Parity nonconservation effects due to neutral weak currents in mesic atoms

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P-odd correlation produced in the single-quantum transition $2S_{1/2} \to 1S_{1/2}$ for mesic atoms as a result of parity-violating interaction of neutral weak muon and nucleon currents, are considered. These correlations include the circular polarization of the γ quanta and the asymmetry of emission of the γ quanta relative to the residual polarization of the muons. It is shown that mesic atoms with $1 < Z \lesssim 10$ are more convenient for the experimental observation of these correlations.

In a preceding paper, [1] the author noted the relatively large value of the circular polarization of the γ quanta in the $2S_{1/2} \to 1S_{1/2}$ transition in the hydrogen μ-mesic atom. This polarization was due to the parity-violating interaction of the neutral weak $\bar{\mu}\mu$ current with the proton. The present paper discusses parity-nonconservation effects in the analogous transition but for mesic atoms with nuclear charge $Z < 10$. As will be shown below, some of these mesic atoms are more convenient objects for the experimental investigation of parity-nonconservation effects than are hydrogen μ-mesic atoms.

The parity-violating interaction of a muon with protons and neutrons in a nucleus can be described with the aid of the effective potential[1]

$$V_{p,n}(\mathbf{r}) = \kappa_{p,n} \frac{G}{2\sqrt{2}m} \vec{\sigma} \{ \hat{\mathbf{p}}, \delta(\mathbf{r}) \}_+ , \qquad (1)$$

Characteristics of $2S_{1/2} \to 1S_{1/2}$ transition in μ-mesic atoms

Atom	$E_{2S} - E_{2P}$ eV	E_γ, keV	$\eta \cdot 10^2$	$W(2S \to 1S)$ sec^{-1}	$W_{2\gamma}(2S \to 1S)$ sec^{-1}
H^1_1	-0.201	1.90	$-3.53\,\kappa_p$	$1.044 \cdot 10^{-3}$	$1.5 \cdot 10^3$
He^4_2	-1.37 ± 0.01	8.21	$-(2.63 \pm 0.02)(\kappa_p + \kappa_n)$	1.156	10^5
Li^6_3	-0.9 ± 0.3	18.60	$(7 \div 14)(\kappa_p + \kappa_n)$	67.29	$1.2 \cdot 10^6$
Be^9_4	1.5 ± 0.9	33.30	$(6 \div 25)\left(\kappa_p + \frac{5}{4}\kappa_n\right)$	$1.202 \cdot 10^3$	$6.7 \cdot 10^6$
C^{12}_6	30 ± 2	75.20	$(1.14 \pm 0.07)(\kappa_p + \kappa_n)$	$6.955 \cdot 10^4$	$7.6 \cdot 10^7$
O^{16}_8	162 ± 7	134.00	$(0.38 \pm 0.02)(\kappa_p + \kappa_n)$	$1.238 \cdot 10^6$	$4.3 \cdot 10^8$

where σ are the Pauli matrices for the muon, $\mathbf{p} = -i\nabla$ is the momentum, and m is the reduced muon mass, G is the Fermi constant, and the factors κ_p and κ_n take into account the relative interaction force of the neutral and charged currents.

The presence of the interaction (1) causes to an admixture of $2P_{1/2}$ state to appear in the $2S_{1/2}$ state of the mesic atom [there is no $2P_{3/2}$ admixture, since the interaction (1) conserves the total muon angular momentum]. This leads in turn to the appearance of P-odd correlations in the single-quantum transition $2S_{1/2} \to 1S_{1/2}$. The magnitudes of these correlations (cf. infra) is determined by the coefficient $\eta = 2FR$, where iF is the size of the admixture of the $2P_{1/2}$ state and R is the amplification coefficient connected with the suppression of the single-quantum transition $2S \to 1S$:

$$iF = \frac{\langle 2P | V | 2S \rangle}{E_{2S} - E_{2P}}, \quad R = \left[\frac{W(2P \to 1S)}{W(2S \to 1S)}\right]^{1/2}. \tag{2}$$

Let us estimate the values of these coefficients for various mesic atoms.

The probability of the single-photon transition $2S \to 1S$ of interest to us depends very strongly on Z, and is proportional to Z^{10} in the lowest order in $(Z\alpha)$:

$$W(2S \to 1S) \equiv W_S = \frac{1}{2^4 3^3} a (Za)^{10} m. \tag{3}$$

This creates favorable conditions for the experimental study of this transition in mesic atoms with $Z > 1$. The $2S \to 1S$ transition probabilities calculated from formula (3) are listed in the table. It is seen from it that whereas in hydrogen W_S is a negligible fraction of the muon decay probability $W_{dec} = 4.5 \times 10^5$ sec^{-1}, in oxygen W_S already exceeds the decay probability. Of course, the increase of W_S leads to a decrease of the amplification coefficient R, so that

$$W(2P \to 1S) = \left(\frac{2}{3}\right)^8 a (Za)^4 m, \tag{4}$$

and consequently,

$$R = 2^6 3^{-5/2} (Za)^{-3} \approx Z^{-3} \cdot 10^7. \tag{5}$$

This effect, however, is cancelled to a considerable degree by the increase of the admixture F. Indeed, the matrix element of the potential (1) for a pointlike nucleus is given by

$$\langle 2P | V | 2S \rangle = -i \frac{G}{32\pi} \sqrt{\frac{3}{2}} m^3 (Za)^4 \{ Z\kappa_p + (A - Z)\kappa_n \}. \tag{6}$$

As to the difference between the energies of the $2S$ and $2P$ levels, on which F also depends, its Z-dependence has a complicated form. For the mesic atoms considered here, the main contribution to $E_{2S} - E_{2P}$ is made by the polarization of the vacuum and by the finite dimensions of the nucleus. These factors act in opposite directions and cancel each other to a considerable degree. Whereas in μ-hydrogen the contribution of the vacuum polarization predominates ($E_{2S} < E_{2P}$), for atoms with $Z \geq 4$ the effect of the finite nuclear dimensions prevails ($E_{2S} > E_{2P}$). For mesic atoms such as Li_3 and Be_4, the energy difference between E_{2S} and E_{2P} is relatively small and the parity-nonconservation effects are particularly large. The table lists estimates of the energy difference $E_{2S} - E_{2P}$ for different mesic atoms, and the corresponding values of the parameter η. The data on the energy difference in hydrogen and helium were taken from[2,3]. For the remaining mesic atoms, the vacuum polarization was taken into account in the lowest order in α, and the level shift due to the finite dimensions of the nucleus was estimated from the formula

$$\delta E_{2S} / |E_{2S}| = \frac{2}{3} Z^2 \frac{\langle r^2 \rangle}{a^2}, \quad \delta E_{2P} \approx 0, \tag{7}$$

where $a = (\alpha m)^{-1}$ and $\langle r^2 \rangle^{1/2}$ is the rms radius of the charge distribution in the nucleus. The experimental values of[4] were used here for $\langle r^2 \rangle$.

We consider now P-odd correlation in the $2S \to 1S$ single-quantum transition. The probability of emitting a γ quantum in the direction $\mathbf{n}$ is given by the formula

$$dW(\mathbf{n}) = W_S \{ 1 + (\vec{\xi}\mathbf{n})(\mathbf{s}\mathbf{n}) - \eta(\mathbf{s}\mathbf{n}) - \eta(\vec{\xi}\mathbf{n}) \} \frac{d\Omega}{8\pi}, \tag{8}$$

where $\mathbf{s} = -i[\mathbf{e}^* \times \mathbf{e}]$ is the photon spin vector, and $\boldsymbol{\xi}$ is the polarization vector of the muon in the $2S_{1/2}$ state. The need for taking into account terms with $\boldsymbol{\xi}$ is brought about by the fact that many mesic atoms retain an appreciable residual polarization of the muons produced in the pion decay (e.g., in carbon, according to[5], we have $|\xi| \sim 1/6$). Therefore, the P-odd correlations connected with this polarization [the second term of (8)] make it difficult to observe the γ-quantum circular polarization connected with the parity nonconservation [third term of (8)].[1)] Indeed, putting in (8) $\mathbf{s} \cdot \mathbf{n} = +1$ for right-polarized and $\mathbf{s} \cdot \mathbf{n} = -1$ for left-polarized quanta (the opposite definition, more customarily used in optics, was employed in[1]), we obtain for the quanta moving in the direction $\mathbf{n}$ the following degree of circular polarization:

$$P_\gamma(\mathbf{n}) = \frac{W_+ - W_-}{W_+ + W_-} = \frac{(\vec{\xi}\mathbf{n}) - \eta}{1 + \eta(\vec{\xi}\mathbf{n})}. \tag{9}$$

In experiments based on observation of the circular polarization in μ-mesic atomic transitions it is therefore necessary to take special measures to decrease the influence of the terms $\sim(\boldsymbol{\xi} \cdot \mathbf{n})$. It is more convenient, however, to use the muon polarization to observe the asymmetry of the emission of the γ quanta relative to the muon polarization vector. This correlation is described by formula (10), which is obtained by summing (8) over the γ-quantum polarizations

$$dW(\mathbf{n}) = W_S \{ 1 - \eta(\vec{\xi}\mathbf{n}) \} \frac{d\Omega}{4\pi}. \tag{10}$$

Measurement of this asymmetry makes it possible to determine η, and consequently also the interaction constants of the neutral currents.

We shall now dwell briefly on estimates of the probabilities of processes that compete with the single-quantum transition $2S \to 1S$. These include first of all the transition $2S \to 1S$ with emission of Auger electrons. According to estimates,[6] the probability of this transition can reach 10^9 sec^{-1}, but it depends strongly on the number of electrons emitted when the muon lands on the $2S$ level. An important role is played also by the $2S \to 1S$ two-quantum transition. The probability of this transition can be estimated by multiplying the probability of the corresponding transition in the hydrogen atom (equal to ~8 sec^{-1}) by $Z^6(m/m_e)$. The estimates obtained in this manner are listed in the table. It is seen from them that in atoms with large Z the probability of the single-quantum $2S \to 1S$ transition is more favorable. With increase of Z, however, the probability of the $2S \to 2P$ $E1$ transition increases sharply, and becomes the predominant process for atoms with $Z > 10$. This circumstance (together with the decrease of η) makes it difficult to measure P-odd correlations in mesic atoms with $Z > 10$. We note that other processes, e.g., μ capture from the $2S$ state, are not serious competitors for the considered mesic atoms.

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