Neutrinoless Double Beta Decay of $^{134}\text{Xe}$

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In view of recent great progress achieved in the experimental study of the neutrinoless double beta decay (0$\nu\beta\beta$-decay) of $^{134}\text{Xe}$ we discuss theoretical aspects of this process. The light and heavy Majorana neutrino exchange as well as the trilinear R-parity breaking contributions to 0$\nu\beta\beta$-decay are considered. We show that the sensitivity of the studied process to the signal of lepton number violation is only by factor 2-3 weaker in comparison with the 0$\nu\beta\beta$-decay of $^{136}\text{Xe}$. The current limits on effective neutrino mass (light and heavy) and trilinear R-parity violating parameter $\lambda_{111}$ deduced from lower limits on the 0$\nu\beta\beta$-decay half-lifes of various nuclei are reviewed and perspectives of the experimental verification of recently announced evidence of the 0$\nu\beta\beta$-decay of $^{76}\text{Ge}$ are discussed.

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The neutrinoless double beta decay (0$\nu\beta\beta$-decay) does exist if the neutrino is a Majorana particle with non-zero mass [4]. Many extensions of the Standard model (SM) breaks lepton number (LN), i.e., generate Majorana neutrino masses, and offer a plethora of 0$\nu\beta\beta$-decay mechanisms mediated by a variety of virtual particles, in particular by exchange of light and heavy neutrinos, supersymmetric (SUSY) particles, leptoquarks etc (for a review see Refs. [2–6]). In connection with the observation of oscillations of solar and atmospheric neutrinos most attention is concentrated to exchange of light and heavy neutrinos, supersymmetric (SUSY) particles, leptoquarks etc (for a review see Refs. [2–6]).

Here, $\lambda_{111}$ is to analyze the light and heavy Majorana exchange and the trilinear R-parity breaking ($\lambda_{111}$) mechanisms for this rare decay [8]. Between them one can find twin isotopes $^{128,130}\text{Te}$ and $^{134,136}\text{Xe}$, which merely differ by two neutrons and are of comparable abundance in the nature. The first pair of isotopes has been discussed often in the literature because of geochemical measurements and the Pontecorvo argument that the ratio of corresponding half-lifes is essentially independent of nuclear physics. A small difference of the corresponding 0$\nu\beta\beta$-decay nuclear matrix elements of the order of 10-20% has been found in nuclear structure studies [3,8]. If the situation would be similar also in the case of xenon isotopes, the importance of the experimental study of the 0$\nu\beta\beta$-decay for $^{134}\text{Xe}$ would be minor due to a significantly smaller Q-value in comparison with that for $^{136}\text{Xe}$, as it implies weaker bounds on the LN violating parameters. A detail theoretical study of this 0$\nu\beta\beta$-decay channel is missing. There is only one prediction for the light neutrino mass mechanism of this process [1].

Recently, a new limit on the half-life of the 0$\nu\beta\beta$-decay of $^{134}\text{Xe}$ to the ground state with $T_{1/2}^{0\nu-\exp} \geq 5.8 \times 10^{25}$ has been obtained at Gran Sasso by means of the 6.5 kg liquid xenon setup of the DAMA experiment [12,13], which is more stringent in comparison with the previous one by about three orders of magnitude [14]. The aim of this contribution is to analyze the light and heavy Majorana exchange and the trilinear R-parity breaking ($\lambda_{111}$) mechanisms for this rare process. A realistic calculation of nuclear matrix elements will be performed within the renormalized Quasiparticle Random Phase Approximation (RQRPA) [15]. A comparison with the 0$\nu\beta\beta$-decay of $^{136}\text{Xe}$ will be presented. The sensitivity of different 0$\nu\beta\beta$-decay experiments looking for signal of LN violation will be compared. In addition, a possible experimental verification of the evidence for the 0$\nu\beta\beta$-decay of $^{76}\text{Ge}$ will be discussed.

The half-life of the 0$\nu\beta\beta$-decay associated with light and heavy Majorana neutrino mass mechanism is given as

$$[T_{1/2}^{0\nu}]^{-1} = G_{01} \frac{\delta m_{\nu}}{m_e} M_{<m_{\nu}>}^{\text{light}} + \eta_N M_{\eta_N}^{\text{heavy}}. \tag{1}$$

The effective light and inverse heavy Majorana masses are

$$\delta m_{\nu} = \sum_k (U_{e k}^L)^2 \xi_k m_k,$$

$$\eta_N = \sum_k (U_{e k}^L)^2 \tilde{\xi}_k \frac{m_p}{M_k}. \tag{2}$$

Here, $m_p$ ($m_e$) is the proton (electron) mass, $U_{e k}^L$ mixing matrix elements and $\xi_k, \tilde{\xi}_k$ phases associated with the charge conjugation of the Majorana neutrino field. $G_{01}$ denotes the phase space factor given in [16,17]. The nuclear matrix elements $M_{<m_{\nu}>}$ and $M_{\eta_N}$ can be written as a sum of Fermi, Gamow-Teller and tensor contributions [4].
\[ M_T = \frac{M_F^2}{g_A^2} + M_{GT}^2 + M_R^2 \] (3)

with \( I = m_{ee} \), \( \eta_N \) and \( g_A = 1.25 \). It is worthwhile to notice that the above matrix elements include contribution from induced nucleon currents. Recently, it has been found that it is significant and leads to a modification of Gamow-Teller and to new tensor contributions [11].

The \( 0\nu\beta\beta \)-decay half-life associated with \( R_p \) SUSY mechanism mediated by exchange of gluinos [10,13] takes the form

\[ [T_{1/2} (0^+ \to 0^+)]^{-1} = G_{01} \left[ \frac{\pi \alpha_s}{6} \frac{\lambda_{111}^2}{G_F^2 m_s^{4/3}} \left( 1 + \left( \frac{m_{d_L}}{m_{u_L}} \right)^2 \right) \right]^2 |M_{\lambda_{111}}|^2. \] (4)

Here, \( G_F \) is the Fermi constant and \( \alpha_s = g_s^2/(4\pi) \) denotes SU(3)c gauge coupling constant. \( m_{u_L}, m_{d_L} \) and \( m_{\tilde{g}} \) are masses of the \( u \)-squark, \( d \)-squark and gluino, respectively. The nuclear matrix element \( M_{\lambda_{111}} \) can be written as sum of one- and two- pion exchange contributions:

\[ M_{\lambda_{111}} = c_A \left[ \frac{4}{3} \alpha^{1\pi} (M_{GT}^{1\pi} + M_T^{1\pi}) + \alpha^{2\pi} (M_{GT}^{2\pi} + M_T^{2\pi}) \right] \] (5)

with \( c_A = m_A^2/(m_p m_e) \) (\( m_A = 850 \text{ MeV} \)). The structure coefficients \( \alpha^{1\pi,2\pi} \) for the one-pion and two-pion exchange contributions are given in [12].

The nuclear matrix elements for light and heavy Majorana neutrino exchange and \( R_p \) gluino exchange in the \( 0\nu\beta\beta \)-decay of \( ^{134}Xe \) are given in Table II. They have been obtained within the proton-neutron RQRPA [15] for \( A = 134 \) and 136, respectively. The details of the nuclear structure approach and the evaluation of the matrix elements can be found in Refs. [10,14].

By glancing to Table II we see that values of matrix elements for \( A = 134 \) are considerably larger (by factor 2-3) in comparison with those for \( A = 136 \). Thus a pair of xenon isotopes offers a different scenario from the pair of tellurium nuclei. As it was discussed in previous publications [11,15] the reason of the suppression of the \( 0\nu\beta\beta \)-decay transition \( ^{136}Xe \to ^{136}Ba \) is that the parent nucleus is a closed shell nucleus for neutrons (N=82). The Pauli blocking effect is strongly suppressing some of the proton-particle neutron-hole Gamow-Teller configurations, in particular (0g7/2, 5h11/2, 0g7/2, 9/2) and (1d3/2, 5h1/2, 0g7/2, 9/2).

In order to compare the sensitivities to the signal of LN violation of the considered \( 0\nu\beta\beta \)-decays for xenon isotopes the corresponding kinematical factors \( G_{01} \) have to be known. Their values are determined by the mass difference between the mother and daughter nuclei. They are \( 3.479 \text{ MeV} \) and \( 1.841 \text{ MeV} \) for \( A = 136 \) and 134, respectively. One finds (assuming \( r_0 = 1.1 \text{ fm} \)): \( G_{01} = 5.91 \times 10^{-14} \) (\( A = 136 \)), \( 2.30 \times 10^{-15} \) (\( A = 134 \)). The sensitivity parameters with respect to different LN violating scenarios have been introduced in previous works [14,18,20] and are given by

\[ \zeta_{\langle m_e \rangle} (Y) = 10^7 |M_{\langle m_e \rangle}| \sqrt{G_{01} \text{ year}}, \]
\[ \zeta_{\eta_N} (Y) = 10^6 |M_{\eta_N}| \sqrt{G_{01} \text{ year}}, \]
\[ \zeta_{\lambda_{111}} (Y) = 10^5 |M_{\lambda_{111}}| \sqrt{G_{01} \text{ year}}. \] (6)

For nuclei of experimental interest their values are presented in Table I. We see that the sensitivity of \( 0\nu\beta\beta \)-decays of \( ^{134}Xe \) to the effective light Majorana mass \( < m_\nu > \) is only by factor 2 smaller in comparison with that for \( ^{136}Xe \). An interesting moment is that in the case of heavy Majorana neutrino and \( R_p \) SUSY modes the corresponding ratio of the sensitivity parameters is larger by about a factor 3. So, if in the xenon \( 0\nu\beta\beta \)-decay experiment half-lives for both isotopes will be measured, one can draw conclusions about the dominance of one of the mechanisms of this process. A necessary condition for it is that the nuclear matrix elements governing this process are calculated correctly.

Knowing the values of sensitivity parameters it is straightforward to deduce upper bounds on the effective LN violating parameters from the experimental lower limits on the \( 0\nu\beta\beta \)-decay half-life \( T^{\text{exp}}_{1/2} \) for a given nucleus:

\[ \frac{< m_\nu >}{m_e} \leq \frac{10^{-5}}{\zeta_{\langle m_e \rangle}} \sqrt{\frac{10^{24 \text{ years}}}{T^{\text{exp}}_{1/2}}}, \]
\[ \eta_N \leq \frac{10^{-6}}{\zeta_{\eta_N}} \sqrt{\frac{10^{24 \text{ years}}}{T^{\text{exp}}_{1/2}}}, \]
\[ (\lambda_{111}^R)^2 \leq \kappa^2 \left( \frac{m_{\tilde{g}}}{100 \text{ GeV}} \right)^4 \left( \frac{m_{\tilde{g}}}{100 \text{ GeV}} \right) 10^{-7} \frac{10^{24 \text{ years}}}{T^{\text{exp}}_{1/2}}. \] (7)
κ is equal to 1.8 (gluino phenomenological scenario [2]).

The current experimental upper bounds on the considered effective LN violating parameters for different nuclei are shown in Table I. We see that the Heidelberg-Moscow [24] and IGEX [25] experiments offer the most restrictive limit for \( m_\nu \), \( \eta_\nu \), and \( \lambda'_{11} \), namely 0.51 eV, \( 8.6 \times 10^{-8} \) and \( 1.2 \times 10^{-4} \) (assuming 100 GeV masses of SUSY particles), respectively. It is interesting to note that upper bounds on these parameters from the search for 0νββ-decay in \( ^{134}\text{Xe} \) are already stronger or comparable with those for \( ^{48}\text{Ca} \).

Recently, evidence for the 0νββ-decay of \( ^{76}\text{Ge} \) with half-life \( (0.8 - 18.3) \times 10^{25} \) years (with best value of \( 1.5 \times 10^{25} \) years) has been reported by the Heidelberg group [25]. This work has attracted a lot of attention of both experimentalists and theoreticians due to important consequences for the particle physics and astrophysics. The positive signal implies neutrino is a Majorana particle and allows to derive potentials of neutrino mass matrix from the observed data, if the light neutrino exchange is the dominant mechanism of this process. By considering matrix elements of Ref. [2], which include contributions from higher order terms of the nucleon current, one finds for \( m_\nu > \) the value 0.52 eV. This is partially surprising as the most favored scenarios of neutrino mixing are preferring \( m_\nu < 0.01 \text{eV} \). It could be that another mechanism is responsible for this process. However, before making some strict theoretical conclusions it is important to clarify some experimental aspects.

The main problem is that the claimed significance of experimental evidence of the 0νββ-decay is not high, around \( 2 \sigma \) and that there is not a consensus among various experimental groups [22]. It seems that we must wait to see what other experiments find. The problem can be solved, if an evidence of the 0νββ-decay will be confirmed or ruled out by another experiment. For that purpose we present the calculated half-lifes for nuclei of experimental interest by assuming the above considered LN violating mechanisms and that the measurement of ref. [21] is correct. They are listed in Table III. In the near future the required half-life value can be achieved within the NEMO III experiment searching for the 0νββ-decay in \( ^{100}\text{Mo} \), which has the chance to reach the level of the half-life up to \( 1. \times 10^{25} \) years.

There are some other ambitious projects in preparation, in particular CAMEO, CUORE, COBRA, ECHO, GENIUS, MAJORANA, MOON, XMASS etc [3]. The next generation of the 0νββ-decay detectors will consist of few tons of the radioactive 0νββ-decay material. This is a great improvement as the current experiments use only few tens of kg's for the source. The above mentioned 0νββ-decay experiments are expected to shed more light on the problem of Majorana neutrinos within the coming decade. Perhaps, there will be a clean evidence of this exotic nuclear transition, which will be generally accepted by the physical community. If it will be the case, the issue of nuclear matrix elements will become crucial.

We note that by knowing nuclear matrix elements with high reliability and the 0νββ-decay half-lifes for transitions to 0+ excited and ground states, it is possible to determine the dominant mechanism [24].

In summary, we have shown that \( ^{134}\text{Xe} \) is a promising nucleus for examining the 0νββ-decay. The nuclear matrix elements governing this process have been found considerably larger in comparison with those for \( ^{136}\text{Xe} \). Thus the sensitivities of both isotopes to the signal of effective light Majorana neutrino are close each to other. By keeping in mind a comparable abundance of both xenon isotopes the results obtained give a strong motivation to search simultaneously for the 0νββ-decay of \( ^{134}\text{Xe} \) and \( ^{136}\text{Xe} \). Finally, the present status of searches for the 0νββ-decay was reviewed. Perspectives of confirming or ruling out the evidence for the 0νββ-decay of \( ^{76}\text{Ge} \) were discussed.

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TABLE I. Nuclear matrix elements of light and heavy Majorana neutrino exchange and trilinear R-parity violating modes for the $0\nu\beta\beta$-decay in $^{134}$Xe and $^{136}$Xe.

| Nucl. | $M_{GT}^{\text{m}_\nu}>$ | $M_{GT}^{\text{m}_\nu}>$ | $M_{GT}^{\text{m}_\nu}>$ | $M_{\text{m}_\nu}>$ | $M_{GT}^{\text{m}_\nu}>$ | $M_{GT}^{\text{m}_\nu}>$ | $M_{\text{m}_\nu}>$ | $M_{\text{m}_\nu}>$ |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $^{136}$Xe | -0.981 | 1.286 | -0.252 | 1.66 | -35.9 | 27.7 | -27.7 | 23.0 |
| $^{136}$Xe | -0.504 | 0.496 | -0.161 | 0.66 | -21.7 | 16.8 | -16.6 | 14.1 |
| $^{136}$Xe | 0.178 | -1.417 | 30.0 | -1.237 | -0.899 | -644. | -614. | -614. |
| $^{136}$Xe | 0.606 | -0.840 | 20.7 | -0.742 | -0.543 | -387. | -387. | -367. |

TABLE II. The present state of the Majorana neutrino mass (light and heavy), and $R_p$ SUSY searches in $0\nu\beta\beta$-decay experiments. $T_{1/2}^{0\nu-\text{m}_\nu}$ is the best presently available lower limit on the half-life of the $0\nu\beta\beta$-decay to the ground state for a given isotope. $\zeta_{\text{m}_\nu}> (Y)$, $\zeta_{\eta_N} (Y)$ and $\lambda_{111} (Y)$ denote according to Eq. (6) the sensitivity of a given nucleus $Y$ to the light neutrino mass, heavy neutrino mass, and $R_p$ SUSY signals, respectively. The corresponding upper limits on LN non-conserving parameters $< m_{\nu}>$, $\eta_N$, and $\lambda_{111}$ (assuming mass of SUSY particles of 100 GeV) are presented.

| Nucleus | $^{48}$Ca | $^{76}$Ge | $^{82}$Se | $^{90}$Zr | $^{100}$Mo | $^{116}$Cd | $^{128}$Te | $^{130}$Te | $^{134}$Xe | $^{136}$Xe | $^{150}$Nd |
|---------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| $T_{1/2}^{0\nu-\text{m}_\nu}$ | 9.5 | 1.6 | 1.4 | 1.0 | 5.5 | 7.0 | 8.6 | 1.4 | 5.8 | 7.0 | 1.7 |
| $\text{[years]}$ | $^{1021}$ | $^{1025}$ | $^{1022}$ | $^{1021}$ | $^{1022}$ | $^{1022}$ | $^{1023}$ | $^{1022}$ | $^{1023}$ | $^{1023}$ | $^{1021}$ |
| C.L. [%] | 80 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 | 90 |
| Ref. | $^{21}$ | $^{22}$ | $^{23}$ | $^{24}$ | $^{25}$ | $^{26}$ | $^{27}$ | $^{28}$ | $^{29}$ | $^{30}$ |
| $\zeta_{\text{m}_\nu}>$ | 2.32 | 2.49 | 4.95 | 4.04 | 7.69 | 5.11 | 1.02 | 4.24 | 0.80 | 1.60 | 17.3 |
| $\zeta_{\eta_N}$ | 0.48 | 2.90 | 5.64 | 3.98 | 7.10 | 3.36 | 1.25 | 5.45 | 1.10 | 3.43 | 18.5 |
| $\lambda_{111}$ | 4.18 | 5.57 | 10.9 | 11.6 | 17.9 | 10.9 | 3.25 | 14.7 | 2.94 | 8.92 | 54.7 |
| $< m_{\nu}>$ [eV] | 22.0 | 0.51 | 8.7 | 40.0 | 2.8 | 3.8 | 17.3 | 3.2 | 27.3 | 3.8 | 7.2 |
| $\eta_N$ [10$^{-7}$] | 2.10 | 0.86 | 15.7 | 79.0 | 6.0 | 7.0 | 27.3 | 4.9 | 38.3 | 3.5 | 13.0 |
| $\lambda_{111}$ [10$^{-4}$] | 8.9 | 1.2 | 5.0 | 9.4 | 2.8 | 3.4 | 5.8 | 2.4 | 6.8 | 2.1 | 3.8 |
TABLE III. Theoretical half-lifes of the $0\nu\beta\beta$-decay to the ground state for nuclei of experimental interest by assuming, that the evidence of the $0\nu\beta\beta$-decay of $^{76}\text{Ge}$ with $T_{1/2}^{0\nu\text{ theor.}} (0^+ \rightarrow 0^+_{\text{g.s.}}) = 1.5 \times 10^{25}$ years is correct. l.n.e and h.n.e. stand for light and heavy Majorana neutrino exchange, respectively.

|         | $^{48}\text{Ca}$ | $^{82}\text{Se}$ | $^{96}\text{Zr}$ | $^{100}\text{Mo}$ | $^{116}\text{Cd}$ | $^{128}\text{Te}$ | $^{130}\text{Te}$ | $^{132}\text{Te}$ | $^{136}\text{Xe}$ | $^{138}\text{Xe}$ | $^{150}\text{Nd}$ |
|---------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| mech.   | $\times 10^{25}$ | $\times 10^{24}$ | $\times 10^{24}$ | $\times 10^{24}$ | $\times 10^{24}$ | $\times 10^{25}$ | $\times 10^{24}$ | $\times 10^{24}$ | $\times 10^{26}$ | $\times 10^{25}$ | $\times 10^{23}$ |
| l.n.e.  | 1.7              | 3.8              | 5.7              | 1.6              | 3.6              | 9.0              | 5.2              | 1.5              | 3.6              | 3.1              |
| h.n.e.  | 5.5              | 4.0              | 8.0              | 2.5              | 4.4              | 8.1              | 4.3              | 1.0              | 1.1              | 3.7              |
| $R_p$   | 2.7              | 3.9              | 3.5              | 1.4              | 3.9              | 4.4              | 2.1              | 54.              | 59.              | 1.6              |