close to the resonant frequency ω_0 will be expressed in the form

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$$n_{\pm} = 1 + \frac{N\,\overline{|V_{\pm}|^2}}{\hbar^2\omega} \left\langle \frac{1}{\omega - \omega_0 - (v/c)\omega_0 + i\Gamma/2} \right\rangle . \quad (1)$$

Here N is the density of the atoms of the medium, Γ is the width of the excited level, $\overline{|V_{\pm}|^2}$ are the squares of the matrix elements for the absorption of right- and left-polarized photons, averaged over the initial polarization of the atoms and summed over the intermediate ones, and the angle brackets $\langle\rangle$ denote averaging over the atom velocities v.

If parity is not conserved, then the matrix elements $V_{\pm}$ are not equal to one another and can be represented in the form

$$V_{\pm} = V \pm \frac{\xi}{2} V_1. \quad (2)$$

where ξ is a dimensionless small parameter and V_1 is a an admixture matrix element of "incorrect" parity. The angle of rotation of the polarization plane is

$$\psi = \frac{1}{2}\frac{\omega}{c} l \,\mathrm{Re}(n_+ - n_-)$$

$$\approx \frac{1}{2} N l \xi \frac{(V^* V_1 + V V_1^*)}{\hbar^2 c} \left\langle \frac{\omega - \omega_0 - (v/c)\omega_0}{\left(\omega - \omega_0 - \frac{v}{c}\omega_0\right)^2 + \frac{\Gamma^2}{4}} \right\rangle, \quad (3)$$

where l is the path length. If the main transition to which the matrix element V corresponds is allowed, then the absorption coefficient α, defined by the relation

$$\alpha = -2\frac{\omega}{c} \mathrm{Im}\, n_{\pm} \approx 2 \frac{N\,\overline{|V|^2}}{\hbar^2 c} \left\langle \frac{\Gamma/2}{\left(\omega - \omega_0 - \frac{v}{c}\omega_0\right)^2 + \frac{\Gamma^2}{4}} \right\rangle \quad (4)$$

is very large. And since the path length l cannot noticeably exceed α^{-1}, it follows that the attainable rotation angle ψ is in this case extremely small.

It is therefore natural to consider the case when the principal and admixture transitions are $M1$ and $E1$, respectively. As is well known, $M1$ transitions occur (without additional suppression) only between fine-structure components. To observe the small rotation angle ψ it is desirable to have this transition in the visible part of the spectrum or near it. This is the situation for the heavy metals antimony, thallium, lead, and bismuth.

In order for the angle ψ not to be too small, the detuning $\Delta = \omega - \omega_0$ should be comparable with the Doppler broadening Δ_D (it is assumed that $\Delta_D \gg \Gamma$). Since ψ is an odd function of Δ, it is clear that both the frequency stability and the line width of the source should at least be comparable with $\Delta_D \approx 10^{-6}\,\omega_0$. In this case both the hyperfine structure and the isotopic shift of the line are resolved.

Assume that parity is not conserved in electron-nucleon interactions. Being interested in the total contribution made to the effect by all the nucleons of the nucleus, we average the weak-interaction Hamiltonian over the nucleon spin. As a result, the P-odd interaction of the electron with the nucleus takes the following form in the nonrelativistic approximation:

$$H = -\frac{G\hbar^3}{\sqrt{2}c^2} Zq \frac{1}{2m} [(\vec{\sigma}\mathbf{p})\delta(\mathbf{r}) + \delta(\mathbf{r})(\sigma\mathbf{p})] . \quad (5)$$

Here $G = 10^{-5} m_p^{-2}$ is the Fermi constant, m, $\sigma/2$, $\mathbf{p}$ and $\mathbf{r}$ are the mass, spin, momentum, and coordinate of the electron. The quantity q depends on the concrete variant of the theory. For concreteness, we use the Weinberg model,[10] in which

$$q = 1 - \frac{A}{2Z} - 2\sin^2\theta , \quad (6)$$

where A is the atomic weight of the element, and θ is the mixing angle and is a parameter of the medium; in the calculations we assume $\sin^2\theta = 0.32$. Obviously, the Hamiltonian (5) leads to a mixing of only the $s_{1/2}$ and $p_{1/2}$ states.

We consider the transition $6p_{1/2} \to 6p_{3/2}$ in thallium, which lies in the near infrared region ($\lambda = 12\,833$ Å), and can also be of the electric quadrupole type. However, simple estimates show that the matrix element of the $E2$ transition is sufficiently small to be able to neglect the quadrupole contribution.

The calculation of the admixture of the $6s^2 ns_{1/2}$ states ($n = 7, 8, \ldots$) to the ground state $6s^2 6p_{1/2}$ is relatively simple (see[3]). Allowance for the relativistic effects leads to a correction factor 8.8 for thallium. The experimental data on the oscillator strengths in thallium[11] are used to find the $E1$-transition amplitudes. The signs of these amplitudes are determined with the aid of the Bates-Damgaard tables.[12] The contribution of the states with $n \gg 9$ (and also apparently of the continuous spectrum by itself) is negligible. The rotation of the polarization plane, obtained in this manner for the transition $F = 1 \to F = 2$ in Tl^{205} at a pressure 100 mm (corresponding to a temperature 1196 °C) and a detuning $\Delta = 2.4\Delta_D$ amounts to 10^{-5} rad/m. The absorption coefficient α is in this case equal to 100 cm^{-1}.

This result for ψ is valid only in order of magnitude. The point is that no account is taken here of the contribution of the $6s6p^2$ contribution. A calculation of this contribution with any degree of accuracy entails considerable difficulties and has not yet been performed. Yet one of these configurations, $6s6p^2\,{}^2P_{3/2}$ seems to make a large contribution to the effect in question.[1)] One can hope, however, that allowance for the indicated phase does not change the order of magnitude of the effect.

Approximately the same rotation is produced also in the plane of polarization in lead vapor ($\lambda = 12\,789$ Å) and bismuth vapor ($\lambda = 8757$ Å, $\lambda = 6478$ Å, $\lambda = 4617$ Å, $\lambda = 3015$ Å). An effect smaller by one order of magnitude (owing to the smaller Z) should be expected in antimony vapor ($\lambda = 11\,748$ Å, $\lambda = 10\,148$ Å, $\lambda = 6099$ Å, $\lambda = 5416$ Å).

Observation of the rotation of the polarization plane at a 10^{-5} rad level is in itself perfectly feasible. At any rate, the greater part of the visible region, as well as the interval 8200—8900 Å, is covered by the existing tunable lasers having the required parameters. A serious problem is elimination of the magnetic field, which also leads to rotation of the polarization plane. To imitate the effect at the 10^{-5} rad/m level, it suffices to have an average magnetic field 10^{-5}—10^{-4} G. For most transitions, the principle imitation mechanism is the difference between the resonant frequencies for the right- and left-polarized quanta, which results from the Zeeman splitting of the lines.[2)]

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1) We note that in the case of cesium it is probable that appreciable contribution is made by the configurations $5p^56s^2$, and this contribution seems to have been disregarded in[3].

2)In view of the inevitable difference between the laser frequency and the resonant frequency, the same mechanism leads in the case of the experiment proposed by Bouchiat[3] to more stringent limitations imposed on the magnetic field than those indicated in[3].

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On page 316 the right-hand column, line 19 from the bottom, read "The absorption coefficient α is in this case equal to 1 m^{-1}," instead of "...equal to 100 cm^{-1}."