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TO THE POSSIBILITY OF THE INVESTIGATION OF THE WEAK NEUTRAL CURRENTS STRUCTURE IN OPTICAL TRANSITIONS IN HEAVY ATOMS

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TO THE POSSIBILITY OF THE INVESTIGATION OF THE WEAK NEUTRAL CURRENTS STRUCTURE IN OPTICAL TRANSITIONS IN HEAVY ATOMS

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abstract

The effects of parity non-conservation in optical transitions in thallium, lead, bismuth and cesium caused by weak interaction of the neutral electron vector and nucleon axial currents are considered. The magnitude of circular polarization of light in usual and strongly forbidden MI transitions is calculated.

1. Presently the experiments aimed at the detection of parity violation effects in heavy atoms (at first such an experiment was discussed in the paper[1]) are going ahead at some groups[2-6]. In our opinion, the most promising of them are the experiments on the search for the rotation of the polarization plane of light in heavy metal vapours which were suggested in the works[7-9]. They have led already to the essential limitation[5] on the constant of weak interaction of neutral nucleon vector current (VC) with electron axial current (AC). Parity non-conservation effects in heavy atoms may be caused also by another type of weak interaction, of nucleon AC and electron VC. The search for this interaction would be in no way less interesting even if the interaction of electron AC with nucleon VC were absent (just such an interpretation of the interim experimental results[5] is most popular now).

Previously we have noted[10,11] the possibility of the investigation of the nucleon AC and electron VC interaction by means of measurement of the angles of rotation of polarization plane of light at the frequencies corresponding to optical transitions between separate hyperfine components of the levels in heavy atoms. The detection of this interaction would be more difficult since its magnitude is roughly speaking Z times smaller (Z is the nucleus charge) than the magnitude of the nucleon VC and electron AC interaction because only a valent nucleon contributes to nucleon AC. However, the accuracy achieved already in the experiments on the search for optical activity of heavy metal vapours is close to that necessary for the detection of the mentioned effect. Besides that, we found the contribution of the considered interaction into circular polarization of radiation in the strongly forbidden MI transitions in cesium, thallium and lead.

It should be noted that other possible manifestations of the interaction between nucleon AC and electron VC in ions, solids and heavy atoms were discussed previously in the works/I2-I6/.

2. Hamiltonian of the interaction between electron VC and nucleon AC looks as follows

$$H_W = \frac{G\hbar^3}{c\sqrt{2}}\varkappa_N(\bar{u}_e\gamma_\mu u_e)(\bar{u}_N\gamma_\mu\gamma_5 u_N) \qquad \text{(I)}$$

where u_e and u_N are electron and nucleon spinors, $G = 10^{-5}/m_p^2$ is the Fermi constant. In fact, the meaning of the experiment discussed is the determination of the constant $\varkappa_N$ which is different, generally speaking, for proton ($\varkappa_p$) and neutron ($\varkappa_n$). The matrix element of the Hamiltonian (I) can be written as follows/I6/ (only the matrix element between $s_{1/2}$ and $p_{1/2}$ electron states is not equal to zero)

$$\langle s_{1/2}|H_W|p_{1/2}\rangle = i\frac{Gm^2\alpha^2Z^2R}{\pi\sqrt{2}}(\nu_s\nu_{p_{1/2}})^{-\frac{3}{2}}\frac{me^4}{2\hbar^2}\frac{2\gamma+1}{3}\varkappa g_I 2\vec{J}_e\vec{I}_\alpha \qquad (2)$$

Here $\gamma=\sqrt{1-(\alpha Z)^2}$, ν_s , $\nu_{p_{1/2}}$ are the effective principal quantum

numbers of electron; R is the relativistic factor (R_{Tl} = 8.5, R_{Pb} = 8.9, R_{Bi} = 9.4, R_{Cs} = 2.8). The factor $\varkappa g_I$ which appears in the formula (2) after calculation of the matrix element of (I) over nucleus wave functions, is defined in such a way that in the nuclear shell model used by us for numerical estimates $\varkappa$ coincides with the corresponding constant for valent nucleon ($\varkappa_{Cs}=\varkappa_{Tl}=\varkappa_{Bi}=\varkappa_p$; $\varkappa_{Pb^{207}}=\varkappa_n$) and $g_I = \langle\sigma_z$ (of valent nucleon)$\rangle/I_{\alpha,z}$ constitutes 2 for thallium, $-2/3$ for Pb^{207}, $-2/11$ for bismuth, $-2/9$ for cesium. The accuracy of this approximation can be expected to be comparable with that of predictions of shell model for the nuclear magnetic momenta which constitutes I0% for Pb^{207}, 30% for cesium and bismuth, 70% for thallium[I].

Parity violation in the considered MI transitions leads to small admixture of EI amplitude in these transitions and to circular polarization of radiation

$$P = -2\,\mathrm{Im}\frac{\langle J'IF'\|E1\|JIF\rangle}{\langle J'IF'\|M1\|JIF\rangle} \qquad (3)$$

Here $\vec{I}$ is spin of nucleus, $\vec{J}$ and $\vec{J}'$ are initial and final an-

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[I] The value of $\varkappa g_I$ in thallium can be found perhaps more precisely if one neglects the contribution of spin-orbit interaction into the configuration mixing in the ground state of thallium nucleus. In this approximation the orbital momentum and spin are conserved separately. Hence, the ground state may be characterized even in the presence of configuration mixing by the values $L = 0$, $S = 1/2$ (in the shell model it is a proton in the state ${}^2S_{1/2}$). Then from the experimentally known /I7/ magnetic moment of the Tl nucleus ($\mu_{Tl}=1.6=\frac{1}{2}g_s^p\langle\sigma_z^p\rangle+\frac{1}{2}g_s^n\langle\sigma_z^n\rangle$, $\langle\sigma_z^n\rangle=1-\langle\sigma_z^p\rangle$) we find that $\langle\sigma_z^p\rangle = 3/4$, $\langle\sigma_z^n\rangle = 1/4$, i.e. $\varkappa_{Tl}=\frac{3}{4}\varkappa_p+\frac{1}{4}\varkappa_n$ and g_I as well as without mixing is equal to 2.

gular momenta of electrons, $\vec{F}=\vec{J}+\vec{I}$ and $\vec{F}'=\vec{J}'+\vec{I}$ are initial and final angular momenta of atom.

For the calculation of the amplitudes of EI transitions it is convenient to use the second quantization representation and the method of summation over intermediate states/I0/. The matrix element of the operator product $\vec{\mathcal{D}}H_W \sim \vec{\mathcal{D}}(\vec{j}_e\vec{I})$ (here $\vec{\mathcal{D}}$ is the operator of electric dipole moment, and $H_W \sim \vec{j}_e\vec{I}$ according to (2)) arising after the summation over intermediate states, can be calculated by means of the decomposition of the product into the sum of irreducible tensors $\mathcal{D}_i j_k = \sum_{s=0}^{2} T_{ik}^{(s)}$ and then by use of the formula/I8/

$$\langle J'IF'\|[T^s\otimes I]^1\|JIF\rangle = \langle J'\|T^s\|J\rangle\langle I\|I\|I\rangle \times$$
$$\times\sqrt{3(2F+1)(2F'+1)}\begin{Bmatrix} J' & J & s\\ I & I & 1\\ F' & F & 1\end{Bmatrix} \qquad (4)$$
$$\langle I\|I\|I\rangle = \sqrt{I(I+1)(2I+1)}$$

The reduced matrix elements $\langle J'\|T^k\|J\rangle$ are calculared in standard way/I0/. Radial integrals necessary for these calculations were taken from the work/I9/ (see also /I0,I5/). Note that the summation over intermediate states is inapplicable if the levels mixed by weak interaction are close. This situation takes place in bismuth for the mixing of the state $6p^2 7s\,{}^4P'_{1/2}$ with $6p^3\,{}^2P_{1/2}$ and $6p^3\,{}^2P'_{3/2}$. In the first case taking into account of the anomalous closeness reduces the result by 40%; in the second case this fact is inessential since the matrix element $\langle 6p^2 7s\,{}^4P'_{1/2}|H_W|6p^3\,{}^2P'_{3/2}\rangle$ is very small. Note also that due to strong cancellations between different contributions, the accuracy of the calculations for the

transition $6p^3\,{}^4S'_{3/2}\to 6p^3\,{}^2D'_{3/2}$ in bismuth is very low.

Making use of the found in this way amplitudes of EI transitions as well as of MI amplitudes from /I0,20/, we determine the degrees of of circular polarization in the transitions discussed. The values of $P/\varkappa$ (see (2),(3)) and the amplitudes of MI transitions $6p_{1/2}\to 6p_{3/2}$ in thallium, $6p^2\,{}^3P'_0\to 6p^2\,{}^3P'_1$ in lead and $6p^3\,{}^4S'_{3/2}\to 6p^3\,{}^2D'_{3/2},\ {}^2D_{5/2},\ {}^2P_{1/2},\ {}^2P'_{3/2}$ in bismuth are presented in the tables I,2. The angles of rotation of polarization plane of light for the transitions between those components of hyperfine structure where these angles are maximal, are presented in the table 3. The degrees of circular polarization and rotation angles are given without taking into account the contribution of the interaction between electronAC and nucleon VC which was calculated previously in the work/I0/.

	F	F'	M1	$\frac{P}{\varkappa}10^8$
Tl	0	1	-0.817	1.430
	1	1	0.577	-0.475
	1	2	-1.290	-0.475
Pb	1/2	1/2	1.07	-0.150
	1/2	3/2	-1.51	0.075

Table I

MI amplitudes $\langle J'IF'\|M\|JIF\rangle/(-|\mu_B|)$ and the degrees of circular polarization in the transitions $6p_{1/2}\to 6p_{3/2}$, λ = I2833 Å in Tl and $6p^2\,{}^3P'_0\to 6p^2\,{}^3P'_1$, λ = I2789 A in Pb

It can be seen from these results that to detect the discused effect in bismuth it is sufficient to increase the accuracy of measurements indicated in the work/5/ by an order of magnitude.

		$^2D'_{3/2}$ $\lambda=8757$ Å		$^2D_{5/2}$ $\lambda=6477$ Å		$^2P_{1/2}$ $\lambda=4616$ Å		$^2P'_{3/2}$ $\lambda=3015$ Å	
F	F′	M1	$\frac{P}{\varkappa}10^9$	M1	$\frac{P}{\varkappa}10^9$	M1	$\frac{P}{\varkappa}10^9$	M1	$\frac{P}{\varkappa}10^9$
3	2			-0.533	11.1				
	3	1.53	-1.64	0.468	16.4			-0.169	3.13
	4	-1.69	-0.25	-0.306	23.5	-0.823	2.85	0.187	7.08
4	3	1.69	-4.09	-0.423	-0.80			-0.187	5.53
	4	0.15	19.5	0.568	6.29	-0.800	2.85	-0.017	-84.9
	5	-1.95	2.17	-0.516	15.2	-0.482	-2.32	0.216	~1
5	4	1.95	-2.63	-0.309	-15.2	-0.652	2.85	-0.216	~-1
	5	-1.21	-2.62	0.570	-6.32	-0.800	-2.32	0.134	11.5
	6	-1.70	5.01	-0.719	4.31			0.189	-6.16
6	5	1.70	-0.75	-0.185	-32.1	-1.12	-2.32	-0.189	-8.49
	6	-2.60	1.34	0.471	-21.5			0.288	-2.56
	7			-0.923	-9.06				

Table 2

MI amplitudes $\langle J'IF'\|M1\|JIF\rangle/(-i\mu_0)$ and the degrees of circular polarization in the transitions from the ground state to the excited states in the configuration $6p^3$ in bismuth

	TRANSITION	F	F′	$\frac{\Psi}{\varkappa}10^8$ RAD/M
Tl	$6p\ P_{1/2} - 6p\ P_{3/2}$	0	1	76
Pb	$6p^2\ {}^3P_0 - 6p^2\ {}^3P_1$	1/2	3/2	2.3
Bi	$6p^3\ {}^4S_{3/2} - 6p^3\ {}^2D'_{3/2}$	5	6	2.7
	${}^2D_{5/2}$	6	7	-1.4
	${}^2P_{1/2}$	6	5	-0.54
	${}^2P'_{3/2}$	6	5	-0.06

Table 3

Maximal angles of rotation of polarization plane of light at the Doppler shape of absorption line and the temperature of vapours I200°C

3. For the completeness we have calculated also EI amplitudes in the strongly forbidden MI transitions $6S_{1/2} \to 7S_{1/2}$ in cesium, $6p_{1/2} \to 7p_{1/2}$ in thallium and $6p^2\,{}^3P_2' \to (6p_{1/2}7p_{1/2})_1, (6p_{1/2}7p_{3/2})_1$ in lead arising due to the interaction (I). Their values are presented in the table 4. For cesium and thallium where the MI amplitudes are known experimentally[2I,3], the degrees of circular polarization are given in the same table.

The circular polarization in these transitions caused by the interaction of electron AC and nucleon VC is presented in the works[2,22] for cesium and [14,I5] for thallium and lead.

Note that if the interaction between electron AC and nucleon VC is absent, it is more convenient perhaps to look for the circular polarization of light due to the interaction (I) in the transition $6p_{1/2} \to 7p_{1/2}$ in thallium rather than in 0 - 0 transitions in Pb^{207} /I4,I5/. The point is that although the quantity $P/\varkappa$ in thallium is three times smaller[2)], the probability

	TRANSITION	F	F′	M1	E1	$P/\varkappa$
Tl	$6P_{1/2} - 7P_{1/2}$	0	1	$0.366\cdot10^{-4}$	$0.748\cdot10^{-11}$	$-1.12\cdot10^{-4}$
	$\lambda = 2927$ Å	1	0	$-0.366\cdot10^{-4}$	$0.359\cdot10^{-11}$	$0.538\cdot10^{-4}$
		1	1	$0.517\cdot10^{-4}$	$-0.274\cdot1\quad 11$	$0.291\cdot10^{-4}$
Pb	$6p^2\,{}^3P_0$ -					
	$6p_{1/2}7p_{1/2}$	1/2	1/2	-	$1.65\cdot10^{-12}$	-
	$\lambda = 2330$ Å	1/2	3/2	-	$1.16\cdot10^{-12}$	-
	$6p^2\,{}^3P_0$ -					
	$6p_{1/2}7p_{3/2}$	1/2	1/2	-	$0.656\cdot10^{-12}$	-
	$\lambda = 2238$ Å	1/2	3/2	-	$0.464\cdot10^{-12}$	-
Cs	$6S_{1/2} - 7S_{1/2}$	3	3	$-0.973\cdot10^{-4}$	$-0.822\cdot10^{-12}$	$-0.463\cdot10^{-5}$
		3	4	$1.69\cdot10^{-4}$	$-1.43\cdot10^{-12}$	$0.465\cdot10^{-5}$
	$\lambda = 5395$ Å	4	3	$-1.69\cdot10^{-4}$	$-1.75\cdot10^{-12}$	$-0.568\cdot10^{-5}$
		4	4	$1.42\cdot10^{-4}$	$-0.932\cdot10^{-12}$	$0.360\cdot10^{-5}$

Table 4

MI, EI amplitudes $\langle J'IF' \| M1 \| JIF \rangle / (-i\mu_B)$, $\langle J'IF' \| E1 \| JIF \rangle / (-i|e|a_0)$ and degrees of circular polarization in strongly forbidden transitions in Tl, Pb^{207} and Cs

of the corresponding transition is almost by three orders of magnitude larger than the probability of 0 - 0 transition in Pb^{207} /I5/.

The effects considered in the present work can be imitated by an external magnetic field. The limitations on the magnetic field in usual MI transitions one can obtain using the results of the works /I0,20/. For most interesting transitions they constitute 10^{-5} - 10^{-6} gauss by order of magnitude.

[2)] In the paper /I5/ the calculations are given at $\varkappa_{Pb^{207}} = - 0.I75$.

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