Parity nonconservation in strongly forbidden T1 transitions in thallium and lead

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We consider transitions in thallium and lead that offer promise from the point of view of searches for neutral currents. The parity nonconservation effects in these transitions are calculated.

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The first sufficiently realistic experiment aimed at observing parity nonconservation in atomic transitions was proposed by Bouchiat.[1] We refer here to the search for circular polarization of photons in the strongly forbidden $M1$ transition $6s-7s$ in cesium. This polarization arises if a weak parity-nonconserving interaction between the nucleon and electron neutral currents exists. By now it has become possible to measure the magnetic moment of the transition itself[2] and to establish the upper bound of the degree of circular polarization[3]: $|P| < 2.6\times10^{-2}$. Within the framework of the popular Weinberg model, one should expect in this transition $P=2\times10^{-4}$.[3]

Soon after the appearance of[1] it was noted that a circular polarization larger by one order of magnitude can be expected in strongly forbidden $M1$ transitions in thallium[4,5] and in lead.[5] The corresponding transitions lie in the range accessible to tunable lasers that use frequency doubling. Now, when experiments with thallium are being carried out[6] and have already yielded the magnetic moment of the $6p_{1/2}\to 7p_{1/2}$ transition (see Table I), a detailed calculation of parity nonconservation in strongly forbidden $M1$ transitions in thallium and lead is timely. Its results are reported in the present article.

The technique of calculating the amplitudes of parity-nonconserving $E1$ transitions in thallium and lead has been considered in sufficient detail in a paper[7] devoted to the calculation of the optical activity of metal vapors near ordinary $M1$ transitions. We therefore present here only a few details of the calculations.

The matrix element of a P-odd interaction of an electron with the nucleus is of the form[8]

TABLE I.

	Initial state	Final state	λ, Å	$\langle f\|M_z\|i\rangle/\|\mu_B\|$	$\langle f\|D_z\|i\rangle/i\|l\|a_0$	P
Tl	$6p_{1/2}$	$7p_{1/2}$	2927	$-2.11\cdot10^{-5}$	$-0.95\cdot10^{-10}$	$-2.5\cdot10^{-3}$
		$8p_{1/2}$	2417	–	$-0.53\cdot10^{-10}$	–
		$9p_{1/2}$	2253	–	$-0.40\cdot10^{-10}$	–
Pb	$6p^2(^3P_0')$	$6p7p(^3P_1')$	2330	–	$1.07\cdot10^{-10}$	–
		$6p7p(^3D_1')$	2238	–	$-1.25\cdot10^{-10}$	–
		$6p^2(^1S_0')$	3394	$0.81\cdot10^{-6}$	$0.95\cdot10^{-13}$	$-6.5\cdot10^{-5}$
		$6p7p(^3P_0')$	2252	–	$-0.95\cdot10^{-13}$	–

$$\langle s_{1/2}|H_w|p_{1/2}\rangle = i\,\frac{Gm_e^2\alpha^2Z^2R}{\pi\sqrt{2}}\,\frac{m_e l^4}{2\hbar^2}\,\frac{1}{\nu_s^{3/2}\nu_{p_{1/2}}^{3/2}}\left[Zq+\frac{2\gamma+1}{3}g_I\,2\mathbf{I}_{\text{nuc}}\mathbf{j}_e\right], \tag{1}$$

where $G=10^{-5}/m_p^2$ is the Fermi constant, $\gamma=\sqrt{1-Z^2\alpha^2}$; ν_5 and $\nu_{p_{1/2}}$ are the effective principal quantum numbers of the electron; R is the relativistic factor ($R_{\text{Tl}}=8.5$; $R_{\text{Pb}}=8.9$). In the Weinberg model (at $\sin^2\theta=0.32$) we have $q_{\text{Tl}}=q_{\text{Pb}}=-0.9$; $g_I(\text{Pb}^{207})=0.12$.

The effect is easiest to calculate for the $6p_{1/2}\to mp_{1/2}$ transitions in thallium. In this case the contribution of the second term in the square brackets of (1) is small in comparison with the first ($\sim 1/Z$) so that the actually measured quantity is the constant q, which characterizes the interaction of the nucleon vector and the electronic axial neutral currents. Mixed in with the initial and final states are both the ordinary levels of opposite parity ns ($n\geq 7$), including the continuous spectrum, and excitations of the type $6s\,6pmp$ of the internal $6s^2$ subshell. The radial integral needed for the calculations were extracted by us from the experimental data, when available, or from the numerical calculations.[7,9] The most essential radial integrals are listed in Table II.

TABLE II. Radial integrals in units of the Bohr radius.

	Tl				Pb		
	$6p_{1/2}$	$7p_{1/2}$	$8p_{1/2}$	$9p_{1/2}$	$6p_{1/2}$	$7p_{1/2}$	$7p_{3/2}$
$6s$	-1.8	-0.13	-0.06	-0.04	-1.6	-0.09	-0.2
$7s$	2.22	-7.62	-0.90	-0.40	1.75	-7.10	-6.67
$8s$	0.67	7.38	-14.7	-1.77	0.66	6.65	8.10
$9s$	0.37	1.58	14.3	-23.8	0.37	1.49	1.35
$10s$	0.28	0.79	2.74	23.5	0.25	0.79	0.68

The results of our calculations for the $E1$ transition amplitudes are given in Table I. For the transition $6p_{1/2}-7p_{1/2}$ this quantity was calculated earlier by the Bouchiats in[10]. Their result ($D_z = i\,|e|\,a_0 \times 0.78 \times 10^{-10}$) differs from ours, since they did not take into account the contribution made to the effect by the excitations of the type $6s6p7p$. The degree of circular polarization obtained by us for this transition

$$P = -2\,\mathrm{Im}\frac{\langle 7p_{1/2}|D_z|6p_{1/2}\rangle}{\langle 7p_{1/2}|M_z|6p_{1/2}\rangle} = -2.5\cdot 10^{-3}, \quad (2)$$

agrees with Neufer's estimate cited in[6]. Since the magnetic moments of the transition $6p_{1/2}\to mp_1$ probably decrease with increasing m, in the two remaining transitions (see Table I) we can expect a circular polarization of the same order or even somewhat larger.

We proceed now to lead. We consider here the transitions $6p^2(^3P_0')\to 6p7p(^3P_1', {}^3D_1')$, for which we can also measure the constant q. An analysis of the spectrum of lead shows that both upper levels are almost pure jj states: $6p_{1/2}7p_{1/2}$ and $6p_{1/2}7p_{3/2}$ respectively.[1)] The radial integrals used in the calculations are given in Table II. Our results for the amplitudes of the $E1$ transitions are contained in Table I. In both transitions we can expect a circular polarization $\sim 3\times 10^{-3}$.

Since the contributions of the different states to the effect are canceled out to a considerable degree, the error of our calculations can be quite large. In contrast to the authors of[4] we believe that the inaccuracies in the atomic calculations will hardly make it possible to establish the isotopic structure of the neutral currents by comparing the effects of parity nonconservation in thallium and cesium. More promising from this point of view is an investigation of the optical activity of vapors of different isotopes of thallium and lead.[7]

We consider now $M1$ transitions in an odd lead isotope, resulting from hyperfine mixing of electronic states with angular momenta 0 and 1. The Bouchiats[4] have noted that detection of circular polarization in the transition $6p^2\,{}^3P_0'\to 6p^2\,{}^1S_0'$ would make it possible to observe a different type of weak interaction, namely between nucleon axial and electronic vector currents (i.e., to determine the constant q_I in formula (1)).

We have previously[11] calculated the magnetic moment of this transition: $\langle {}^1S_0'|M_z|{}^3P_0'\rangle = 0.81\times 10^{-6}|\mu_B|$. (The Bouchiats[4] give values $(0.27-0.69)\times 10^{-6}$ for the numerical coefficient.) The dipole moment obtained by us for the $E1$ transition is given in Table I. We note that the calculation in this case is somewhat more reliable than the calculations given above, since the main contribution to the effect is made by admixture of one configuration ($6p7s\,{}^3P_1'$). The result for the degree of circular polarization in this transition $P=-0.65\times 10^{-4}$, is smaller by almost one order of magnitude than the result of[4].

We have considered also the analogous transition $6p^2\,{}^3P_0' - 6p7p\,{}^3P_0'(6p_{1/2}7p_{1/2})$. We can expect in it a larger circular polarization, owing to the smaller value of $\langle M_z\rangle$. An important advantage in this case is apparently the presence of an allowed transition from the excited state, which facilitates observation of the process.

We note in conclusion that effects similar to those considered above can be observed also in analogous transitions in indium and in tin.

Note added in proof (from Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 5). The result of M.A. and C.C. Bouchiat[1] for the $\langle 7p_{1/2}|D_z|6p_{1/2}\rangle$, amplitude, is cited in this paper with an incorrect sign (p. 000, line 00). The authors thank M.A. Bouchiat for pointing out the error, which found its way also in the preprint of their original article. Taking the correction into account, our result for the $6p_{1/2} \to 7p_{1/2}$ transition in thallium differs from the result of[10] by only 20%.

1)We define these functions in such a way that in the second-quantization formalism they are equal to $b^{+}_{6,1/2}b^{+}_{7,1/2}|0\rangle$ and $[(\sqrt{3}/2)b)^{+}_{6,-1/2}c^{+}_{7,1/2} - \frac{1}{2}b^{+}_{6,1/2}c^{+}_{7,1/2}]|0\rangle$, respectively (see[7]).

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