WEAK NEUTRAL CURRENTS IN ATOMS AND μ-MESIC ATOMS

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It is shown that weak neutral $\bar{e}e$ currents lead to circular polarization of the photons in the single-quantum transition $2S_{1/2} \to 1S_{1/2}$ in the hydrogen atom, with a value $-0.25\times10^{-3}\ G_0/G$, where G_0/G is the ratio of the interaction constants of the neutral and charged currents. The polarization of the gamma quanta in the analogous transition in the mu-mesic hydrogen atom is $5\times10^{-2}\ G_0/G$.

Recent reports of observation of neutral weak $\bar{\nu}\nu$ currents in neutrino experiments have aroused great interest in the problem of neutral currents as a whole. We show in the present paper that weak neutral $\bar{e}e$ and $\bar{\mu}\mu$ currents lead to relatively large parity-nonconservation effects in certain atomic and mesic-atom transitions. An experimental study of these transitions makes it possible to determine the interaction constant of these currents with the nucleons or, in the absence of such currents, to establish the upper limit of their existence.

To estimate the magnitudes of the effects produced by neutral currents, we consider contact ep interaction of the V - A type with a coupling constant $G_0 = \kappa G$, where G is the Fermi constant, and the numerical factor κ characterizes the strength of the interaction of the neutral and charged currents. The amplitude of such an interaction is given by

$$A = \frac{\kappa G}{\sqrt{2}}[\bar{u}_p\gamma_\mu(1+\gamma_5)u_p][\bar{u}_e\gamma^\mu(1+\gamma_5)u_e]. \tag{1}$$

This amplitude corresponds to a P-odd ep-interaction potential

$$V(\mathbf{r}) = \frac{\kappa G}{2\sqrt{2}m}\sigma\{\hat{\mathbf{p}},\ \delta(\mathbf{r})\}_+\ , \tag{2}$$

where m is the electron mass, $\hat{\vec{p}} = -i\nabla$ is its momentum, and $\vec{s} = \vec{\sigma}/2$ is the electron spin. In the derivation of (3), the proton was assumed to be infinitely heavy, and averaging was carried out over its spin, so that the effects connected with the hyperfine structure of the levels are not considered. The presence of the potential (2) leads to a maixing of levels with opposite parity. This mixing is particularly appreciable when levels of opposite parity are close in energy. In the hydrogen atom, for example, such levels are $2S_{1/2}$ and $2P_{1/2}$, which are separated by the Lamb shift $E_{2S} - E_{2P} = 7.8\alpha^5 m/6\pi^2$. In the presence of the interaction (2), the wave functions of these states take the form $\Psi(2S_{1/2}) + iF\Psi(2P_{1/2})$ and $\Psi(2P_{1/2}) + iF\Psi(2S_{1/2})$, where the value of the admixture F is determined by the formula

$$iF = \frac{\langle 2P_{1/2}|V|2S_{1/2}\rangle}{E_{2S} - E_{2P}}\ . \tag{3}$$

Using (2), we obtain

$$\langle 2P_{1/2}|V|2S_{1/2}\rangle = -i\frac{\sqrt{3}}{32\pi\sqrt{2}}\kappa G\alpha^4 m^3, \tag{4}$$

and consequently

$$F = -0{,}029\kappa G m^2\alpha^{-1} = -1{,}2\cdot10^{-11}\kappa. \tag{5}$$

Level mixing leads in electromagnetic transitions to circular polarization of the emitted photons, owing to the interference of amplitudes of transitions with different parity. This polarization is large if the amplitudes of the main and admixture transitions are comparable in magnitude, i.e., when the main transition is suppressed for some reason. From this point or view, interest attaches to the M1 transition $2S_{1/2} \to 1S_{1/2}$ transition, the admixture transition for which is the E1 transition $2P_{1/2} \to 1S_{1/2}$ (Lyman series, $\lambda \simeq 1215.68$ Å). The single-photon M1 transition $2S_{1/2} \to 1S_{1/2}$ is forbidden in the nonrelativistic limit because of the orthogonality of the coordinate functions of the 2S and 1S state, and is allowed only on account of the relativistic corrections to the electron wave functions. The amplitude of this transition is therefore of order of smallness α^3 in comparison with the E1 transition, and not of order α as usual [2]. More accurately speaking, the amplitude of the transition from the state $\Psi(2S_{1/2}) + iF\Psi(2P_{1/2})$ to the state $\Psi(1S_{1/2})$ takes the form

$$A = A_S + iFA_P = i\frac{4}{9}\sqrt{\frac{2\pi a}{3}}a^3 a_0 \omega C^{1/2\mu}_{1/2\nu 1M}\{[\mathbf{e}^*_\times \mathbf{n}] + iFR\mathbf{e}^*\}_M , \qquad (6)$$

where $\omega \simeq E_{2S} - E_{1S} = (3/8)\alpha^2 m$ is the photon frequency, $\alpha_0 = (\alpha m)^{-1}$ is the Bohr radius, $\vec{e}$ is the photon polarization radius, μ, ν, and M are the projections of the angular momenta of the initial and final states and of the photon, respectively,

$$R = A_P/A_S = \sqrt{w_P/w_S} .$$

The total probability of the M1 transition $2S_{1/2} \to 1S_{1/2}$ is given by

$$w_S = \frac{2^5}{3^6}a_0^2 a^7 \omega^3 = \frac{1}{2^4 3^3}a^{11} m = 0{,}56 \cdot 10^{-5}\ \text{sec}^{-1}, \qquad (7)$$

and the probability of the E1 transition $2P_{1/2} \to 1S_{1/2}$ [2] is

$$w_P = \frac{2^{17}}{3^{11}} a_0^2 a \omega^3 = (2/3)^8 a^5 m = 0{,}63 \cdot 10^9\ \text{sec}^{-1},$$

therefore

$$R = \frac{2^6}{9\sqrt{3a^3}} = 1{,}06 \cdot 10^7 .$$

The circular polarization of the photons in this transition is

$$P \equiv \frac{w_R - w_L}{w_R + w_L} = \frac{2A_S \cdot F A_P}{A_S^2 + F^2 A_P^2} \approx 2FR = -0{,}25 \cdot 10^{-3}\kappa . \qquad (8)$$

Measurement of this relatively large polarization would make it possible to determine κ, i.e., the neutral current interaction constant. The main difficulty of this experiment lies in the fact that the $2S_{1/2}$ state goes over into $1S_{1/2}$ mainly not via a single-quantum transition, but via a two-quantum transition [2] with probability $w \sim 7$ sec^{-1}.

Analogous experiments with deuterium or tritium atoms are of great interest. The presence of a neutron in the nucleus has practically no effect on the frequencies and probabilities of the electromagnetic transitions, but alter significantly the value of F, which is determined by the sum of the ep- and en-interaction constants. A comparison of the polarization in hydrogen and in deuterium or tritium would make it possible to establish the isotopic structure of the neutral currents. It should be noted, however, that the usual weak interactions can bring about effects of the type considered above even in the absence of neutral currents. Indeed, they lead to an axial part of the hadron electromagnetic current, in the form

$$J^A_\mu \sim eG\bar{u}(q^2\gamma_\mu - 2Mq_\mu)\gamma_5 u . \qquad (9)$$

Interaction of this current with the electromagnetic current of the electron leads to an effective ep potential of the type (2), where $\kappa \sim \alpha$. Observation of neutral currents in these experiments is therefore possible if $\kappa \gtrsim \alpha$.

What is quite promising is the performance of similar experiments with μ-mesic atoms, where parity nonconservation effects turn out to be much larger than in ordinary atoms. If we disregard, as before, the nucleon recoil (neglecting corrections of order m_μ/m_p) and the finite nucleon dimensions, then the formulas presented above hold true for μ-mesic hydrogen, provided we replace in them the electron mass by the muon mass m_μ. An exception is the energy difference between the $2S_{1/2}$ and $2P_{1/2}$ states, since the hydrogen μ-mesic atom the main contribution is made to this difference by the vacuum polarization. If we use the theoretical value $E_{2S} - E_{2P} = -0.2$ eV, then we obtain for the admixture the value

$$F_\mu \sim 2{,}3 \cdot 10^{-9} \kappa_\mu . \qquad (10)$$

The ratio of the probabilities of the different electromagnetic transitions and the associated enhancement of the effects does not depend on the lepton mass and remains the same in the hydrogen μ-mesic atom as in the ordinary atom. Therefore the circular polarization of the γ quanta in the $2S_{1/2} \to 1S_{1/2}$ transition ($E_\gamma \sim 2.11$ keV) turns out to be

$$P \sim 2RF_\mu \sim 4{,}9 \cdot 10^{-2} \kappa_\mu . \qquad (11)$$

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Note. After completing this paper, the author learned that similar questions were considered in a paper by Ya. B. Zel'dovich (Zh. Eksp. Teor. Fiz. 36, 964, 1959 [Sov. Phys.-JETP 9, 681, 1959). In addition, research by C. Bouchiat on the same topic is mentioned in a review by C. H. Llewellyn-Smith (CERN Preprint TH 1710). The author thanks L. B. Okun' for supplying this information.

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