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A b s t r a c t

The contribution of a weak electron-electron interaction is calculated to the circular polarization of light and to optical activity of the Tl, Pb, and Bi vapors near the MI-transitions.

At the present time the experiments on a search for the optical activity of the vapors of heavy metals firstly proposed in /1-3/, are carried out by several experimental groups /4-6/. The optical activity may be caused both by the P-odd interaction of the electrons with the nucleus and P-odd interaction of the electrons with each other. The contribution of a weak electron-electron interaction to the parity violation effects in heavy atoms was firstly considered in /7/ where its upper estimate was given. The contribution of this interaction is smaller than the electron-nucleon one by a factor Z (Z is the nucleus charge). However, if the P-odd interaction of the electrons with nucleons is anomalously small or absent at all (this is the interpretation of experimental results /4, 5/ that is most popular now), then the contribution of the electron-electron interaction to the parity violation effects may be essential. For this reason, it is timely, in our opinion, to carry out its accurate calculation. In the present paper the circular polarization of light due to the P-odd electron-electron interaction is calculated in the transitions $6p_{1/2} \to 6p_{3/2}$, $7p_{1/2}$, $7p_{3/2}$ in Tl, $6p^2\,{}^3P_0' \to 6p^2\,{}^3P_1$ in Pb, and $6p^3\,{}^4S_{3/2}' \to 6p^3\,{}^2D_{3/2}'$, ${}^2D_{5/2}'$, ${}^2P_{1/2}'$, ${}^2P_{3/2}'$ in Bi.

The Hamiltonian of a weak electron-electron interaction looks as follows

$$H_w = \frac{G}{\sqrt{2}}\,\bar\Psi\gamma_\mu(h_V + h_A\gamma_5)\Psi\;\bar\Psi\gamma_\mu(h_V + h_A\gamma_5)\Psi \qquad (1)$$

where $G = 10^{-5}/m_p^2$ is the Fermi constant. In the experiments on the search for the parity violation the constant $\eta = h_V h_A$ may be measured. Below it will be shown that the main contribution to the effect comes from the interaction of a valent electron with the internal ones at short distances from the nucleus

($r \sim a_B/Z$, a_B is the Bohr radius). At these distances $\frac{V}{c} \sim Z\alpha$, i.e. $\frac{e^2}{\hbar v} \sim \frac{1}{Z}$, and therefore there is no necessity to take account of the Coulomb repulsion of the electrons in calculating the matrix element of the Hamiltonian (1). The inetraction (1) admixes the levels of an opposite parity with excitation of both one and two electrons to the unperturbed state of the atom. Nevertheless, it is easy to verify that the contribution of the two-particle excitations to the effect is very small. Therefore, the P-odd part of the Hamiltonian (1) may be reduced to the effective one-particle Hamiltonian for the external electron

$$H_{eff} = 2\frac{G}{\sqrt{2}}\eta\, n(r)\, \psi^+\gamma_5\psi \qquad (2)$$

where $n(r)$ is the electron density. In deriving the equation (2) we have taken into account that the exchange interaction is equal to the direct one (there is no difficulty to verify it by means of the Fierz transformation).

Since $n(r)$ decreases rapidly (for example, in the Thomas-Fermi model $n(r) \leq \frac{const}{r^{3/2}}$), the main contribution to the matrix element of the Hamiltonian (2) comes from $r \sim a_B/Z$. At these distances the density $n(r)$ is mainly determined by K-electrons, i.e. the external electron interacts only with several internal ones. This is the reason for that the contribution of the electron-electron interaction to the P-odd effects is by Z times smaller than the contribution of the electron-nucleon interaction which is proportional to the number of nucleons in a nucleus. Since the matrix element of a weak interaction with the nucleus is proportional to Z^3 (see, for example, /7/), the matrix element of the operator (2) is proportional to Z^2.

In this work we need the matrix elements of the Hamiltonian (2) between the states $s_{1/2}$ and $p_{1/2}$, and also $d_{3/2}$ and $p_{3/2}$. Let's write down them in the following form

$$\langle s_{1/2}|H|p_{1/2}\rangle = -\frac{iG\eta}{\sqrt{2}\pi}\frac{m^2\alpha^2Z^2}{(\nu_s\nu_{p_{1/2}})^{3/2}}K(s_{1/2}p_{1/2})\frac{me^4}{2\hbar^2} \qquad (3)$$

$$\langle d_{3/2}|H|p_{3/2}\rangle = -\frac{iG\eta}{\sqrt{2}\pi}\frac{m^2\alpha^2Z^2}{(\nu_{d_{3/2}}\nu_{p_{3/2}})^{3/2}}K(d_{3/2}p_{3/2})\frac{me^4}{2\hbar^2} \qquad (4)$$

where $K(ij) = 4\pi\frac{(\nu_i\nu_j)^{3/2}}{Z^2}a_B^3\int_0^\infty (g_if_j - f_ig_j)n(r)dr$; the functions $g(r)$ and $f(r)$ are determined by the equality

$$u = -\frac{1}{r}\begin{pmatrix} g(r)\,\Omega_{jem} \\ i f(r)\,\Omega_{je'm} \end{pmatrix} \qquad (5)$$

u and Ω_{jem} are the Dirac and spherical spinors, ν_i and ν_j are the effective principal quantum numbers of the electron. The quantities $K(ij)$ have been determined by us in such a way that they are approximately equal for all heavy atoms. Indeed, the main contribution to these integrals are given by the distances $\sim a_B/Z$ (90% of contribution to $K(sp)$ arises from the distances $r \leq 1.2\,a_B/Z$, to $K(dp)$ — $r \leq 4.6\,a_B/Z$) where $n(r) \sim Z^3$, and for the wave functions of external electrons the quasiclassical approximation Fermi-Segre is correct: $g \sim f \sim \frac{1}{(Zr)^{3/2}}$. We find the integrals $K(ij)$ by means of the wave functions obtained by a numerical integration of the Dirac equation in the effective potential proposed in /8/. This potential reproduces the energies of both the external electrons and internal ones with an accuracy not worse than several percent. In Fig.1 the density $n(r)$ which has been found by direct summa-

tion of the contributions of different subshells is presented. The numerical values of the quantities $K(i,j)$ are:

$$K(nS_{\frac12}6P_{\frac12}) = 2.3 \qquad K(nS_{\frac12}7P_{\frac12}) = 2.0 \qquad n \geq 6$$
$$K(5d_{\frac32}6P_{\frac32}) = -0.69 \qquad K(5d_{\frac32}7P_{\frac32}) = -0.60 \qquad (6)$$
$$K(nd_{\frac32}6P_{\frac32}) = -0.37 \qquad K(nd_{\frac32}7P_{\frac32}) = -0.32 \qquad n \geq 6$$

In MI-transitions under consideration in Tl, Pb, and Bi the calculation of the circular polarization degree P ($P = -2\,\mathrm{Im}\frac{E}{M}$, where M and E are the main MI and admixture EI amplitudes) is carried out by using (3), (4) in the same way as in /9/ for the electron-nucleus interaction. The necessary radial integrals for the transitions into the discrete spectrum levels are given in /10, 11/, the contribution of a continuous spectrum is found by the numerical calculation. For the MI-transitions inside the ground configurations in Tl, Pb, and Bi the main contribution to a degree of the circular polarization is due to the weak interaction mixing of the $S_{\frac12}$ and $P_{\frac12}$ levels (the contribution of the $d-p$ mixing decreases the result by 10%), i.e. in this case, the effect is similar to that caused by the interaction of the electron with the nucleus where *only $S-p$ mixing exists* . Therefore, for all these transitions the circular polarization degree due to the weak electron-electron interaction (P_e) is approximately proportional to the circular polarization degree due to the weak interaction of the electron with the nucleus (P_N), which was calculated in /9/:

Tl, transition $6P_{\frac12} \to 6P_{\frac32}$; $P_e/P_N = -\frac{1}{4.2Z}\frac{\eta}{q}$

Pb, transition $6p^2\,{}^3P_0' \to 6p^2\,{}^3P_1$; $P_e/P_N = -\frac{1}{4.4Z}\frac{\eta}{q}$ (7)

Bi, transition $6p^3\,{}^4S_{\frac32}' \to 6p^3\,{}^2D_{\frac32}', {}^2D_{\frac52}', {}^2P_{\frac12}', {}^2P_{\frac32}'$; $P_e/P_N = -\frac{1}{4.6Z}\frac{\eta}{q}$

The parameter q characterizes the P-odd interaction of the electron with the nucleus; in /9/ it was assumed that $q = -0.9$. The numerical values of quantities P_e are presented in Table 1. The corresponding angles of optical rotation at 1200°C, the collision broadening cross-section $\sigma = 0.5\cdot10^{14}$ cm^2, and the detuning from a resonance chosen in such a way that the absorption length is equal to 1 metre, are also given in Table 1 (for a more detail consideration of experimental conditions see /9/).

Now we calculate a degree of the circular polarization and optical activity caused by the weak electron-electron interaction in the suppressed MI-transition $6P_{\frac12} \to 7P_{\frac12}$ in Tl. In this case, a large contribution to the effect (~50%) comes from the mixing of the states $7P_{\frac12}$ and $6d_{\frac12}$, since the distance between them is less than 1000 cm^{-1}. The ratio P_e/P_N constitutes

$$P_e/P_N = -\frac{1}{1.8Z}\frac{\eta}{q} \qquad (8)$$

The quantity P_N was calculated in /12/, the numerical value P_e is presented in Table 1.

Note that the ratio P_e/P_N for the transition $6P_{\frac12} \to 7P_{\frac12}$ is significantly different from those for the allowed MI-transitions (6) because of a large contribution of $d-p$ mixing. This circumstance may, in principle, allow to determine what interaction leads to the parity violation - the electron-nucleon interaction or electron-electron one.

We have also considered the strongly-forbidden MI-transition $6P_{\frac12} \to 7P_{\frac12}$ in Tl. In this case, only S and P levels are mixed, and the ratio $P_e/P_N = -\frac{1}{3.8Z}\frac{\eta}{q}$ (P_N is calculated in /8, 10/).

As it was mentioned above, the upper estimate for a quantity P_e/P_N in heavy atoms was obtained previously in /7/. Our values are by 5-16 times lower than this estimate.

In conclusion, dwell on the interpretation of the experimental results on a search for the optical activity of the Bi vapor. In /4, 5/ the following limitations for the circular polarization degree were obtained: transition $^4S_{3/2}' \to {}^2D_{3/2}'$, $P = (1.4 \pm 6.4)\cdot 10^{-8}$ /4/; transition $^4S_{3/2}' \to {}^2D_{5/2}'$, $P = (-5.4 \pm 9.4)\cdot 10^{-8}$ /5/. If one assumes that the P-odd interaction of the electron with the nucleus is absent, then using the Table 1, one can find the limitation for a constant of the P-odd electron-electron interaction (see eq.(1))

$$\eta = -10 \pm 40 \qquad (9)$$

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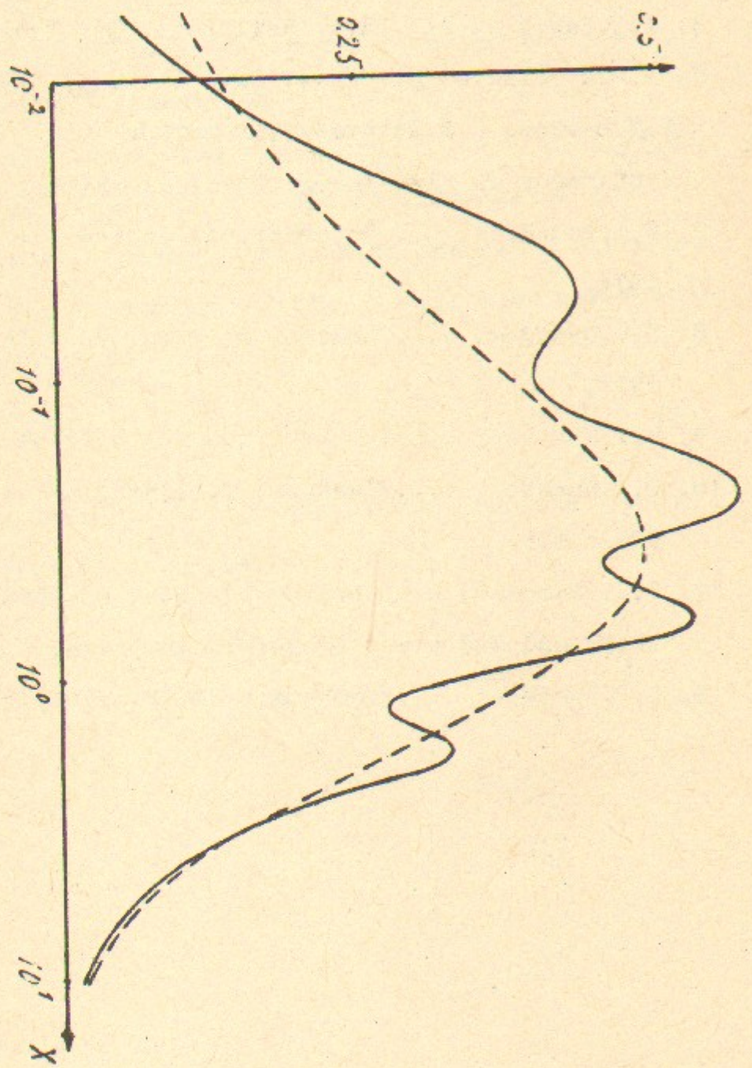

Fig.1

The continuous line is the plot of the function $\frac{4\pi\chi^2 n(x)}{Z^2}$ ($\chi = 0.885\, Z^{-\frac{1}{3}} \chi_0$) for Tl ($Z = 81$). The dotted line is the plot of the same function in the Thomas-Fermi model.

	Initial state	Final state	λ, Å	$\frac{P}{\eta} 10^9$	F	F'	$\lvert\frac{\Psi}{\eta}\rvert \cdot 10^9$ rad./m
Tl	$6p_{\frac{1}{2}}$	$6p_{\frac{3}{2}}$	12833	1.3	1	2	34
		$7p_{\frac{3}{2}}$	2844	-11	1	2	~5
		$7p_{\frac{1}{2}}$	2927	$-9\cdot10^3$			
Pb	$6p^2\,{}^3P_0'$	$6p^2\,{}^3P_1$	12789	1.0	0	1	35
Bi	$6p^3\,{}^1S_{\frac{3}{2}}'$	$6p^3\,{}^2D_{\frac{3}{2}}'$	8757	1.0	6	6	7.6
		${}^2D_{\frac{5}{2}}'$	6477	1.2		7	1.7
		${}^2P_{\frac{1}{2}}$	4616	2.2		5	4.4
		${}^2P_{\frac{3}{2}}'$	3015	3.4		6	0.6

Table I

Circular polarization degrees $P = -2\,Im\frac{E}{M}$ and optical rotation angles ψ in Tl, Pb, and Bi vapors. Rotation angles are presented for transitions between maximal F and F'.

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