ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2016. Т. 47. ВЫП. 6

LIMITS OF MAJORANA NEUTRINO MASS FROM COMBINED ANALYSIS OF DATA FROM ^{76}Ge AND ^{136}Xe NEUTRINOLESS DOUBLE BETA DECAY EXPERIMENTS

A. A. Klimenko *, *N. S. Rumyantseva*

Joint Institute for Nuclear Research, Dubna

We present effective Majorana neutrino mass limits $\langle m_{\beta\beta} \rangle$ obtained from the joint analysis of the recently published results of ^{76}Ge and ^{136}Xe neutrinoless double beta decay ($0\nu\beta\beta$) experiments, which was carried out by using the Bayesian calculations. Nuclear matrix elements (NMEs) used for the analysis are taken from the works in which NMEs of ^{76}Ge and ^{136}Xe were simultaneously calculated. This reduced systematic errors connected with NME calculation techniques.

The new effective Majorana neutrino mass limits $\langle m_{\beta\beta} \rangle$ less than 85.4–197.0 meV are much closer to the inverse neutrino mass hierarchy region.

PACS: 13.15.+g; 23.40.Bw; 23.40.-s; 14.60.Pq.

INTRODUCTION

The neutrino oscillation experiment results demonstrated non-zero neutrino masses $\delta m_{ij}^2 = m_i^2 - m_j^2$ and mixing, and moved to implying physics beyond the Standard Model (SM) of particle physics [1]. All existing neutrino oscillation data are perfectly described by the minimal scheme of neutrino mixing.

In this connection questions arise as to the absolute neutrino mass spectrum, nature of neutrino, i.e., are they Majorana or Dirac particles, and type of the neutrino mass hierarchy.

A set of experiments provide some information about the neutrino mass spectrum.

The end-point beta-decay experiments present the neutrino mass result as

$$m_\beta^2 = \sum_{i=1}^{3} \mid U_{ei} \mid^2 \times m_i^2 = c_{12}^2 c_{13}^2 m_1^2 + s_{12}^2 c_{13}^2 m_2^2 + s_{13}^2 m_3^2,$$

*E-mail: klimenko@nusun.jinr.ru

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$, and $m_i (i = 1, 3)$ are mass eigenvalues; and now we have $m_\beta < 2.0$ eV (95% C.L.) [2].

Observations of the angular power spectrum of temperature anisotropies in the cosmic microwave background (CMB) from the Planck satellite [3], polarization measurements from the Wilkinson microwave anisotropy [4], and observations of baryonic acoustic oscillations (BAOs) [5] give the sum of neutrino masses. A constraint on the sum of neutrino masses from these experiments

$$\sum m_\nu < 0.23 \text{ eV}, \ 95\% \text{ C.L.}$$

has been obtained for active neutrinos and excludes most of the quasi-degenerate region of the light neutrino mass spectrum [6].

Some extensions of the SM predicts the possibility of the $0\nu\beta\beta$ process.

This process violates the lepton number conservation law by two units, $\Delta L = 2$:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+2}X + 2e^-.$$

We analyze the results of the experiments connected with the following transitions:

$$^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-, \quad {}^{136}\text{Xe} \rightarrow {}^{136}\text{Ba} + 2e^-.$$

The half-life for such a process is given by

$$T^{0\nu}_{1/2}(0^+_i \rightarrow 0^+_f)^{-1} = |\langle m_{\beta\beta}\rangle|^2 G^{0\nu} M^2_{0\nu},$$

where $G^{0\nu}$, $M_{0\nu}$ and $\langle m_{\beta\beta}\rangle$ are the phase space factor, NME, and the effective Majorana mass of the neutrino

$$\langle m_{\beta\beta}\rangle = \sum_{i=1}^{3} |\ U_{ei}\ |^2\, m_i.$$

For the standard parametrization of the mixing matrix, we have

$$\langle m_{\beta\beta}\rangle = c^2_{12}\, c^2_{13} m_1 + s^2_{12} c^2_{13} m_2\, e^{i\phi_2} + s^2_{13} m_3\, e^{i\phi_3},$$

where ϕ_i denotes relative Majorana phases connected with CP violation.

Detailed analysis of the theoretical aspects of the Majorana mass from the $0\nu\beta\beta$ process as a tool for probing the absolute neutrino mass scale is given in [7, 8].

We have a set of the $0\nu\beta\beta$ experiments with the results on $\langle m_{\beta\beta}\rangle$ in the region of $\approx 140-400$ meV.

Currently, there are two combined results of the germanium and xenon $0\nu\beta\beta$ experiments, which are given in [9, 10] with $\langle m_{\beta\beta}\rangle$ in the region of $\approx 120-300$ meV for NMEs used in those works.

We performed a combined analysis of the results of the ^{76}Ge and ^{136}Xe $0\nu\beta\beta$ experiments with the Bayesian approach.

1. CALCULATION METHOD

Limits on the Majorana neutrino mass were calculated using the Bayesian Analysis Toolkit (BAT) [16]; it was used to perform the combined analysis of the data sets and to extract the posterior distribution of $0\nu\beta\beta$ events ($N_{0\nu\beta\beta}$) after marginalization over all nuisance parameters.

BAT is a software package designed to help solve statistical problems encountered in Bayesian inference and is based on Bayes' theorem and is realized with the use of Markov Chain Monte Carlo.

Bayes' theorem is given by

$$P(\boldsymbol{\lambda}|D) \propto P(D|\boldsymbol{\lambda})P_0(\boldsymbol{\lambda}),$$

where $P(D|\boldsymbol{\lambda}) = L(\boldsymbol{\lambda})$ is the likelihood function, i.e., the conditional probability of the data for the parameter set, and $P_0(\boldsymbol{\lambda})$ is the a priori probability of $\boldsymbol{\lambda}$.

This gives an access to the full posterior probability distribution and enables straightforward estimation of the parameter $\boldsymbol{\lambda}$, limit setting, and uncertainty propagation.

BAT is implemented in C++ and allows a flexible definition of mathematical models and applications while keeping in mind the reliability and speed requirements of the numerical operations. It provides a set of algorithms for numerical integration, optimization, and error propagation. Predefined models exist for standard cases. In addition, methods to judge the goodness-of-fit of a model are implemented.

In general, the likelihood function (MLM) is defined as

$$L = \prod_{i=1}^{N_{\rm ch}} \prod_{j=1}^{N_{\rm bin}} \frac{\lambda^{n_{ij}}}{n_{ij}!}\, {\rm e}^{-\lambda_{ij}}, \tag{1}$$

where $N_{\rm ch}$ and $N_{\rm bin}$ are the number of channels and bins; n_{ij} and λ_{ij} are the observed and expected number of events in the jth bin of the ith channel. The expected number of events is calculated via

$$\lambda_{ij} = \left(\sum_{k=1}^{N_p} \lambda_{ijk}\right) = \left(\sum_{k=1}^{N_p} \lambda_k\right) f_{ijk}\epsilon_{ik},$$

where f_{ij} is the bin content of the jth bin in the normalized template of the kth process in the ith channel; ϵ_{ik} is the efficiency of the kth process in the ith channel specified when setting the template, and λ_k is the contribution of the kth process to a free parameter of fit.

2. ANALYSIS

The energy spectra and other experimental parameters obtained in the latest experiments on the search for $0\nu\beta\beta$ — GERDA [9, 11], HdM [12], IGEX [13], EXO-200 [14] and KamLAND-Zen [10] were used to estimate the limits on the Majorana neutrino mass.

In our case we have seven channels for BAT — the GOLDEN and the BEGe runs of the GERDA, HdM, IGEX, EXO-200, KamLAND-Zen I, II experimental spectra, and two processes — the background of each spectrum and the expected signal $N_{0\nu\beta\beta}$ with weights equated to exposures for each channel (Exp, see below).

The GOLDEN and the BEGe runs of the first phase of the GERDA experiment were used for this analysis (the spectra are presented in Fig. 1). The GOLDEN run has an exposure of $8.83 \cdot 10^{25}$ at $\cdot$ y, full width at half maximum (FWHM) equal to (4.8 ± 0.2) keV, and energy region of 1930–2190 keV. The

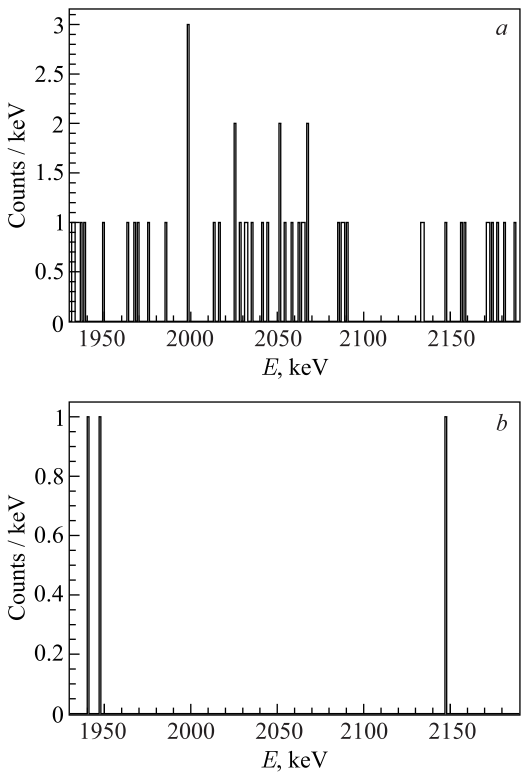

Fig. 1. GOLDEN (*a*) and BEGe (*b*) GERDA runs from [11]

BEGe run has an exposure of $1.27 \cdot 10^{25}$ at · y, FWHM = (3.2 ± 0.2) keV, and energy region 1930–2190 keV.

The data of the Heidelberg–Moscow (HdM) experiment were taken from [12], with FWHM = 4.23 keV and exposure $25.16 \cdot 10^{25}$ at · y.

The data of the IGEX experiment were taken from [13], with FWHM = 4.0 keV and exposure $6.47 \cdot 10^{25}$ at · y.

The spectra of the IGEX and the HdM experiments are presented in Fig. 2.

The spectra of the ^{136}Xe experiments are presented in Figs. 3 and 4.

We omit the description of the setups and other details of the experiments from which we took the spectra because this is not the purpose of our investigations.

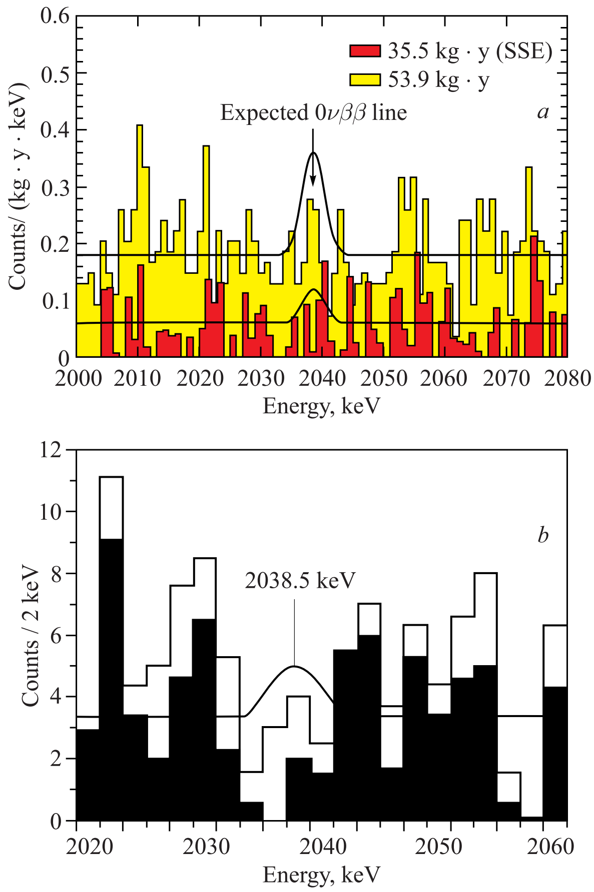

Fig. 2. HdM [12] (*a*) and IGEX [13] (*b*) energy spectra without and with PSD

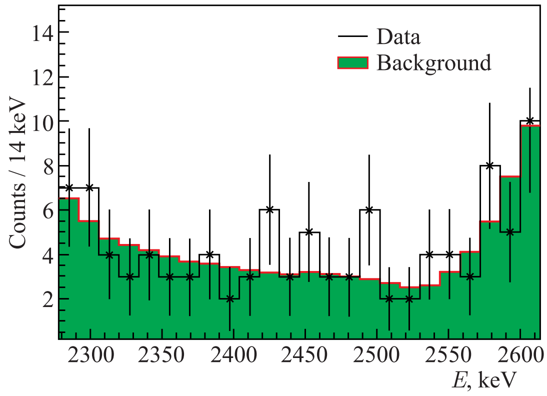

Fig. 3. EXO-200 energy spectra, measured and calculated background [14]

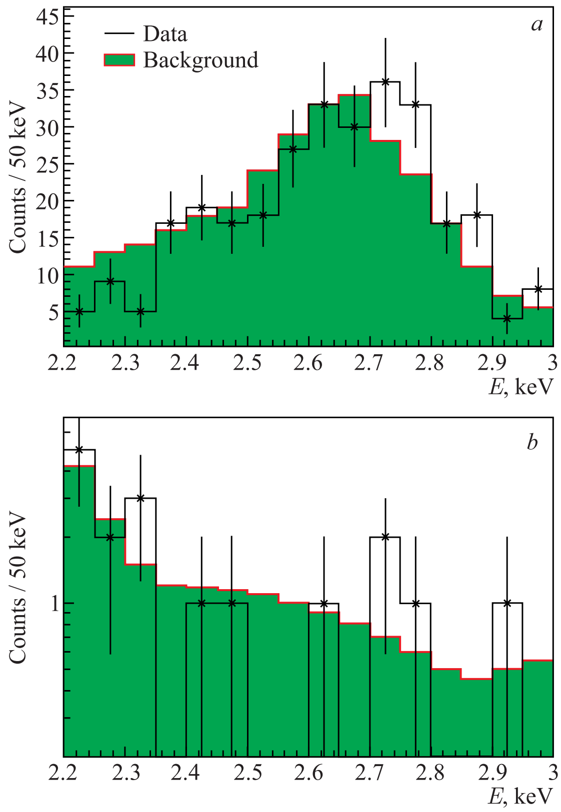

Fig. 4. KamLAND-Zen: phase I (*a*) [10] and phase II (*b*) [15]

Table 1. **Characteristics of the spectra used in the analysis**

<table>
<tr><th rowspan="2">Isotope
$Q_{\beta\beta}$, keV</th><th rowspan="2">Run</th><th>Exp, 10^{25},</th><th>FWHM,</th><th>ΔE,</th><th colspan="2">NME</th><th>BCK</th></tr>
<tr><th>at · y</th><th>keV</th><th>keV</th><th>$\xi = 5.14$</th><th>$\xi = 0.85$</th><th>type</th></tr>
<tr><td rowspan="4">^{76}Ge
2039.1</td><td>GOLDEN</td><td>8.83</td><td>4.83</td><td rowspan="2">230</td><td rowspan="4">4.6</td><td rowspan="4">5.09</td><td rowspan="4">Line</td></tr>
<tr><td>BEGe</td><td>1.27</td><td>3.24</td></tr>
<tr><td>HdM</td><td>25.16</td><td>4.23</td><td>80</td></tr>
<tr><td>IGEX</td><td>6.47</td><td>4.0</td><td>42</td></tr>
<tr><td rowspan="3">^{136}Xe
2457.8</td><td>EXO-200</td><td>37.39</td><td>88.6</td><td>262</td><td rowspan="3">4.22</td><td rowspan="3">1.89</td><td rowspan="3">Calc.</td></tr>
<tr><td>KLAND-1</td><td>39.63</td><td>243.7</td><td rowspan="2">800</td></tr>
<tr><td>KLAND-2</td><td>12.19</td><td>232.1</td></tr>
</table>

A full set of the characteristic parameters of the spectra used in the analysis is presented in Table 1.

According to BAT scheme, we defined channels as the energy spectra of the corresponding runs with two processes for each channel — the background and the signal.

The model of the background is individual for each channel in contrast to the signal, which is common for all channels, and in our case it is $N_{0\nu\beta\beta}$.

A flat distribution of the background in the region of interest (ROI) is used for the channels corresponding to the germanium experiments.

The background spectra calculated for each xenon experiment are used for our analysis.

The signal process is presented as sum of Gaussian peaks for suitable channels with the energy $Q_{\beta\beta}$ and σ_E for each experiment and with common signal events $N_{0\nu\beta\beta}$.

Another important point of this analysis is using NMEs [17] for the corresponding isotope and for conversion of xenon exposure to germanium one.

There are many publications devoted to calculation of NME for different isotopes using different methods. We chose ^{76}Ge and ^{136}Xe NMEs from [18] such that they had an extreme ratio and were similar to pairs of NMEs (EDF and SkM-HFB-QRPA models) for the marginal ^{76}Ge–^{136}Xe half-life lines in Fig. 2 [9]. These two pairs of NMEs allow us to assume that systematic error of the calculation technique is small. The exposure (Exp) is defined in the following expression for the half-life:

$$T^{0\nu}_{1/2} = \ln(2) \cdot \mathrm{Exp}/N_{0\nu\beta\beta},$$

and Exp is the effective number of double beta decay nuclei for time of measurements.

For connection of the ^{76}Ge and ^{136}Xe data we use formula for conversion of the ^{136}Xe exposition to the Ge one so as we were handling the ^{76}Ge and ^{136}Xe spectra simultaneously and exposures are weight for corresponding spectrum in joint set:

$$\mathrm{Exp}_{\mathrm{Ge}} = \mathrm{Exp}_{\,\mathrm{Xe}}\left|\frac{ME_{\mathrm{Xe}}}{ME_{\mathrm{Ge}}}\right|^2 \frac{G_{0\nu}^{\mathrm{Xe}}}{G_{0\nu}^{\mathrm{Ge}}} = \xi \cdot \mathrm{Exp}_{\,\mathrm{Xe}},$$

where the matrix elements are taken from [18], the ratio of the phase space factors is

$$\frac{G_{0\nu}^{\mathrm{Xe}}}{G_{0\nu}^{\mathrm{Ge}}} = 6.17,$$

and

$$\xi = \left|\frac{ME_{\mathrm{Xe}}}{ME_{\mathrm{Ge}}}\right|^2 \frac{G_{0\nu}^{\mathrm{Xe}}}{G_{0\nu}^{\mathrm{Ge}}},$$

which is the relative decay probability of the ^{136}Xe nucleus to ^{76}Ge.

The above-described spectra of the experimental runs and their backgrounds, the exposures and run resolutions are the values needed for BAT input and for the formation of the MLM function in (1). The priors of all parameters, seven backgrounds and signal, are taken uniform according to the Bayesian procedure.

The number of excluded signal events, which were obtained with BAT, are given in the third column for two ^{76}Ge/^{136}Xe NMEs combinations.

By taking this $N_{0\nu\beta\beta}$ for obtaining the limit on the half-life, we use formula from [19] with scaling of the parameters g_A and r_0 and results of [20] for calculations of $\langle m_{\beta\beta}\rangle$.

Final results of the analysis are presented in Table 2.

The method of the calculations was cross-checked using the combined ^{136}Xe and ^{76}Ge data sets presented here.

The resulting limits are

$$T_{1/2}^{0\nu}(^{136}\mathrm{Xe}^{\mathrm{comb}}) > 3.3 \cdot 10^{25}\ \mathrm{y},\ 90\%\ \mathrm{C.L.},$$
$$T_{1/2}^{0\nu}(^{76}\mathrm{Ge}^{\mathrm{comb}}) > 3.2 \cdot 10^{25}\ \mathrm{y},\ 90\%\ \mathrm{C.L.}$$

We observe acceptable agreement of our results with the GERDA result [9] $T_{1/2}^{0\nu}(^{76}\mathrm{Ge}^{\mathrm{comb}}) > 3.0{\cdot}10^{25}$ y and KamLAND-Zen result [10] $T_{1/2}^{0\nu}(^{136}\mathrm{Xe}^{\mathrm{comb}}) > 3.4 \cdot 10^{25}$ y.

For completeness, in addition to the ^{136}Xe and ^{76}Ge data, we also used the ^{100}Mo data [21] and ^{130}Te data [22] with the NMEs from those works and

Table 2. **Final results of the analysis**

ME, Ge/Xe	ξ	Exp, 10^{25} at · y ^{76}Ge	$N_{0\nu\beta\beta}$, counts 90% C.L.	$T_{1/2}^{0\nu}$, 10^{25} y	$\langle m_{\beta\beta}\rangle$, meV
5.1/1.9	0.85	118.26	17.2	4.8	170.0–97.0
4.6/4.2	5.14	501.24	16.8	20.7	85.4–94.7

obtained the neutrino mass limits $\langle m_{\beta\beta}\rangle$ less than 83.7–157.1 meV using the procedure described here for ^{76}Ge, ^{136}Xe, ^{130}Te and ^{100}Mo spectra which will be published in the near future.

CONCLUSIONS

The Bayesian approach was used to obtain the range of limits on the Majorana neutrino mass with allowance for the results of the recent ^{76}Ge and ^{136}Xe double beta decay experiments.

As a result, the new effective majorana neutrino mass range of limits $\langle m_{\beta\beta}\rangle$ less than 85.4–197.0 meV is obtained. This result together with the cosmological limit $\sum m_\nu < 230$ meV rejects the most part of mass region of the quasi-degenerate neutrino mass hierarchy.

Acknowledgements. We are grateful to B. Schwingenheur for initiation of this work and fruitful discussions. The work was supported in part by the Russian Foundation of Basic Research (Grant 13-02-00489).

REFERENCES

1. *Fukuda Y. et al. (SK Collab.).* Determination of Solar Neutrino Oscillation Parameters Using 1496 Days of Super-Kamiokande-I Data // Phys. Lett. B. 2002. V. 539. P. 179–187;
Ahmad Q. R. et al. (SNO Collab.). Measurement of the Rate of Interactions Produced by Solar Neutrinos at the Sudbury Neutrino Observatory // Phys. Rev. Lett. 2001. V. 87. P. 071301-1–071301-6;
Educhi K. et al. (KamLAND Collab.). First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance // Phys. Rev. Lett. 2003. V. 90. P. 021802-1–021802-6;
Gavrin V. N. et al. (SAGE Collab.). Measurement of the solar neutrino capture rate in SAGE // Nucl. Phys. B (Proc. Suppl.). 2003. V. 118. P. 39–51;
Abdurashitov J. N. et al. (SAGE Collab.). Solar Neutrino Flux Measurements by the Soviet-American Gallium Experiment (SAGE) for Half the 22-Year Solar Cycle // J. Exp. Theor. Phys. 2002. V. 95. P. 181–193;
Hampel W. et al. (GALLEX Collab.). GALLEX Solar Neutrino Observations: Results for GALLEX IV // Phys. Lett. B. 1999. V. 447. P. 127–133;
Bellotti E. et al. (GALLEX Collab.). First Results from GNO // Nucl. Phys. B (Proc. Suppl.). 2001. V. 91. P. 44–49.
2. *Yao W. M. et al. (PDG Collab.).* Review of Particle Physics // J. Phys. G. 2006. V. 33. P. 1–1232;
Aseev V. N. et al. Measurement of the Electron Antineutrino Mass in Tritium Beta Decay in the Troitsk Nu-Mass Experiment // Phys. At. Nucl. 2012. V. 75. P. 464–478.

3. *Ade P. A. R. et al. (Planck Collab.).* Planck 2015 Results. XIII Cosmological Parameters. arXiv:1502.01589 [astro-ph.CO].

4. *Bennet C. L. et al. (WMAP Collab.).* Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Final Maps and Results // Astrophys. J. Suppl. Ser. 2013. V. 208. P. 20–74.

5. *Anderson L. et al. (SDSS-III Collab.).* The Clustering of Galaxies in the SDSS-III Baryon Oscillation Spectroscopic Survey: Baryon Acoustic Oscillations in the Data Release 9 Spectroscopic Galaxy Sample // Mon. Not. Roy. Astron. Soc. 2012. V. 427. P. 3435–3467.

6. *Fogli G. L. et al.* Observables Sensitive to Absolute Neutrino Masses. II // Phys. Rev. D. 2008. V. 78. P. 033010-1–033010-5;
Mitra M., Senjanovich G., Vissani F. Heavy Sterile Neutrinos and Neutrinoless Double Beta Decay. arXiv:1205.3867 [hep-ph].

7. *Bilenky S. M., Giunti C.* Neutrinoless Double-Beta Decay: A Probe of Physics beyond the Standard Model. arXiv:1411.4791 [hep-ph].

8. *Bhupal Dev P. S. et al.* Constraining Neutrino Mass from Neutrinoless Double Beta Decay. arXiv:1305.0056 [hep-ph].

9. *Agostini M. A. et al. (GERDA Collab.).* Results on Neutrinoless Double β Decay of ^{76}Ge from Phase I of the GERDA Experiment // Phys. Rev. Lett. 2013. V. 111. P. 122503-1–122503-6.

10. *Gando A. et al. (KamLAND-Zen Collab.).* Limit on Neutrinoless Decay of ^{136}Xe from First Phase of KamLAND-Zen and Comparison with the Positive Claim in ^{76}Ge // Phys. Rev. Lett. 2013. V. 110. P. 062502-1–062502-5.

11. *Agostini M. A. et al. (GERDA Collab.).* The Background in the Neutrinoless Double Beta Decay Experiment GERDA // Eur. Phys. J. C. 2014. V. 74. P. 2764-1–2764-25;
Agostini M. A. et al. (GERDA Collab.). The GERDA Experiment for the Search of $0\nu\beta\beta$ Decay in ^{76}Ge // Eur. Phys. J. C. 2013. V. 73. P. 2330-1–2330-29;
Agostini M. A. et al. (GERDA Collab.). Pulse Shape Discrimination for GERDA Phase I Data // Ibid. P. 2583-1–2583-17.

12. *Klapdor-Kleingrothaus H. V. et al. (HdM Collab.).* Latest Results from the Heidelberg–Moscow Double Beta Decay Experiment // Eur. Phys. J. A. 2001. V. 12. P. 147–154.

13. *Aalseth C. E. et al. (IGEX Collab.).* The IGEX Ge-76 Neutrinoless Double-Beta Decay Experiment: Prospects for Next Generation Experiments // Phys. Rev. D. 2002. V. 65. P. 092007-1–092007-6.

14. *Albert J. B. et al. (EXO-200 Collab.).* Search for Majorana Neutrinos with the First Two Years of EXO-200 data. arXiv:1402.695 [nucl-exp].

15. *Asakura A. et al. (KamLAND-Zen Collab.).* Results from KamLAND-Zen. arXiv:1409.0077v1 [physics.ins-det].

16. *Caldwell A., Kroninger K.* Signal Discovery in Sparse Spectra: A Bayesian Analysis // Phys. Rev. D. 2006. V. 74. P. 092003-1–092003-7.

17. *Šimkovic F. et al.* $0\nu\beta\beta$ and $2\nu\beta\beta$ Nuclear Matrix Elements, Quasiparticle Random-Phase Approximation, and Isospin Symmetry Restoration // Phys. Rev. C. 2013. V. 87. P. 045501-1–045501-9;
Meroni A., Petkov S. T., Šimkovic F. Multiple CP Non-Conserving Mechanisms of $(\beta\beta)_0\nu$-Decay and Nuclei with Largely Different Nuclear Matrix Elements // J. High Energy Phys. 2013. V. 02. P. 025-1–025-27;
Suhonen J., Civitarese O. Effects of Orbital Occupancies and Spin–Orbit Partners on $0\nu\beta\beta$-Decay Rates // Nucl. Phys. A. 2010. V. 847. P. 207–232.

18. *Rodriguez T. A., Martinez-Pinedo G.* Energy Density Functional Study of Nuclear Matrix Elements for Neutrinoless $\beta\beta$ Decay // Phys. Rev. Lett. 2010. V. 105. P. 252503-1–252503-4;
Mustonen M. T., Engel J. Large-Scale Calculations of the Double-Beta Decay of ^{76}Ge, ^{130}Te, ^{136}Xe, and ^{150}Nd in the Deformed Self-Consistent Skyrme Quasiparticle Random-Phase Approximation. arXiv:1301.6997 [nucl-th].

19. *Smolnikov A., Grabmayr P.* Conversion of Experimental Half Life Time to Effective Electron Neutrino Mass in $0\nu\beta\beta$ Decay // Phys. Rev. C. 2010. V. 81. P. 028502-1–028502-4.

20. *Kotila J., Iachello F.* Phase-Space Factors for Double Beta Decay // Phys. Rev. C. 2012. V. 85. P. 034316-1–034316-13.

21. *Arnold R. et al. (NEMO-3 Collab.).* Search for Neutrinoless Double Beta Decay with the NEMO-3 Detector // Phys. Rev. D. 2014. V. 89. P. 111101-1–111101-6.

22. *Andreotti E. et al. (CUORE Collab.).* ^{130}Te Neutrinoless Double Beta Decay with CUORICINO // Astropart. Phys. 2011. V. 34. P. 822–831.