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ON THE PROBABILITY OF DOUBLE BETA DECAY

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As is well known, the experimental searches for double β decay undertaken up to now have not met with success, although the accuracy of the experiments has increased so greatly that one of the latest papers[1] gives for the lower limit on the half-life $T_{1/2}$ a value of 0.7×10^{19} years. On the other hand theoretical calculations give for $T_{1/2}$ (in the Majorana scheme, $\nu \equiv \tilde{\nu}$) a quantity of the order of 10^{12} to 10^{19} years.[2-6] Therefore the negative results of searches for double decay can be interpreted as an indication that the neutrino is not a Majorana particle. At present, however, the accuracy of the experiments is still not great enough for the discovery of double β decay with Dirac neutrinos ($\nu \neq \tilde{\nu}$).

In view of the new situation in the theory of β decay it is useful to make a theoretical reexamination of the problem of the probability of double β decay, with due regard to effects of parity nonconservation and nonconservation of the leptonic charge (the latter possibility is evidently not very probable, but cannot as yet be finally rejected). The Hamiltonian of the β interaction with nonconservation of parity and leptonic charge has been discussed by Pauli.[7] Enz,[8] starting from Pauli's results, obtained the expression in general form for the probability of double β decay. We note the fact that the probability of double β decay is proportional to a combination of the squares of the quantities

$$I_{ij} = C_i C_j - C_i' C_j', \quad J_{ij} = C_i C_j' - C_j C_i'. \tag{1}$$

where C and C′ are the coupling constants for the terms conserving parity and not conserving it, and the indices i, j take the values S, V, T, A, P.

It can be seen from Eq. (1) that (for i = j) even in the case of the Majorana neutrino the probability of double β decay can be much smaller than the value previously given if $|C| \approx |C'|$, or can even be exactly zero if $|C| = |C'|$. One can get an idea of the ratio of the constants C and C′ from the data of experiments to measure the longitudinal polarization of β-ray electrons or the circular polarization of γ-ray quanta. At present the precision of these experiments is such that the equality $|C| = |C'|$ is established with an accuracy of 10 to 20 percent. In this scheme the theoretical value of the half-value period of double β decay can be written as follows (i = j = V; the order of magnitude of $T_{1/2}$ is practically independent of the choice of type of interaction):

$$T_{1/2} \leqslant 1 \cdot 10^{19} \frac{(ft)^2}{|I|^2 K(\varepsilon)} \frac{A^{2/3}}{Z^2} \text{ sec}, \tag{2}$$

where ft is the well known quantity characteristic of β decay, Z and A are the atomic number and mass number, and $K(\epsilon)$ is a function depending on the energy ϵ of the transition (its values* for several nuclei are given in the table).† Setting $|C| = 0.8|C'|$, we get for Ca^{48} the result $T_{1/2} \leq 2 \cdot 10^{19}$ years.

As can be seen from Eq. (1), in the case of equality of the constants, $|C| = |C'|$, double β decay can occur only for the following choice of the signs of the constants: $C_i = -C_i'$, $C_j = C_j'$, or $C_i = C_i'$, $C_j = -C_j'$. But the very latest data on the polarization of β-ray electrons evidently agree with $C_S/C_S' = C_T/C_T' = 1$ and $C_V/C_V' = C_A/C_A' = -1$.[9] Using also the fact that the Fierz interference terms vanish, we get only the following two possible combinations of interaction types with which double β decay can occur: i = S, j = A, and i = V, j = T. It is well known, however, that double β decay occurs mainly between nuclei in 0^+ states. The probability of double β decay will be proportional to the product of the squares of the Fermi (M_F) and Gamow-Teller (M_{GT}) matrix elements. For allowed transitions M_F gives the selection rules $\Delta J = 0$ (no), whereas the allowed M_{GT} give the rules $\Delta J = 0, \pm 1$ (no), with $0 \rightarrow 0$ forbidden. Therefore double β decay can occur only through the level 1^- (or through levels with higher angular momentum), but then both the first transition ($Z \rightarrow Z+1$) and the second transition ($Z+1 \rightarrow Z+2$) will be singly forbidden. The

Element	$K(\varepsilon)$	$F(\varepsilon)$
Ca^{48}	$2.1 \cdot 10^3$	$2.0 \cdot 10^3$
Zr^{96}	$4.8 \cdot 10^2$	$4.4 \cdot 10^2$
Te^{130}	$2.7 \cdot 10^2$	$2.4 \cdot 10^2$
Cd^{116}	$3.2 \cdot 10$	$2.8 \cdot 10$
Sn^{124}	3.5	2.8

latest data on the β decay of neutrons[9] evidently show that in β decay the V and A interaction types are realized; the precision of the experiment does not, however, exclude the possibility that there may also be present small amounts of the S and T types. Therefore it is of interest to calculate the probability of double β decay also in this scheme (transitions $0^+ \rightarrow 1^- \rightarrow 0^+$). We have obtained the following expression for the half-value period

$$T_{1/2} \leqslant 2 \cdot 10^{15} (ft)^2 Z^2 / (|I|^2 + |J|^2) F(\varepsilon) \text{ sec}, \tag{3}$$

where $F(\epsilon)$ is a function that depends on the energy ϵ of the transition (see table). A large uncertainty in the value of $T_{1/2}$ is introduced by the quantity ft, which for the transitions in question can neither be calculated theoretically nor satisfactorily estimated from the experimental data. Making the usual assumption that $ft = 10^7$ for first-forbidden transitions,[10] and supposing that $|C_S/C_A| = 0.1$ (or $|C_T/C_V| = 0.1$), we get for Ca^{48} the value $T_{1/2} = 2 \times 10^{22}$ years.

The results of our calculations show that at the present time the question of the existence of neutrinoless double β decay cannot be regarded as finally settled by the work of Dobrokhov and others[1] and the search for this effect for the purpose of establishing higher values of the lower limit on $T_{1/2}$ is of real interest for the theory.

In conclusion the writer expresses his deep gratitude to I. S. Shapiro for the suggestion of this topic and help in studying it.

*The function $f(\varepsilon)$ used in references 2, 5, and 6 differs from our $K(\varepsilon)$ by the fact that in obtaining it account was taken of the energy dependence of the Coulomb correction factors. In references 5 and 6 the Coulomb factors are regarded as independent of the energy, but the writers use $f(\varepsilon)$ instead of $K(\varepsilon)$.

†In Eqs. (2) and (3) the β-decay constant is included in ft, so that $0 < |C| \leq 1$.

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PAIR PRODUCTION BY A CIRCULARLY POLARIZED PHOTON

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THE theoretical prediction and experimental detection of longitudinally polarized electrons and positrons in the β decay of non-oriented nuclei has heightened interest in the problem of bremsstrahlung and electron-positron pair production, taking into account the polarization properties of the particles participating in these processes. Since the bremsstrahlung of a polarized electron has already been examined in references 1 to 4, we confine our investigation here to the pair production process. The bremsstrahlung and pair production process in the ultrarelativistic case was considered in reference 5.

In the present work, we investigate pair production by a circularly polarized photon in the field of a point nucleus. The treatment is general, and is suitable for all values of angles and energies.

In the Born approximation, the effective cross section for pair production is given by the formula

$$d\sigma_p(\theta_+, \theta_-)\, d\Omega_+ d\Omega_- = \frac{Z^2}{\pi^2}\left(\frac{e^2}{c\hbar}\right)^3 \frac{K_+ K_- k_+ k_- dK_+}{\varkappa \varkappa'^4} (S^+S)_p\, d\Omega_+ d\Omega_-, \tag{1}$$

where $(S^+S)_p$ is the square of the matrix element for pair production, $E_\pm = c\hbar K_\pm = c\hbar\sqrt{k_0^2 + k_\pm^2}$, $\hbar \mathbf{k}_\pm$ are the total energies and momenta of the positron and the electron, $\epsilon_{ph} = c\hbar\kappa = E_+ + E_-$, $\hbar\boldsymbol{\kappa}$ are the energy and momentum of the photon, $\hbar\boldsymbol{\kappa}' = \hbar\boldsymbol{\kappa} - \hbar\mathbf{k}_+$