Effects of parity nonconservation in heavy ions

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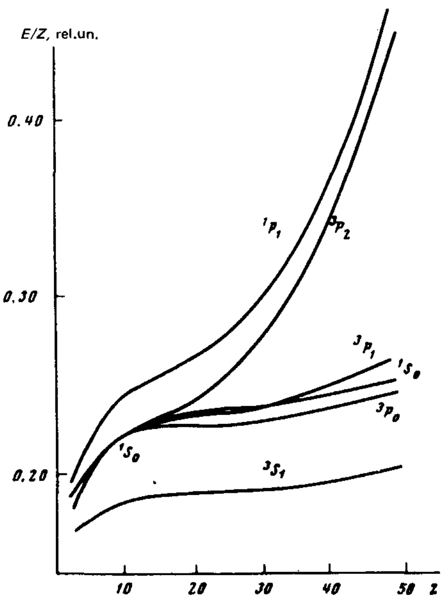
It is shown that for single-quantum transitions in the heavy ions C V and Cu XXVIII the degree of photon circular polarization produced in the presence of weak interactions reaches 10^{-3} in Weinberg's model.

Parity violation in atomic processes can result from weak interactions. If there were no neutral weak currents, as had been assumed until recently, parity violation in atoms would occur only in terms of order $Gm^2\alpha$, where G and α are the weak and electro-dynamic interaction constants, and m is the electron mass. [1–3] In recent neutrino experiments, [4] neutral currents were observed, with a constant on the order of the usual weak constant G. This leads to the possibility of observing parity violation in terms of order Gm^2. In[1,3], they investigated Parity-nonconservation effects that became manifest in the appearance of circular polarization of the photons in the hydrogen-atom emission. Optical transitions in heavy neutral atoms (Cs), connected with parity nonconservation, were considered in[5]. In the present article we calculate the degree of photon circular polarization in the spectra of heavy ions with two electrons, and discuss the experimental possibilities of its measurement. Beams of heavy two-electron ions are presently obtainable and their intensities are apparently sufficient for the observation of the proposed effect. [6]



The level scheme of ions with two electrons was calculated in[7] at all values of the charge Z for the configuration $1s2s+1s2p$, and is shown in the figure. We consider a single-photon transition from the state 2^1S_0 to the ground state 1^1S_0 in ions with nuclei having a magnetic moment. As the result of the hyperfine interaction, the state 2^3S_1 is mixed in with the state 2^1S_0. The weak interaction of the electrons with the nucleus causes the state 2^3P_1 with different parity to become mixed in with the 2^1S_0 state. The admixture of other levels makes a negligibly small contribution. The states 2^3S_1 and 2^3P_1 go over to the ground state with emission of $M1$ and $E1$ photons, the interference of the amplitudes of which leads to the circular polarization. As a result, the amplitude of the single-photon transition from the state 2^1S_0 takes the form (we use relativistic units with $\hbar=c=1$):

$$A = A_s H + A_p i W \,, \tag{1}$$

$$\begin{aligned} A_s &= \langle FM_F\, 2\,^3S_1 |\hat{A}| FM_F'\, 1\,^1S_0 \rangle; \quad w_s = \frac{4}{3}\omega_s |A_s|^2, \\ A_p &= \langle FM_F\, 2\,^3P_1 |\hat{A}| FM_F'\, 1\,^1S_0 \rangle; \quad w_p = \frac{4}{3}\omega_p |A_p|^2, \end{aligned} \tag{2}$$

$$H = \langle FM_F\, 2\,^3S_1 \,|\, V_H \,|\, FM_F\, 2\,^1S_0 \rangle\, \Delta E_H^{-1},$$

$$W = \langle FM_F\, 2^3P_1 \,|\, V_w \,|\, FM_F\, 2^1S_0 \rangle\, \Delta E_W^{-1}, \quad (3)$$

where V_H and V_W are the effective operators of the hyperfine and weak interactions, F, M_F, and M'_F are the total angular momentum of the atom and its initial and final projections, $w_{s,p}$ are the probabilities of the magnetic and electric transitions, $\omega_s \approx \omega_p \equiv \omega$ are the frequencies of these transitions, $\Delta E_H = E(2^1S_0) - E(2^3S_1)$; $\Delta E_W = E(2^1S_0) - E(2^3P_1)$. The operator V_W is of the form

$$V_W = \frac{G}{\sqrt{2}}(a_{ZN}\gamma_5^{(e)} + b_{ZN}\,\vec{\alpha}^{(e)}\vec{\sigma}^{(n)}), \quad (4)$$

where γ_5, $\boldsymbol{\alpha}$, and $\boldsymbol{\sigma}$ are the Dirac and Pauli matrices, the symbols e and n pertain to the electron and the nucleus, and a_{ZN} and b_{ZN} are coefficients that determine the dependence of the electron-nuclear neutral current on the number of protons Z and neutrons N in the nucleus. In our case, only the second term in (4), which contains the dependence on the nuclear spin, is effective. According to the Weinberg model[8]

$$b_{ZN}^W = \frac{1}{2}(4\sin^2\Theta_W - 1)(N - Z)/f_A \approx 0{,}24\,(N - Z).$$

In other models we have $b_{ZN}^W \leqslant b_{ZN} \leqslant A$, where A is the mass number. The probability of the single-quantum transition is

$$w_{1\gamma} = w_s H^2 + w_p |W|^2 + 2\,\mathrm{Re}\sqrt{w_s w_p}\, H W^* (i\,\mathbf{n}[\mathbf{e}\times\mathbf{e}^*]), \quad (5)$$

where $\mathbf{n}$ and $\mathbf{e}$ are the radiation interaction and the polarization of the photon. Inasmuch as in our case $w_s H^2 \gg w_p |W|^2$, it follows that the degree of polarization is determined by the relation

$$\mathcal{P} = \frac{2\,\mathrm{Re}W}{H}\sqrt{\frac{w_p}{w_s}}.$$

For the different quantities that enter in $\mathcal{P}$, we obtain the following values:

$$H = -\frac{9}{8}\sqrt{\frac{20}{3}}(\alpha Z)^4 m^2 g / AM_p\,\Delta E_H, \quad (6)$$

$$W = \frac{3}{64\pi}\sqrt{\frac{5}{2}}\, Gm^3 b_{ZN}(\alpha Z)^4 (R/a_0)^{-(\alpha Z)^2} / \Delta E_W + \frac{i}{2}\Gamma_W, \quad (7)$$

where g is the gyromagnetic factor, M_p is the proton mass, R is the radius of the nucleus, and a_0 is the Bohr radius. In the expression for W we have introduced the width Γ_W, since ΔE_W can be quite small. We now obtain for $\mathcal{P}$:

$$\mathcal{P} = \frac{27\sqrt{3}}{512\pi\sqrt{2}}\, Gm^2 b_{ZN} AM_p (R/a_0)^{-(\alpha Z)^2}\,\mathrm{Re}\frac{\Delta E_H}{\Delta E_W + \frac{i}{2}\Gamma_W}\sqrt{\frac{w_p}{w_s}}. \quad (8)$$

Since $\sqrt{w_p/w_s} \sim 1/\alpha Z$, it follows from (8) that the $\mathcal{P}(Z)$ dependence is determined mainly by the ratio $\Delta E_H / \Delta E_W + i\Gamma_W/2$. Thus, the most convenient are the values of Z at which the levels 2^3P_1 and 2^1S_0 cross. As seen from the figure, this occurs at $Z = 6$ (C V) and $Z = 29$ (Cu XXVIII). The values of the energy differences for the crossing points are $\Delta E_H(\mathrm{C}) \approx \Delta E_H(\mathrm{Cu}) = 0.050\ m\alpha^2 Z$; $\Delta E_W(\mathrm{C}) = 6.0\times10^{-4}\ m\alpha^2$; $\Gamma_W(\mathrm{C}) \ll \Delta E_W(\mathrm{C})$; $\Delta E_W(\mathrm{Cu}) = 2.0\times10^{-3}\ m\alpha^2$; $\Gamma_W(\mathrm{Cu}) = 1.0\times10^{-3}\ m\alpha^2$. We have taken the values $w_s(\mathrm{Cu}) = 1.0\times10^{-12}\ m$ and $w_p(\mathrm{Cu}) = 1.0\times10^{-7}\ m$ from[9]. As the result we obtain for the degree of polarization in the Weinberg model $\mathcal{P}^W(\mathrm{C}) = 1.6\times10^{-3}$ (for the isotope with $A = 13$) and $\mathcal{P}^W(\mathrm{Cu}) = 2.4\times10^{-3}$ (for the isotope with $A = 65$). For the other models we have $\mathcal{P} = \mathcal{P}^W(b_{NZ}/b_{NZ}^W) \geqslant \mathcal{P}^W$. We indicate also the transition frequencies: $\omega(\mathrm{C}) = 300$ eV and $\omega(\mathrm{Cu}) = 8.34$ keV.

The principal mode of the decy of the 2^1S_0 level is the two-qunatum decay. Its probability is $w_{2\gamma}(\mathrm{Cu}) = 4.7\times10^{-2}\ m$.[6] The ratio of the last term in (6), responsible for the parity nonconservation, to $w_{2\gamma}$ is $\sim10^{-5}$ for Cu and $\sim10^{-9}$ for C. The absolute value of the last term in (5) is (for $Z = 29$) $0.3\times10^{-16} m = 0.3\times10^5\ \mathrm{sec}^{-1}$, which is larger by 14 orders of magnitude than the corresponding quantity in the hydrogen atom.[3] This eliminates the danger of the extraneous background fields[10] influencing the effect. For $Z = 6$, the margin in comparison with hydrogen amounts to four orders of magnitude.

We can use also other transitions and other ions. Favorable for the measurements are the single-quantum $M1$ transition from the state 2^3S_1 to the ground, which interferes with the $E1$ transition from the admixture of the 2^1P_1 state. The degree of polarization in this transition turns out to be of the order 10^{-5} at $Z = 26$ (Fe XXV), but the two-quantum transition in this case is suppressed because it is spin-forbidden, and the $M1$ mode is the fundamental one. There is also a possibility of separately measuring the electron-electron neutral currents. For example, one can mix in with the s states such states of other parity, whose wave functions behave as $\gamma \to 0$ in such a way that the matrix elements of the electron-nuclear weak currents vanish (d and f states). In this case there is no parity violation as the result of interaction with the nucleus. If there are no neutral terms, then, as noted above, we obtain for the degree of polarization a value which is smaller by one or two orders of magnitude than the one given above (in this case $b_{NZ} \sim \alpha Z$). At the present state of the experimental art, the measurement of such quantities is apparently also possible.

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[1]Ya. B. Zel'dovich, Zh. Eksp. Teor. Fiz. **36**, 964 (1959) [Sov. Phys.-JETP **9**, 682 (1959)].
[2]F. Curtis-Michel, Phys. Rev. **138B**, 408 (1965).
[3]A. N. Moskalev, ZhETF Pis. Red. **19**, 229 (1974) [JETP Lett. **19**, 141 (1974)].
[4]E. J. Hasert *et al.*, Phys. Lett. **46B**, 138 (1972).
[5]M. A. Bouchiat and C. C. Bouchiat, Phys. Lett. **48B**, 111 (1974).
[6]R. Marrus, Nucl. Inst. **110**, 333 (1973).
[7]G. L. Klimchitskaya and L. N. Labzovaskiĭ, Opt. Spektr. **34**, 633 (1973).
[8]S. Weinberg, Phys. Rev. **D5**, 1412 (1972).
[9]G. L. Klimchitskaya, U. I. Saffonova, and L. N. Labzovskii, Opt. Spektr. (in press).
[10]Ya. I. Azimov, A. A. Ansel'm, A. N. Moskalev, and R. M. Ryndin, ZhETF Pis. Red. (in press).