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OPTICAL ACTIVITY OF THALLIUM AND LEAD VAPORS NEAR SUPPRESSED M1 TRANSITIONS

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abstract

The magnitude of parity nonconservation effects in $6p_{1/2} - 7p_{3/2}$ transition in thallium is calculated, and the feasibility of experimental detection of optical activity near it is pointed. Analogous calculation is carried out for $6p^2\,{}^3P_0' - 6p7p\,{}^3D_1'$ transition in lead.

Experimental searches for parity nonconservation in atomic transitions are being carried out presently by several experimental groups/1-5/. These experiments have attracted great interest since their results are critical for the check of theoretical schemes unifying electromagnetic and weak interactions of elementary particles. The most advanced studies in this direction seem to be now the searches for optical activity of heavy metal vapors/3-5/ which have led already to essential limitations on the parameters of mentioned schemes.

Up to now when discussing the possibilities of searches for optical activity, only usual M1 transitions between the levels belonging to the same configuration were always considered. The transitions $6p_{1/2} \to 6p_{3/2}$ in thallium, between the levels of the configuration $6p^2$ in lead and $6p^3$ in bismuth were up to now under discussion. All the experiments were carried out on bismuth.

In the paper/6/ the principal possibility of the search for optical activity near suppressed M1 transition $6p_{1/2} \to 7p_{3/2}$ in thallium was mentioned. However, the feasibility of corresponding experiment was estimated in that article very pessimistically. Here we have calculated the degree of circular polarization of photons in this transition as well as the corresponding rotation angles of light polarization plane in thallium vapors. From the results obtained it follows from our point of view that the detection of optical activity near this transition is sufficiently feasible. We have calculated also the optical activity for an analogous transition in lead.

Begin with the amplitude of M1 transition $6p_{1/2} - 7p_{3/2}$ in thallium. Numerical calculations carried out in the work/6/ have shown that although principal quantum numbers of the initial and final states are different, this amplitude is suppressed by an order of magnitude only. Its value can be easily found analytically as well. The spin-orbit interaction leads to the mixing of the states 6p and 7p:

$$|7p_{3/2}\rangle' = |7p_{3/2}\rangle + \frac{1}{2}\,\frac{\xi_{6,7}}{E_{7p_{3/2}} - E_{6p_{3/2}}}\,|6p_{3/2}\rangle$$
$$|6p_{1/2}\rangle' = |6p_{1/2}\rangle - \frac{\xi_{6,7}}{E_{6p_{1/2}} - E_{7p_{1/2}}}\,|7p_{1/2}\rangle \qquad (1)$$

Here $\xi_{n,n'}$ is the radial matrix element of spin-orbit interaction. Since the main contribution to this matrix element is given by small distances from a nucleus, $\xi_{6,7} = \sqrt{\xi_{6,6}\,\xi_{7,7}}$ (we assume that all radial wave functions are positive at $r \to 0$). Now using experimental values of the energies of corresponding states, we get

$$\langle 7p_{3/2}, j_z = \tfrac{1}{2}|M_z|6p_{1/2}, j_z = \tfrac{1}{2}\rangle = \frac{\sqrt{2}}{3}\,0.09\,|\mu_B| \qquad (2)$$

The modulus of this matrix element is in agreement with the corresponding value from/6/, but the results differ in sign.

The transition $6p_{1/2} - 7p_{3/2}$ can go also as an electrical quadrupole one. Numerical calculation/6/ gives $\langle 7p_{3/2}|r^2|6p_{1/2}\rangle = -6.7\,a_B^2$. Hence the reduced matrix element of the operator $Q_{\alpha\beta} = \frac{\sqrt{3}}{4}\frac{e\omega}{c}(r_\alpha r_\beta - \frac{1}{3}r^2\delta_{\alpha\beta})$ is equal to

$$\langle 7p_{3/2}\|Q\|6p_{1/2}\rangle = -\frac{1}{\sqrt{15}}\frac{e\omega}{c}\langle 7p_{3/2}|r^2|6p_{1/2}\rangle \approx -0.55\,|\mu_B| \qquad (3)$$

The calculation of the parity nonconservation effects in this transition is sufficiently simple. The matrix element of P - odd weak interaction of electron with nucleus looks as follows/7/

$$\langle s_{1/2}|H|p_{1/2}\rangle = iq\,\frac{G m_e^2 \alpha^2 Z^3 R}{\pi\sqrt{2}}\,\frac{1}{(\nu_s \nu_{p_{1/2}})^{3/2}}\,\frac{m_e e^4}{2\hbar^2} \qquad (4)$$

where $G = 10^{-5}/m_p^2$ is the Fermi constant, ν_s and $\nu_{p_{1/2}}$ are effective principal quantum numbers of the electrons, R is a relativistic factor ($R_{Tl} = 8.5$; $R_{Pb} = 8.9$), q is a dimensionless constant that should be determined experimentally. At our calculations we shall use for definiteness the Weinberg model at $\sin^2\theta = 0.32$, i.e., we take $q = 1 - \frac{A}{2Z} - 2\sin^2\theta = -0.9$. The calculation of mixing E1 amplitudes is carried out in standard way described in/7/. Final value of the matrix element of operator of E1 transition is

$$\langle 7p_{3/2}, j_z = \tfrac{1}{2}|D_z|6p_{1/2}, j_z = \tfrac{1}{2}\rangle = i\,\frac{\sqrt{2}}{3}\,2.3\cdot 10^{-10}\,|e|\cdot a_B \qquad (5)$$

It should be noted that in computation of matrix elements of D_z the contributions of different admixing states are mutually compensating considerably, therefore the inaccuracy of the calculation may be rather large.

The quantity $P_0 = -2\,\mathrm{Im}\frac{\langle D_z\rangle}{\langle M_z\rangle}$ for the $6p_{1/2} - 7p_{3/2}$ transition in thallium constitutes $-1.4\cdot 10^{-6}$. In the present case due to large contribution of electrical quadrupole, P_0 does not coincide in general with the degree of circular polarization of photons P which is

$$P = P_0\,\frac{\frac{1}{3}\langle F'\|M\|F\rangle^2}{\frac{1}{3}\langle F'\|M\|F\rangle^2 + \frac{1}{5}\langle F'\|Q\|F\rangle^2} \qquad (6)$$

and varies from one hyperfine transition to another. Using (2) and (3) we find

$$P(0\to 1) = P_0 = -1.4\cdot 10^{-6}. \qquad P(0\to 2) = 0.$$
$$P(1\to 1) = P_0/55 = -2.5\cdot 10^{-8}. \quad P(1\to 2) = 5P_0/59 = -1.2\cdot 10^{-7} \qquad (7)$$

Due to small hyperfine splitting of the $7p_{3/2}$ level the resolution of its hyperfine structure may be impossible. In this case at any F

$$P = P_0/19 = -0.74\cdot 10^{-7} \qquad (8)$$

Note that although the values of $\langle M_z\rangle$, $\langle D_z\rangle$ and $\langle r^2\rangle$ found by us agree [redacted] with those obtained in/6/ (at any rate, up to a sign), the value of P from (7), (8) exceeds considerably the prediction of the work/6/: $P = -1.67\cdot 10^{-8}$. May be just this underestimate of the degree of circular polarization is the explanation of the pessimistic estimate of the feasibility of the experiment under discussion given in/6/.

Besides the transition $6p_{1/2} \rightarrow 7p_{3/2}$, the transitions $6p_{1/2} \rightarrow 8p_{3/2}$, $9p_{3/2}$ may be of some interest from the point of view of search for optical activity. The degree of circular polarization in them is, crudely speaking, the same as that in $6p_{1/2} \rightarrow 7p_{3/2}$ since with the increase of the principal quantum number of the upper level the values of $\langle M \rangle$, $\langle D \rangle$ and $\langle Q \rangle$ fall off approximately in the same way.

Due to the absence of quadrupole absorption, suppressed M1 transition $6p^2\,{}^3P_0' \rightarrow 6p7p\,{}^3D_1'$ in lead has some advantage in comparison with the transitions discussed in thallium. (In our works[8,9] this transition in lead was erroneously called strongly forbidden.) For this transition using the wave function of the ground state $6p^2\,{}^3P_0'$ from [7] and taking the state ${}^3D_1'$ as a pure jj one $(6p_{1/2}7p_{3/2})_1$, we get in the same way as in thallium

$$\langle 6p7p\,{}^3\mathcal{D}_1' | M_z | 6p^2\,{}^3P_0' \rangle = -\tfrac{2}{3}\,0.085\,|\mu_B| \qquad (9)$$

The matrix element of the admixed E1 transition was found in the work[8]

$$\langle 6p7p\,{}^3\mathcal{D}_1' | \mathcal{D}_z | 6p^2\,{}^3P_0' \rangle = -i\,\tfrac{2}{3}\,1.9\cdot 10^{-10}\,|e|\,a_B \qquad (10)$$

The degree of circular polarization is

$$P = -1.2\cdot 10^{-6} \qquad (11)$$

Now about the optical activity of thallium and lead vapors. For the light of frequency ω near a line with frequency ω_0 the absorption coefficient α and the angle of rotation of polarization plane at the unit length ψ are given by the formulae

$$\alpha = \frac{4\pi}{\hbar c}\,\frac{N}{(2I+1)(2J+1)}\,\frac{\omega}{\Delta_D}\left[\tfrac{1}{3}\langle F'J' \| M \| FJ \rangle^2 + \tfrac{1}{5}\langle F'J' \| Q \| FJ \rangle^2\right]\cdot f(u,v)$$

$$\psi = -\frac{2\pi}{\hbar c}\,\frac{N}{(2I+1)(2J+1)}\,\frac{\omega}{\Delta_D}\,\tfrac{1}{3}\langle F'J' \| M \| FJ \rangle^2\,P_0\cdot g(u,v) \qquad (12)$$

where I is the spin of nucleus, J and J' are initial and final angular momentá of electrons, F and F' are initial and final angular momenta of atom, N is the density of atoms, $\Delta_D = \sqrt{\frac{2kT}{m_a c^2}}\,\omega$, $u = (\omega-\omega_0)/\Delta_D$ is the detuning, $v = \Gamma/2\Delta_D$, Γ is the line width, and finally f(u,v) and g(u,v) are dimensionless functions which describe the Doppler broadening of the line:

$$\left\langle \frac{\Delta_D}{\omega-\omega_0+i\Gamma/2} \right\rangle = g(u,v) - i\,f(u,v) \qquad (13)$$

By means of formulae (12) it can be easily found that at the temperature 1200°C (the pressure of thallium vapor is 100 mm, that of lead is 17 mm[10]) at the wing of line the angles of rotation of polarization plane can reach 10^{-6} rad/m at the absorption length 1 m. Limitation on accidental external magnetic field imitating the effect is $\sim 10^{-4}$ Gauss in thallium and $\sim 10^{-3}$ Gauss in lead.

Note in conclusion that the accuracy reached in the experiments with bismuth is quite sufficient for measurement of angles $\sim 10^{-6}$ rad/m. Therefore, in the situation when the search for the parity nonconservation in a strongly forbidden M1 transition $6p_{1/2} \rightarrow 7p_{3/2}$ in thallium is going on already[2], the experiment discussed by us on the detection of optical activity of thallium vapors in the same frequency region seems to be quite realistic one.

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