

Neutrinoless double beta decay experiment

Yong-Hamb Kim
Center for Underground Physics, Institute for Basic Science (IBS), Daejeon 34126, Korea
University of Science and Technology (UST), Daejeon 34113, Korea
Korea Research Institute of Standards and Science (KRISS), Daejeon 34113, Korea
E-mail: yhk@ibs.re.kr

Abstract. The search for neutrinoless double beta decay ($0\nu\beta\beta$) is one of the key experiments for determining unresolved properties of neutrinos. Experimental observation of $0\nu\beta\beta$ would provide a clear demonstration of the Majorana nature of neutrinos and a lepton number violating process in particle physics. This report is a brief review describing the $0\nu\beta\beta$ process and its significance. The detector technologies used in the present and proposed $0\nu\beta\beta$ experiments are compared among their recent experimental results. Moreover, the sensitivities for $0\nu\beta\beta$ discovery in a number of present and proposed $0\nu\beta\beta$ experiments are introduced.

1. Introduction
Neutrinoless double beta decay ($0\nu\beta\beta$) is a hypothetical decay process related to the fundamental understanding of particle physics and the universe. This rare decay process can occur only if neutrinos are massive Majorana particles (i.e., their own anti-particles). Moreover, the decay is allowed only when lepton number conservation is violated in the physical process. In principle, a new understanding of particle physics would need to be introduced to explain lepton number violation (LNV) process beyond the standard model (SM).

Recent experimental and theoretical studies have revealed various properties of neutrinos that are a class of elementary particles. Recent observations of neutrino oscillations [1, 2, 3, 4] have demonstrated that the flavor states are expressed as mixed combinations of mass eigenstates established via a characteristic matrix known as the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [5]. These results suggest that neutrinos have a nonzero mass. Moreover, the mass eigenstates evolve in time, resulting in oscillating appearance and disappearance of the flavor states.

Experimentally, the square differences of the mass eigenstates have been found from oscillation measurements of atmospheric and solar neutrinos [1, 2, 3]. However, their absolute mass scales are still unknown. Moreover, it has not yet been concluded whether neutrinos are Majorana or Dirac particles. That is a fundamental question linked to an in-depth understanding of particle physics [6].

2. General aspects of neutrinoless double beta decay
A normal double beta decay ($2\nu\beta\beta$) is a second order weak process in nuclear physics. The two neutrino mode of double beta decay was first predicted from the study of a nuclear structures [7]. The $2\nu\beta\beta$ process is always associated with the emission of two electrons and two antineutrinos
expressed as

\[(Z, A) \rightarrow (Z + 2, A) + 2\beta^- + 2\bar{\nu}_e.\]  

(1)

About 10 nuclei have been found to undergo double beta decay with a variety of half-lives on the order of \(T^{2\nu}_{1/2} \approx 10^{19–24}\) among the 35 nuclei for which the process is energetically allowed \[9\].

On the other hand, in the case of \(0\nu\beta\beta\) no neutrinos are emitted in association with the decay process, expressed as

\[(Z, A) \rightarrow (Z + 2, A) + 2\beta^- .\]  

(2)

This hypothetical process violates lepton number conservation by 2. The possibility of neutrinoless decay was first discussed independently by E. Majorana and G. Racah \[10, 11\]. W.H. Furry made a specific discussion of the neutrinoless process in \(\beta\beta\) decay based on the Majorana theory \[12\].

Because a \(0\nu\beta\beta\) process is associated with the emission of only two electrons, the decay energy is shared between the two electrons with a negligible amount by the daughter nucleus. Consequently, \(0\nu\beta\beta\) events appear as the peak at the end point of a broad electron energy spectrum of \(2\nu\beta\beta\) decay as shown in Fig. 1. The \(0\nu\beta\beta\) decay rate is highly exaggerated in this figure. Backgrounds and statistical fluctuations are not included in the spectra.

In general, the decay rate \(\Gamma_{0\nu}\) of the \(0\nu\beta\beta\) process is expressed as

\[\Gamma_{0\nu} = 1/T^{0\nu}_{1/2} = \sum_x G_{0\nu}^x |M_{0\nu}^x\eta_x|^2\]  

(3)

where \(T^{0\nu}_{1/2}\) is the \(0\nu\beta\beta\) half-life of the element, \(x\) and \(\eta_x\) denote physics mechanisms and their corresponding functions for LNV processes, and \(G_{0\nu}^x\) and \(M_{0\nu}^x\) are the phase space factors and the nuclear matrix elements (NMEs) of each mechanism for the decay, respectively \[13\]. In the case of the light neutrino exchange model (i.e., a commonly accepted mechanism for interpreting \(0\nu\beta\beta\)), the decay rate becomes

\[1/T^{0\nu}_{1/2} = G_{0\nu}^0 |M_{0\nu}^0|^2 m_{\beta\beta}^2.\]  

(4)

where \(m_{\beta\beta}\) is the effective Majorana mass. In this interpretation, no other mechanism contributes to the zero-neutrino mode of \(\beta\beta\) decays. The phase space factor \(G_{0\nu}\) is exactly calculable in atomic physics \[14\]. However, uncertainties by factors of 2–3 are found in the NME \(M_{0\nu}^0\) calculation for all isotopes of \(0\nu\beta\beta\) candidates \[15\].

Because the decay rate calculations for the \(\beta\) and \(2\nu\beta\beta\) processes are adjusted with the effective axial-vector coupling constant \(g_A\), similar quenching process may exist in \(0\nu\beta\beta\). It is noted that even with small \(g_A^{\text{eff}}\) values, \(0\nu\beta\beta\) rates are reduced by factors of only 2–6 because \(g_A\) is largely incorporated with the NMEs \[16\]. On the other hand, some theoretical predictions

![Figure 1: Energy spectra the electrons from the \(2\nu\beta\beta\) and \(0\nu\beta\beta\) processes.](image)
suggest no or reduced quenching might be needed in 0νββ because the quenching process
depends on the energy scale [17]. This subject will require further theoretical and experimental
investigations.

Although 0νββ discovery would be a clear demonstration of Majorana neutrinos and LNV
process allowed in particle physics, it should be noted that Eq. (4) is an interpretation of general
LNV mechanisms. Other theoretical models also exist that lead to 0νββ rates expected to be
of the same order as the light neutrino exchange mechanism [18]. Therefore, full understanding
of 0νββ process requires 0νββ measurements in more than one isotope to clarify the model
responsible for 0νββ. Moreover, the uncertainties of the NME calculations enhance the need for
0νββ search experiments using various nuclei.

3. Neutrinoless double beta decay and neutrino mass

Because of the virtual neutrino exchange in the standard process, the effective Majorana mass
in Eq. (4) is a coherent sum of the neutrino masses expressed as

\[ m_{\beta\beta} = \left| \sum U_{ei}^2 m_i \right| \]  

(5)

where the \( U_{ei} \) are the elements of the PMNS matrix containing the mixing angles and CP phases,
and \( m_i \) are the mass eigenvalues. On the other hand \( m_{\beta\beta} \) is a measurable quantity of neutrino
mass from a half-life measurement based on the light neutrino exchange model.

Because the \( \nu \) oscillation measurements have yielded only the squared differences of the
mass eigenvalues, which neutrino state is the lightest is not known. Two possible cases of
mass ordering exist. By setting \( m_1 \) or \( m_3 \) as the lightest of the mass eigenstates, the mass
ordering becomes either \( m_1 < m_2 < m_3 \) (normal ordering, NO) or \( m_3 < m_1 < m_2 \) (inverted
ordering, IO), respectively. The relation between \( m_{\beta\beta} \) and the mass of the lightest neutrino
\( m_{\text{lightest}} \) can be established by using the parameters obtained in up-to-date studies of neutrino
phenomenology. Fig. 2 shows the allowed regions of the mass parameters in both ordering cases.
The dark areas colored in light blue and in orange indicate allowed regions originating from the
unknown CP phases for NO and IO, respectively. These allowed regions are widened when the
experimental uncertainties on the parameters obtained from neutrino oscillation measurements
are considered as shown by the light-colored regions. This plot indicates the general sensitivity of
a 0νββ experiment in the light \( \nu \) exchange model. The half-life of 0νββ is inversely proportional
to \( m_{\beta\beta}^2 \). Thus the smaller \( m_{\beta\beta} \) is the harder it will be to discover 0νββ. Notably, the allowed
regions for \( m_{\beta\beta} \) and \( m_{\text{lightest}} \) are broadened not by the NME calculation uncertainties but by
the unknowns and constraints related to the \( \nu \) parameters.

In comparison with other experimental approaches, 0νββ experiments provide the highest
detection sensitivity for neutrino mass measurement. 0νββ searches set the absolute mass scale
of neutrinos in spite of model dependent decay mechanisms. On the other hand, a model
independent approach to detect the neutrino mass is the precise measurement of the end point
of a beta decay spectrum in KATRIN and ECHo projects [19, 20]. In such direct detection
of neutrino mass, the mass observable is expressed as \( m^2_{\beta} = \sum |U_{ei}|^2 m_i^2 \). The most up-to-date
limit on \( m_3 \) is 1.1 eV from the KATRIN project [21]. Furthermore, observational cosmology
constrains a strong but model-dependent limit on the sum of the neutrino masses, \( m_{\text{tot}} = \sum m_i \).

Considering all the measured information on neutrino properties including \( m_{\beta\beta} \), \( m_{\text{lightest}} \),
\( m_{\text{tot}} \), and neutrino oscillations, a global Bayesian analysis was performed to estimate the
discovery probability distribution for 0νββ [22]. This analysis yielded a probable region for the
discovery rather than the allowed region indicated in Fig. 2. According to the prediction,
if an experiment is carried out with a \( m_{\beta\beta} \) sensitivity of 20 meV, then the discovery potential
for 0νββ observation is expected to be 95% in the case of IO. Even in the case of NO, the
discovery potential becomes as high as 50% with 20 meV detector sensitivity. In NO, achieving
90% chance of 0νββ discovery will require 5 meV sensitivity.
4. Neutrinoless double beta decay experiments

Although all the extant experiments have developed their own technologies for detecting the zero-neutrino mode of the decay, common strategies exist for increasing detection sensitivity. Greater exposure (i.e., the product of the amount of the $\beta\beta$ isotope and the measurement time) increases the chance of detecting rare events. Because the energy resolution defines the energy region of interest (ROI), higher resolution also improves the detection sensitivity in the presence of backgrounds. Finally, it is crucial to minimize the background events present in the ROI for a $0\nu\beta\beta$ search. These strategies have long motivated various technological developments in terms of detection methods, active and passive shields, purification and radio assays, laboratory controls/maintenance, and online/offline analysis.

A number of experiments worldwide have investigated and are currently investigating $0\nu\beta\beta$ decays in several different nuclei. This review introduces several $0\nu\beta\beta$ experiments based on commonly used isotopes, categorized in detector technologies. Brief descriptions of present and future experiments are provided, including presentations from the 16th International Conference of Topic in Astroparticle and Underground Physics (TAUP), Toyama, Japan, 2019. The most recent results are listed in Table 1. There exist many other $0\nu\beta\beta$ projects not covered in the review.

4.1. Loaded liquid scintillators

Loaded liquid scintillators (LSs) are a popular choice of target materials in neutrino research. A large amount of additive acting as the target for neutrino interactions can be loaded into an organic LS with extremely low level of radioimpurities. Large exposure, a low background rate, and easy scalability are the evident advantages of using loaded LSs for $0\nu\beta\beta$ searches.

The present best limit on the $0\nu\beta\beta$ rate is set by KamLAND-Zen using a LS hosted in a thin transparent balloon loaded with 400 kg of $^{136}$Xe gas [26]. The half-life limit sensitivity and corresponding $m_{\beta\beta}$ limit are $T^{0\nu}_{1/2} > 1.07 \times 10^{26}$ years and $m_{\beta\beta} < (0.061-0.165)$ eV, respectively. The gray region in Fig. 2 indicates the upper limit of $m_{\beta\beta}$. The width of the limit band is attributed to the NME uncertainties [15]. The upper limit on the lightest neutrino has also been estimated to be $m_{\text{lightest}} < (0.18-0.48)$ eV from the relation between $m_{\beta\beta}$ and $m_{\text{lightest}}$ as indicated by the vertical gray region in Fig. 2. A similar analogy can be applied to the other observables of neutrino mass, $m_3$ and $m_{\text{tot}}$, not discussed here. The KamLAND-Zen measurement has been resumed with 800 kg of $^{136}$Xe in 2019, and this experiment is expected to continue improving its sensitivity for $0\nu\beta\beta$ discovery.
SNO was a heavy water Cherenkov detector that discovered the oscillation of $\nu_e$ to neutrinos of other flavors. Now, it has become SNO+, which is being filled with liquid scintillator. One of the science goals of SNO+ is the search for $0\nu\beta\beta$ of $^{130}\text{Te}$. Because of the large active volume, at 0.5% nat-Te loading the detector contains 1.33 tons of $^{130}\text{Te}$ and 20% of that amount is in the fiducial volume [27]. $^{130}\text{Te}$ was chosen as the $\beta\beta$ isotope because of its high natural abundance of 34.1% (see Table 1). SNO+ expects to reach a $2.1 \times 10^{26}$ years sensitivity with a 5-year run [28].

4.2. Ge semiconductors

High-purity Ge (HPGe) detectors are a common class of radiation detectors for a variety of applications. Taking advantage of the mature technologies developed for commercial and research detectors, HPGe detectors consisting of isotopically enriched $^{76}\text{Ge}$ can be prepared for a $0\nu\beta\beta$ experiment. HPGe detectors provide the highest energy resolution (e.g., 2.5 keV FWHM at $Q_{\beta\beta}$ of $^{76}\text{Ge}$) among the technologies used in $0\nu\beta\beta$ experiments [29]. Moreover, the PSD features used to differentiate between bulk and surface events and between single-site and multi-site events are another powerful tool of Ge detectors for the $0\nu\beta\beta$ search.

The search for $0\nu\beta\beta$ with Ge detectors started in the 1960s, and a number of experiments have contributed to continuing progress in sensitivity [30]. GERDA-II improved its background using an active veto consisting of a liquid Ar bath hosting Ge crystals with low-mass holder [31]. This experiment found a lower limit of $T_{1/2}^{0\nu}$ at $1.1 \times 10^{26}$ years with $m_{\beta\beta} < (0.10–0.23)$ eV [23]. Majorana Demonstrator employed the conventional configuration of Ge detectors in a vacuum cryostat and high-Z shielding. The copper used for the detector holder was electroformed and machined in the underground facility of their experimental site. A lower limit of $T_{1/2}^{0\nu}$ at $2.7 \times 10^{25}$ years was found in the Majorana Demonstrator [32].

Recently, researchers involved in both GERDA and Majorana initiated the LEGEND collaboration. LEGEND will combine the strengths of the two groups, the low mass holder and active Ar veto of GERDA and radiopure materials and components of Majorana. LEGEND-200 is to be prepared with 200 kg of $^{76}\text{Ge}$ for a half-life limit sensitivity of $10^{27}$ years. Eventually, a ton-scale detector will be built aiming at reaching a sensitivity of $10^{28}$ years [33].

4.3. Time projection chambers (liquid & gas)

The time projection chamber (TPC) is another technology of choice in $0\nu\beta\beta$ experiments. TPCs, which can be built in liquid and gas phases, have several attractive features that are advantageous detecting $\beta\beta$ events at the Q value. Their scalability and self-shielding effect (e.g., in a liquid Xe TPC) are relevant. TPCs can also provide two detection channels for ionization and scintillation signals allowing particle identification (PID). This two-channel detection provides competitive resolutions for energy, position and topology determinations.

EXO-200, a single-phase liquid Xe TPC was built with an active Xe mass of 110 kg with 80.6% $^{136}\text{Xe}$ enrichment [34]. The ionization and scintillation channels consist of wire grids and avalanche photodiodes, respectively. A total exposure of 234.1 kg-year was completed resulting in limit sensitivities of $T_{1/2}^{0\nu} > 3.5 \times 10^{25}$ year and $m_{\beta\beta} < (0.093–0.286)$ eV [35]. The collaboration now plans to build nEXO, a 5-ton scale liquid Xe TPC reaching limit sensitivities of $9.2 \times 10^{27}$ years and $(0.009–0.018)$ eV with a 10-year run [36].

Gas TPCs represent another promising technology for the $0\nu\beta\beta$ search. A TPC with pressurized Xe gas has shown an extrapolated energy resolution of 0.6% FWHM at $Q_{\beta\beta}$ in the NEXT project [37]. NEXT-100, deployed with 100 kg of $^{136}\text{Xe}$ at 15 bar, will reach projected sensitivities of $9 \times 10^{25}$ years and $(0.07–0.13)$ eV [37].

PandaX-III is another high pressure gas TPC being built using about 100 kg $^{136}\text{Xe}$ for $0\nu\beta\beta$ search [38]. It employs microbulk micromegas modules for the ionization channel. PandaX-III will reach a $T_{1/2}^{0\nu}$ sensitivity of $9 \times 10^{26}$ years in one module experiment of a 3-year run with
possibility for multi-module detection.

4.4. Low-temperature thermal calorimeters

Low-temperature (LT) thermal calorimeters operating at mK temperatures represent one of the promising techniques used in rare-event experiments including $0\nu\beta\beta$ searches. Such an LT detector uses a sensitive thermometer to measure the temperature increase of a crystal absorber caused by an input of energy to the system. Semiconductor thermistors (e.g., NTD Ge sensors), metallic magnetic calorimeters (MMCs), and transition edge sensors (TESs) are those thermometers used in thermal equilibrium detection providing a high energy resolution [39]. Various $\beta\beta$ decay isotopes can be chosen as constitutive elements of absorber crystals for $0\nu\beta\beta$ search. When a scintillating crystal is used as the absorber target, the light channel can be exploited in addition to the heat channel detection, enabling efficient PID.

In a series of advances for searching $0\nu\beta\beta$ using LT detectors for the last 30 years, it is CUORE that is searching for $0\nu\beta\beta$ of $^{130}$Te using 741 kg of TeO$_2$ crystals with NTD Ge thermistors [40]. The detector has an energy resolution of 5 keV FWHM at the $^{130}$Te $Q_{\beta\beta}$. Its $T_{1/2}^{0\nu}$ sensitivity has reached $2.3 \times 10^{25}$ years corresponding to $m_{\beta\beta} < (0.09–0.42) \text{ eV}$ [23].

Using Zn$^{82}$Se scintillating crystals containing enriched $^{82}$Se, CUPID-0 carried out a $^{82}$Se $0\nu\beta\beta$ search using the simultaneous detection method for heat and light signals resulting in a limit sensitivity of $2.4 \times 10^{25}$ years [21]. Similarly, CUPID-Mo exploits Li$_2$MoO$_4$ crystals in the heat and light detection resulting in a sensitivity of $3 \times 10^{24}$ years [42]. Recently, CUPID collaboration has formed a plan to search for $^{100}$Mo $0\nu\beta\beta$ using Li$_2^{100}$MoO$_4$ as the target crystal aiming at limit sensitivities of $T_{1/2}^{0\nu} > 1 \times 10^{27}$ years and $m_{\beta\beta} < \sim 0.02 \text{ eV}$ [43].

AMoRE is another LT detector searching for $0\nu\beta\beta$ of $^{100}$Mo. MMCs are employed as the sensor technology for the heat and light detection with high energy and timing resolutions [44]. A pilot stage of AMoRE with 1.9 kg of 48deplCa$^{100}$MoO$_4$ composed of doubly enriched isotopes was completed resulting in a $T_{1/2}^{0\nu}$ sensitivity of $9.5 \times 10^{22}$ [55]. Presently, AMoRE-I is being prepared with 6 kg of 48deplCa$^{100}$MoO$_4$ and Li$_2^{100}$MoO$_4$. Moreover, AMoRE-II has been fully funded, with plan of building a 200 kg LT detector aiming at limit sensitivities of $T_{1/2}^{0\nu} > 5 \times 10^{26}$ years and $m_{\beta\beta} < (0.017–0.029) \text{ eV}$ [46].

4.5. Other calorimeters

NEMO-3 uses electron tracking calorimeters using thin source foils for many $\beta\beta$ isotopes including 1 kg of $^{82}$Se and 7 kg of $^{100}$Mo [47, 24]. The most stringent $T_{1/2}^{0\nu}$ limits for $^{100}$Mo have been set by NEMO-3 (see Table 1). SuperNEMO is focused on searching for $0\nu\beta\beta$ of $^{82}$Se using the tracking calorimeter method to reach a half-life sensitivity of $10^{26}$ years for the present goal.

CANDELS uses 305 kg of CaF$_2$ scintillating crystals placed in liquid scintillator to search for $0\nu\beta\beta$ of $^{48}$Ca. Recently, CANDELS improved the sensitivity to $6.2 \times 10^{22}$ years for $0\nu\beta\beta$ of $^{48}$Ca [48]. Moreover, the group has started a low temperature experiment with CaF$_2$. A few successful measurements were carried out with CaF$_2$ crystals with MMC readouts for heat and light detection resulting in a clear PID capability [48].

5. Conclusion

Many experiments are using well-established technologies to carry out careful but promising approaches to probe the possibility of double beta decay in the zero-neutrino mode. It will be important to reach a $m_{\beta\beta}$ sensitivity of 20 meV to achieve 90% discovery potential in IO scenario. Doing so will prove or disprove that $m_3$ is the lightest one of the Majorana neutrinos. Moreover, even if the NO case holds true, as suggested by recent results from a few experiments
Table 1: Measured and proposed limits on $T_{1/2}^{0\nu}$ and $m_{\beta\beta}$ from $0\nu\beta\beta$ search experiments using commonly used isotopes, sorted by mass number and chronological order of publication.

| Isotope, Q, NA | $T_{1/2}^{0\nu}$ | $T_{1/2}^{0\nu}$ | $m_{\beta\beta}$ | Experiment | Ref. | Year |
|---------------|-----------------|-----------------|-----------------|------------|-----|------|
| $^{48}$Ca, 4.268, 0.187 | $4.4^{+0.6}_{-0.5}$ | $>0.058$ | $<3.5–22$ | ELEGANT-IV | [49] | 2008 |
| $^{76}$Ge, 2.039, 7.8 | $165^{+14}_{-12}$ | $>90^d$ | $<0.10–0.23^d$ | GERDA-II | [23] | 2019 |
| $^{82}$Se, 2.998, 8.8 | 9.2±0.7 | $>0.36$ | $<0.89–2.43$ | NEMO-3 | [47] | 2011 |
| $^{100}$Mo, 3.034, 9.7 | 0.71±0.04 | $>1.1$ | $<0.33–0.62$ | NEMO-3 | [24] | 2015 |
| $^{130}$Te, 2.528, 34.1 | 69±13 | $>20^d$ | $<0.09–0.42^d$ | CUORE | [25] | 2019 |
| $^{136}$Xe, 2.458, 8.9 | 219±6 | $>107$ | $<0.061–0.165$ | KamL.-Zen400 | [26] | 2017 |

*a* Q values from [54]. *b* Natural abundances [55]. *c* Recommended values from [8]. *d* Limits adapted from the corresponding TAUP presentations, as listed in the Ref. column. *e* Proposed limit-setting sensitivities for ongoing or future experiments. *f* Proposed schedules for data taking, subject to change. *g* Value from [27].

That favor NO at $3\sigma$, this sensitivity will provide a 50% probability of discovering $0\nu\beta\beta$. Several experiments have been either funded or proposed that are expected to cover the sensitivity region near 20 meV in the next decade.

$0\nu\beta\beta$ discovery would be a clear demonstration of Majorana neutrinos and the existence of LNV mechanisms. To clarify the physics mechanism responsible for $0\nu\beta\beta$, many experiments with various isotopes and different detection methods will be required. Research on $g_A$ and NMEs will gain advantages from studies with many isotopes. In this sense, $0\nu\beta\beta$ experiments are not just a neutrino mass experiment but also also provide an avenue of studying neutrino mass to gain a fundamental understanding of particle physics.
Acknowledgments
This work was presented in the plenary session of TAUP 2019. It was supported by Grant No. IBS-R016-G1.

References
[1] Fukuda Y et al. (Super-Kamiokande Collaboration) 1998 Phys. Rev. Lett. 81(8) 1562–1567
[2] Cleveland B T et al. 1998 The Astrophysical Journal 496 505
[3] Ahmad Q R et al. (SNO Collaboration) 2001 Phys. Rev. Lett. 87(7) 071301
[4] Fogli G L et al. 2012 Phys. Rev. D 86(1) 013012
[5] Maki Z et al. 1962 Progress of Theoretical Physics 28 870–880
[6] Avignone F T et al. 2008 Rev. Mod. Phys. 80(2) 481–516
[7] Goeppert-Mayer M 1935 Physical Review 48 512
[8] Barabash A 2015 Nuclear Physics A 935 52–64
[9] Tretjak V I and Zdesenko Y G 2002 Atomic Data and Nuclear Data Tables 80 83–116
[10] Majorana E 1937 Il Nuovo Cimento 14 171
[11] Racah G 1937 Il Nuovo Cimento 14 322
[12] Furry W H 1939 Phys. Rev. C 56(12) 1184–1193
[13] Rodejohann W 2012 Journal of Physics G: Nuclear and Particle Physics 39 124008
[14] Kotila J and Iachello F 2012 Phys. Rev. C 85(3) 034316
[15] Engel J and Menéndez J 2017 Reports on Progress in Physics 80 046301
[16] Suhonen J 2017 Physical Review C 96 055501
[17] Dolinski M J et al. 2019 Annual Review of Nuclear and Particle Science 69 219–251
[18] Furry W H 1939 Phys. Rev. C 56(12) 1184–1193
[19] Drexlin G 2019 Direct neutrino mass measurement Talk presented at TAUP-2019 Toyama, Japan
[20] Agostini M et al. 2017 Phys. Rev. D 96(5) 053001
[21] Wiesinger C 2019 Results and post-upgrade performance of GERDA Phase II Talk at TAUP Toyama, Japan
[22] Arnold R et al. (NEMO-3 Collaboration) 2015 Phys. Rev. D 92(7) 072011
[23] Wolf J et al. 2011 Nucl. Instr. and Meth. A 623 442–444
[24] Gando A et al. (KamLAND-Zen Collaboration) 2016 Phys. Rev. Lett. 117(8) 082503
[25] Shimizu I and Chen M 2019 Frontiers in Physics 7 33
[26] Kaptanoglu T 2019 neutrinoless double beta decay with SNO+ Talk presented at Conference on Science at the Sanford Underground Research Facility 2019, Lead, South Dakota, USA
[27] Auger M et al. (CUORE Collaboration) 2018 Phys. Rev. Lett. 120(13) 132502
[28] Avignone III F T and Elliott S R 2019 The European Physical Journal C 78 388
[29] Agostini M et al. (Gerda Collaboration) 2018 The European Physical Journal C 78 388
[30] Alvis S I et al. (Majorana Collaboration) 2019 Phys. Rev. C 100(2) 025501
[31] Zsigmond A J 2019 LEGEND: The future of neutrinoless double-beta decay search with germanium detectors Talk presented at TAUP-2019 Toyama, Japan
[32] Han K 2019 Neutrinoless Double Beta Decay Searches: Status and Prospects Talk presented at the 8th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology, Shanghai, China
[33] Enss C (ed) 2005 Cryogenic particle detection vol 99 (Springer)
[34] Alfonso K et al. (CUORE Collaboration) 2015 Phys. Rev. Lett. 115(10) 102502
[35] Antons C E et al. (Majorana Collaboration) 2018 Phys. Rev. Lett. 120(13) 132502
[36] Alivizoti O et al. 2018 Phys. Rev. Lett. 120(23) 232502
[37] Schmid B 2019 First data from the CUPID-Mo 0νββ experiment Talk at TAUP Toyama, Japan
[38] Pavan M 2019 CUPID: Cuore Upgrade with Particle ID Talk at TAUP-2019 Toyama, Japan
[39] Kim G B et al. 2017 Astroparticle Physics 91 105 – 112
[40] Alenkov V et al. 2019 The European Physical Journal C 79 791 ISSN 1434-6052
[41] Seo K 2019 The Status of AMoRE 0νββ Experiment Talk at TAUP-2019 Toyama, Japan
[42] Barabash A S et al. 2011 Physics of Atomic Nuclei 74 312–317
[43] Shimizu I and Chen M 2019 Frontiers in Physics 7 33
[44] Han K 2019 Neutrinoless Double Beta Decay Searches: Status and Prospects Talk presented at the 8th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology, Shanghai, China
[45] Enss C (ed) 2005 Cryogenic particle detection vol 99 (Springer)
[46] Alfonso K et al. (CUORE Collaboration) 2015 Phys. Rev. Lett. 115(10) 102502
[47] Antons C E et al. 2018 Phys. Rev. Lett. 120(23) 232502
[48] Schmid B 2019 First data from the CUPID-Mo 0νββ experiment Talk at TAUP Toyama, Japan
[49] Pavan M 2019 CUPID: Cuore Upgrade with Particle ID Talk at TAUP-2019 Toyama, Japan
[50] Kim G B et al. 2017 Astroparticle Physics 91 105 – 112
[51] Alenkov V et al. 2019 The European Physical Journal C 79 791 ISSN 1434-6052
[52] Seo K 2019 The Status of AMoRE 0νββ Experiment Talk at TAUP-2019 Toyama, Japan
[53] Barabash A S et al. 2011 Physics of Atomic Nuclei 74 312–317
[54] Shimizu I and Chen M 2019 Frontiers in Physics 7 33
[55] Han K 2019 Neutrinoless Double Beta Decay Searches: Status and Prospects Talk presented at the 8th Workshop on Flavor Symmetries and Consequences in Accelerators and Cosmology, Shanghai, China
[50] Barabash A S et al. 2017 Nucl. Instr. and Meth. A 868 98–108
[51] Gando Y 2019 First results of KamLAND-Zen 800 Talk presented at TAUP-2019 Toyama, Japan
[52] Saldanha R 2019 Science Goals and Sensitivity of the nEXO Neutrinoless Double Beta Decay Experiment Talk presented at TAUP-2019 Toyama, Japan
[53] Ni K et al. 2019 Chinese Physics C 43 113001
[54] Wang M et al. 2017 Chinese Physics C 41 030003
[55] Meija J et al. 2016 Pure and Applied Chemistry 88 293–306