Study of the neutrino mass in a double β decay

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Experiments on the search for the 2β decay, which can yield unique information on the presence of a Majorana mass in a neutrino and a possible nonconservation of lepton number are proposed. A search for $2\beta^+$ decays is especially promising in view of the possibility of a pure isolation of the coincidence signal of four annihilation γ-ray quanta.

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As a result of the recently reported[1] experimental evidence of the existence of a neutrino of nonzero mass, the question of its physical nature has become especially important. A neutrino mass may indicate the existence of new spiral states (a right-handed neutrino and a left-handed antineutrino), which would make the neutrino like all the rest of the fermions that have a Dirac mass. There is, however, another possibility—the neutrino mass is realized by transitions of a left-handed neutrino to a right-handed antineutrino—Majorana mass. In the experiments of Ref. 1 or the proposed experiments of Ref. 2 the effects of the neutrino mass do not depend on its nature. A unique method of proving the existence of Majorana mass in a neutrino involves a search for a double neutrinoless ($2\beta_{0\nu}$) β decay.

A double β decay can occur in heavy nuclei, which are stable with respect to a normal β decay, because of nucleon pairing; this makes a transition with a two-unit change in the charge of the nucleus energetically possible. Such transitions can be caused either by a simultaneous β decay of two neutrons (protons) in the nucleus with the emission of two (anti) neutrinos

$$(2\beta_{2\nu}) : (A, Z \mp 2) \to (A, Z) + 2e^{\mp} + 2\tilde{\nu}_e(\nu_e)$$

or with the process that violates the lepton-number conservation

$$(2\beta_{0\nu}) : (A ; Z \mp 2) \to (A, Z) \to 2e^{\mp}$$

which is caused by the chain of processes

$$\begin{array}{ccc} n \to p + e + \tilde{\nu}_e & \qquad & p \to n + e^+ + \nu_e \\ \nearrow & & \uparrow \\ \text{mass} & & \text{mass} \\ \swarrow & & \swarrow \\ n + \nu_e \to p + e & & p + \tilde{\nu}_e \to n + e^+ \end{array}$$

The amplitude of the second process is proportional to the Majorana mass of the neutrino. (See Refs. 3-10 for more details about the 2β decay.)

The analysis of indirect data[12] on the 2β decay of Te^{128} in Ref. 11 showed that this decay must occur preferentially by means of the $2\beta_{0\nu}$ channel, which corresponds to an appropriately averaged Majorana mass of 30-40 eV, bearing in mind a possible mixing of the neutrino states. Detection of the product of the 2β decay makes it possible to distinguish the $2\beta_{0\nu}$ process from the $2\beta_{2\nu}$ process only in terms of the overall rate of the process. The calculation involves an indeterminacy in the matrix elements of the nucleus. The evaluation of the data on the decay of Te^{128} with the formation of Xe^{128} in $2\beta_{0\nu}$ with a Majorana mass $m_\nu \sim 30$-40 eV has not yet yielded conclusive results. Therefore, a direct observation of the 2β decay has special importance. The probability of the $2\beta_{0\nu}$ decay is

$$\Gamma^{\mp}_{0\nu} = a^{\mp}_{0\nu} \mid g_V^2 M_F - g_A^2 M_{GT} \mid^2 F_0(T),$$

where

$$a^{\mp}_{0\nu} = \frac{1}{2} \left| \frac{\Sigma}{j} m_j U_{ej}^2 H(R, m_j) \right|^2 \frac{G_F^4 m_e^5}{(2\pi)^5} \left(\frac{2\pi aZ}{1 - \exp(\mp 2\pi a Z)} \right)$$

$$F_0(T) = \frac{1}{15} T(T^4 + 10T^3 + 40T^2 + 60T + 30),$$

m_j are the masses of the Majorana mass states of the ν_j neutrino, U_{ej} are the elements of the mixing matrix of the neutrino, which determine the contribution of the ν_j states to the ν_e state,

$$T = \frac{M_A - M_B - 2m_e}{m_e}$$

is the energy release in the $A \to B + 2e$ process, g_V and g_A are the vector and axial constants of the weakly charged nucleon current, m_F and m_{GT} are the matrix elements of the "Fermi" and "Gamow-Teller" nuclear $A \to B$ transitions,[1)] and

$$H(r, m_j) = \frac{1}{2\pi^2} \int d\mathbf{q} \frac{\exp(i\mathbf{qr})}{q_0 (q_0 + \mu_0)} \approx \begin{cases} \frac{1}{r} \frac{2}{\pi} [\,\mathrm{ci}(\rho)\sin\rho - \mathrm{si}(\rho)\cos] \approx \mu_0; & m_j << \mu_0 \\ \frac{1}{r} \exp(-m_j r) & m_j >> \mu_0 \end{cases}$$

$$\rho = \mu_0 r; \quad R = 1{,}2\ A^{1/3}\ \text{Fermi}, \quad q_0 = (|\mathbf{q}|^2 + m_j^2)^{1/2}.$$

The quantity $\mu_0 = \langle E_n \rangle - (m_0 - m_B)/2$ characterizes the average energy of the excited intermediate states n in the $A \to n \to B$ transitions.

The probability of a double neutrino $2\beta_{2\nu}$ decay is given in the same notations [ignoring the contribution of the $\Delta^- \to p + 2e + 2\tilde{\nu}$ mechanism, which amounts to about 20% for the largest energy release (2–4 MeV) and is highly suppressed[11] at a lower energy release] by the expression[11]

$$\Gamma_{2\nu}^{\mp} = a_{2\nu} | (g_V^2 m_F - g_A^2 m_{GT})(\mu_0)^2 F_2(T),$$

where

$$a_{2\nu} = \frac{1}{4} \frac{G_F^4 m_e^{11}}{2\pi^7} \left(\frac{2\pi a Z}{1 - \exp(\mp 2\pi a Z)} \right)^2,$$

$$F_2(T) = \frac{1}{7!\,495} T^7 (T^4 + 22T^3 + 990T + 1980),$$

and the total electron (positron) energy distribution (in m_e units) of the $2\beta^{\pm}_{e\nu}$ decay has the form

$$P(\epsilon) = \text{const}\ (T - \epsilon)^5 \epsilon (\epsilon^4 + 10\epsilon^3 + 40\epsilon^2 + 60\epsilon + 30).$$

For $|\Sigma_j m_j U_{ej}^2| = 30$ eV the theoretical estimates[8] of the probability of the Ca^{40}, Ge^{76}, Se^{82}, Te^{128}, and Te^{130} decays give a value of $\sim 10^{-23}$–10^{-24} yr^{-1}. The corresponding half-decay probabilities of $2\beta_{0\nu}$ are two to three orders of magnitude greater (except for Te^{128}, for which the probability is $\Gamma_{0\nu}^- \sim 2\Gamma_{2\nu}^-$ for the chosen Majorana mass). Similar predictions have also been obtained for the 2β decays of $U^{238} \to Pu^{238}$ and $Th^{232} \to U^{232}$. Therefore, determination of the products of double β decay in all cases (except possibly Te^{128}) gives no information on the type of decay or the Majorana mass of the neutrino. However, because of strong suppression of the $2\beta_{2\nu}$ decay in the region $\epsilon \sim T$, we hope that the $2\beta_{0\nu}$ events can be identified experimentally by directly recording the individual events and by measuring the energy of the decay electrons. In fact, at $\epsilon > 0.8T$ the $2\beta_{2\nu}$ decay is suppressed by a factor of 10^3 and the $2\beta_{0\nu}$ decay dominates, and at $\epsilon > 0.9T$ it is suppressed by a factor of 10^5, so that the signal of the $2\beta_{0\nu}$ decay exceeds the contribution of the $2\beta_{2\nu}$ decay by two to three orders of magnitude. The ratio of the probabilities of $2\beta_{2\nu}$ and $2\beta_{0\nu}$ decays does not depend on the nuclear matrix elements m_{GT} and m_F; therefore, an experimental measurement of this ratio allows an almost unambiguous (with an accuracy equal to an uncertainty of the magnitude μ_0) determination of $(\Sigma_j m_j U_{ej}^2)$.

The search for $2\beta^+$ decays is very attractive from the viewpoint of isolating the signal above the total background. The detection of four coincidence γ quanta from the annihilation of two positrons would serve as a characteristic indicator of the $2\beta^+$ decay.

The complete list of stable isotopes that have $2\beta^+$ decays includes $_{44}Ru^{96}$ (6% relative abundance; $T = 0.66$ MeV), $_{44}Cd^{106}$ (1.2%; 0.73 MeV), $_{56}Ba^{130}$ (0.1%; 0.54 MeV), $_{56}Ce^{138}$ (0.2%; 0.4 MeV), and $_{54}Xe^{124}$ (0.1%; 1 MeV). These are rare, proton-enriched isotopes that escape nucleosynthesis). A rough estimate of the probability for the $2\beta^+_{2\nu}$ decay with a maximum T–$Xe^{124} \to Te^{124} + 2e^+ + 2\nu$–gives $10^{-26}\,yr^{-1}$ [the relative suppression of $2\beta^+$ decays compared with $2\beta^-$ decays for comparable matrix elements and energy release is attributable to the Coulomb factor $\alpha[\exp(2\pi\alpha Z)]$. For $|\Sigma_j m_j U_{ej}^2| = 30$ eV we can expect the same half-life for its $2\beta^+_{0\nu}$ decay.

A 2β decay can also occur due to a direct lepton-number-nonconserving interaction.[13] A broadening of the search for the 2β decay (as well as for $2K$ captures or $e^- \to e^+$ processes in nuclei) would make it possible, in principle, to determine the mechanisms of the lepton-number-nonconserving processes.

The predicted probabilities of the $2\beta_{0\nu}$ decays are two to five orders of magnitude lower than the experimental thresholds that have been reached up to now. However, a relatively recent example[9,14,15] of a major advance in the search for the 2β decay of Te^{130}, along with planned and already performed experiments on the search for the proton decay with a probability of 10^{-30}–$10^{-32}\,yr^{-1}$ clearly demonstrate the capabilities of the current experiments. Further progress and broadening of the search for the 2β decay are extremely important.

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[1)]The initial and final states A and B have 0 spin; the intermediate state n has 0 spin for F and 1 for GT transitions.

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