

Double beta decays and neutrino masses

Hiro Ejiri

JASRI, SPring-8, Mikazuki-cho, Hyogo, 679-5198, Japan
Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
E-mail: ejiri@rcnp.osaka-u.ac.jp

Abstract. Neutrino-less double beta decays($0\nu\beta\beta$) are of great interest for studying the Majorana nature of ν 's and the absolute ν -mass scale. The present report is a brief review of the $0\nu\beta\beta$ studies with emphasis on future experiments with the mass sensitivity of an order of $25 \sim 100$ meV and on experimental probes for investigating $0\nu\beta\beta$ nuclear matrix elements.

1. Neutrino-less double beta decays and neutrino masses

High sensitivity studies of double beta decays ($0\nu\beta\beta$), which violate the lepton-number conservation law by $\Delta L = 2$, are very powerful and realistic for investigating the Majorana ν nature and the absolute ν -mass scale beyond the standard EW model(SM). Recent ν oscillation experiments for solar, atmospheric and reactor ν 's provide evidences for non-zero differences of ν -masses and ν -mixing angles.

In case of $0\nu\beta\beta$ experiments, nuclei are used as micro-laboratories for ν studies to enhance by many orders of magnitudes the ν -exchange process between two neutrons in the nucleus and to get free from huge single- β BG's.

The present review reports briefly Majorana ν -mass studies by $0\nu\beta\beta$ decays in nuclear micro-laboratory. Details of double beta decays are found in recent review articles [1,2,3,4,5] and references therein.

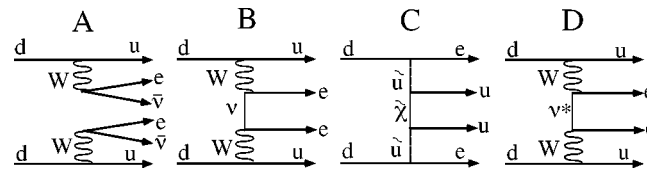


Figure 1. Schematic diagrams of $2\nu\beta\beta$ and $0\nu\beta\beta$ decay processes. A: $2\nu\beta\beta$ decay. B: $0\nu\beta\beta$ decay with the light- ν exchange. C: $0\nu\beta\beta$ with the SUSY particle exchange. D: $0\nu\beta\beta$ decay via heavy- ν exchange [1]

Schematic diagrams of $2\nu\beta\beta$ and $0\nu\beta\beta$ processes are shown in Fig.1. The $0\nu\beta\beta$ beyond SM is caused by the light- ν exchange (Fig. 1B), the SUSY particle exchange (Fig. 1C), the heavy- ν

exchange (Fig. D), and others. In the present report we discuss mainly the $0\nu\beta\beta$ due to the light ν -mass term in Fig. 1B. The $0\nu\beta\beta$ decay rate is given as

$$T^{0\nu} = G^{0\nu} |M^{0\nu}|^2 |< m_\nu >|^2, \quad (1)$$

where $G^{0\nu}$ and $M^{0\nu}$ are the phase-space factor and the nuclear matrix element, and $< m_\nu >$ is the effective Majorana ν -mass. The effective mass is given by

$$< m_\nu > = \sum_i |U_{ei}|^2 m_i e^{i\alpha_i} = C_{12}^2 C_{13}^2 m_1 + C_{13}^2 S_{12}^2 m_2 e^{i\phi_2} + S_{13}^2 m_3 e^{i\phi_3}, \quad (2)$$

where $\phi_2 = \alpha_2 - \alpha_1$ and $\phi_3 = -\alpha_1 - 2\delta$ are the phases for $|m_2 >$ and $|m_3 >$. The ν masses m_1, m_2 and m_3 are rewritten by using the mass-square differences $\delta m_{ij}^2 = m_i^2 - m_j^2$.

Here we consider the three cases of the neutrino mass spectra; the normal mass hierarchy (NH) with $m_1 < m_2 \ll m_3$, the inverted hierarchy (IH) with $m_3 \ll m_1 < m_2$, and the quasi-degenerate (QD) with $m_1 \sim m_2 \sim m_3 \gg \sqrt{\delta m_{ij}^2}$.

The effective masses $< m^{NH} >$ and $< m^{IH} >$ for the NH and IH spectra are evaluated by using the mass-square differences and the mixing parameters, which are obtained from the oscillation experiments. The effective masses are plotted as a function of the lightest mass (m_1 for NH and m_3 for IH) in Fig.2.

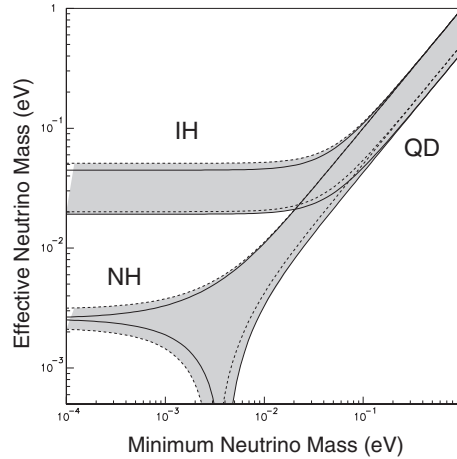


Figure 2. The effective masses $< m^{NH} >$ and $< m^{IH} >$ for the NH and IH spectra as a function of the lightest mass of $m_1(m_3)$. The shaded region reflects the CP phases. The solid and dotted lines refer to the experimental uncertainties of the oscillation parameters [1]

Next generation DBD experiments with high mass-sensitivity of the order of 100 and 20 meV are of great interest to establish $0\nu\beta\beta$ and the ν -mass spectrum in cases of QD and IH, respectively. R&D for future DBD experiments with ultra-high mass sensitivity of the order of 2 meV should be encouraged for future experiments in case of NH. Here nuclear matrix elements are of vital importance for obtaining the effective ν -mass from $0\nu\beta\beta$ experiments.

2. Present status of double beta decay experiments

Nuclei used for $\beta\beta$ experiments are selected by taking into accounts the matrix element, the phase space, the Q value, the isotopic abundance (A) and the feasibility of isotope separation.

So far, $\beta\beta$ experiments have been made mostly on $\beta^-\beta^-$ nuclei with large phase space, as given in the reviews [1,2,3,4,5] and references therein.

Calorimetric experiments with ^{76}Ge detectors and Te bolometers give the stringent upper limits on the $0\nu\beta\beta$ rates. The half-life limit obtained by the IGEX collaboration gives the ν -mass limit of 0.33~1.35 eV, depending on the nuclear matrix elements [6]. CUORICINO with 41 kg TeO_2 gives the 10^{24} y, corresponding to the mass limit of 0.26 ~ 1.4 eV [7].

Spectroscopic experiments with ELEGANT and TPC on ^{100}Mo , ^{82}Se , ^{150}Nd give upper limits of a few eV on the effective ν mass. Recently NEMO III with large tracking chambers gives quite stringent limits of 0.7~2.8 eV and 1.8~4.9 eV for ^{100}Mo and ^{82}Se , respectively [8].

Recently a claim for the $0\nu\beta\beta$ peak in the ^{76}Ge spectrum was made by a part of the HM group [9]. The peak yield gives the effective ν -mass of 0.44 eV. Several groups, however, have raised serious questions on the data analyses and the data handlings. In fact this claim is inconsistent with other HM works. These are described in the review [1].

It is noted that the neutrino masses to be studied by the present detectors are limited by their mass sensitivity of $m_\nu(\text{min}) \sim 0.2 - 1$ eV. Among them CUORICINO and NEMO III are expected to reach the mass sensitivity of 0.2 - 0.5 eV in near future. New generation experiments with higher sensitivity of 100 - 30 meV are crucial for studying the QD and IH ν masses as suggested by ν -oscillation experiments.

3. Perspectives of $\beta\beta$ experiments

Experimental proposals for future $\beta\beta$ experiments with QD and IH ν -mass sensitivities have been made on several $\beta\beta$ isotopes, as listed in Table I.

Table 1. Isotopes and detectors used for future $\beta\beta$ experiments [1]. A : the isotope abundance ratio. $Q_{\beta\beta}$: Q value in unit of MeV. S_N : nuclear sensitivity in unit of $10^{-24} \text{ y}^{-1} (\text{eV})^{-2}$

Isotope	A %	$Q_{\beta\beta}$ MeV	$S_N 10^{-24} \text{ y}^{-1} (\text{eV})^{-2}$	Experiment/collaboration
^{48}Ca	0.187	4.276	0.11	CANDLES
^{76}Ge	7.8	2.039	0.22	MAJORANA GENIUS GERDA
^{82}Se	9.2	2.992	0.86	Super-NEMO
^{100}Mo	9.6	3.034	2.02	MOON
^{116}Cd	7.5	2.804	0.90	COBRA CAMEO
^{130}Te	34.5	2.528	0.73	CUORE, COBRA
^{136}Xe	8.9	2.467	0.13	EXO, XMASS
^{150}Nd	5.6	3.368	11.3	DCBA

CANDLES for ^{48}Ca $\beta\beta$ decays. CANDLES(CALcium fluoride for studies of Neutrinos and Dark matter by Low Energy Spectrometers) is an array of CaF_2 crystals to study $\beta\beta$ decays of ^{48}Ca and dark matter [10]. It is based on the ELEGANT VI experiment with CaF_2 crystals surrounded by CsI active shields. The $Q_{\beta\beta}$ is large, but the natural abundance of ^{48}Ca is only 0.2 %. CANDLES aims at studying the QD ν -mass region with 3.2 ton CaF_2 crystals immersed in liquid scintillator.

MAJORANA for ^{76}Ge $\beta\beta$ decays. MAJORANA aims at high-sensitivity studies of ^{76}Ge $\beta\beta$ decays by means of a high purity ^{76}Ge detector array, being based on the IGEX [11]. The detector consists of Ge detectors with a total mass of an order of $M \approx 100$ kg of isotopically enriched ^{76}Ge . Pulse shape discrimination (PSD) and segmentation of detector (SED) are powerful to reduce various kinds of BG's. It aims at the sensitivity around $T_{1/2} = 4 \cdot 10^{26}$ y, which corresponds to a mass sensitivity of 100 meV, depending on the matrix element.

It should be noted that the BG contribution from ^{68}Ga can be reduced by SSTC (Signal Selection by Time Correlation), i.e. anti-coincidence with the preceding X rays in the time interval of $\Delta T \approx 5$ hours.

GENIUS and GERDA ^{76}Ge $\beta\beta$ decays. GENIUS has proposed an array of enriched Ge detectors surrounded by a huge liquid- N_2 to avoid BG's from RI impurities in copper, while GERDA uses liquid-Ar active shields around the Ge detector array to reduce BG contributions from internal and external RI impurities [12]. Currently GERDA is under progress to check the QD mass region

NEMO III and Super-NEMO. The sensitivity of NEMO III will be improved by eliminating the Rn BG contribution. The expected sensitivity for 5 y run is $4 \cdot 10^{24}$ y for ^{100}Mo and $8 \cdot 10^{23}$ y for ^{82}Se , corresponding to the effective masses of $0.2 \sim 0.35$ eV and $0.65 \sim 1.8$ eV [8]. Super-NEMO is a large scale detector array, which consists of many NEMO-type detectors.

CUORICINO and CUORE for ^{130}Te $\beta\beta$ decays. CUORE (Cryogenic Underground Observatory for Rare Events) [7] is a calorimetric cryogenic bolometer detector to measure the $0\nu\beta\beta$ of ^{130}Te . CUORICINO, which is a prototype for CUORE, is now running with 64 TeO_2 crystals (the total mass of 41 kg).

CUORE is a scale-up of CUOREICINO. It consists of 988 TeO_2 crystals with the total mass of 600kg. Then CUORE aims at the mass sensitivity of $(24-130) \sim (16-90)$ meV by reduced BG rates of 0.01 - 0.001/kev y [7].

EXO for ^{136}Xe $\beta\beta$ decays. EXO (Enriched Xenon Observatory) is a $\beta\beta$ experiment of ^{136}Xe with $Q = 2.467$ MeV [13]. The unique feature of EXO is to identify the decay product of ^{136}Ba by means of a laser spectroscopy technique. The 1 ton enriched Xe detector with a energy resolution of $\sigma = 2.8\%$ gives a sensitivity of $T_{1/2} \approx 8.3 \cdot 10^{26}$ y for a 5 y run. The 10 ton Xe with th improved energy resolution of $\sigma = 2\%$ will give the sensitivity of $1.3 \cdot 10^{28}$ y. The ν -mass sensitivities are $51 \sim 150$ meV and $13 \sim 37$ meV for the 1 and 10 ton detectors, respectively [13]

DCBA for ^{150}Nd $\beta\beta$ decays. DCBA (Drift Chamber Beta-ray Analyzer) uses a tracking chamber in a magnetic field to study the ^{150}Nd $\beta\beta$ decays [14]. The β energy is obtained by the β ray trajectory analysis. The energy resolution is crucial to reduce the BG contribution from the $2\nu\beta\beta$. DCBA plans to build 40 modules, each consisting of 1.8 m^3 drift chamber with 15 kg source. The goal is to achieve the half-life sensitivities of 10^{25} and 10^{26} y with natural and enriched ^{150}Nd sources, respectively.

MOON for ^{100}Mo and other $\beta\beta$ decays. MOON (Molybdenum Observatory Of Neutrinos), which is an extension of ELEGANT V [15], aims at spectroscopic $0\nu\beta\beta$ studies with a sensitivity of around 30 meV for ^{100}Mo , and others (^{82}Se , ^{150}Nd) [16]. It is used also for realtime studies of ^7Be solar ν 's as well.

The MOON detector consists of multi-layer detector modules [16]. Each module is composed by a plastic scintillator (PL) plate with PMT's around the 4-sides of PL, two position-sensitive detector planes and a thin $\beta\beta$ source film interleaved between the two planes. The vertex point is identified by the position sensitive detector planes, while the two β -rays are measured in coincidence by two adjacent PL plates. All other modules (layers) are used as active shields to reject background events.

Individual β rays emitted opposite to each other are measured in coincidence by the two adjacent PL plates to confirm the ν -mass term in the $0\nu\beta\beta$. The multi-module structure makes it realistic to build a compact detector to accommodate ton-scale $\beta\beta$ isotopes. Since the $\beta\beta$

source is not integrated into the $\beta\beta$ detector, one can select the best one or two $\beta\beta$ nuclides in view of the nuclear matrix element, the phase space, the signal energy, and the $2\nu\beta\beta$ rate.

A prototype MOON-1 detector consists of 6-layer PL scintillator plates, each with $53 \times 53 \times 1 \text{ cm}^3$. ^{100}Mo films are interleaved between the PL plates in the MOON-1 detector. The energy resolution is given by $\sigma_{PL} = \sigma E^{-1/2}$ with $\sigma = 5.0 \pm 0.2\%$, which leads to $\sigma = 2.9 \pm 0.1\%$ at the ^{100}Mo $Q = (3.034 \text{ MeV})$ [16]. This is just what is required for the mass sensitivity of 30 meV.

4. Nuclear responses for $\beta\beta$ decays by nuclear-, γ - and ν -probes

Extensive calculations have been made on $\beta\beta$ matrix elements by using shell models and QRPA methods, as given in reviews and references therein [1,2,4]. Theoretical calculations of $M^{0\nu}$ are sensitive to the nuclear interactions to be used. In this section we discuss experimental studies of $M^{0\nu}$ and nuclear spin isospin responses relevant to $\beta\beta$ decays. In fact, $M^{0\nu}$ are expressed in terms of the successive single- β processes through intermediate states.

Single β matrix elements are given by spin isospin responses of $Q_{TSLJ} = \tau^T [i^L r^L Y_L \times \sigma^S]$. Note that $2\nu\beta\beta$ involves mainly the angular momentum $L=0$, while $0\nu\beta\beta$ does $L=0,1,2,3,\dots$ up to $L \sim 6$. They are studied experimentally by using nuclear-, γ -, and ν -probes.

4.1. Charge-exchange nuclear reactions with nuclear probes

Nuclear charge-exchange reactions with nuclear probes are used to study nuclear spin isospin responses relevant to β and $\beta\beta$ decays [1]. Extensive studies of charge-exchange reactions are carried out by means of (p,n) (n,p), (d, ^2He), (^3He , t) (t, ^3He), (^7Li , ^7Be), and others. Medium energy projectiles with $E_i = 0.1 \sim 0.3 \text{ GeV}$ are used for studying $\tau\sigma$ responses because of the relatively large spin-isospin interaction ($V_{\tau\sigma}$) and the small distortion interaction (V_0) at the medium energy.

The cross-section with the transferred momentum (q) and energy (ω) is given as

$$\sigma_\alpha(q, \omega) = K(E_i, \omega) \exp(-\frac{1}{3}q^2 < r^2 >) N_\alpha^D |J_\alpha|^2 B(\alpha), \quad (3)$$

where $K(E_i, \omega)$, N_α^D , J_α , and $B(\alpha)$ are the kinematical factor, the nuclear distortion factor, the volume integral of the spin-isospin interaction, and the nuclear spin isospin response, respectively. α denotes the isospin and spin channel, $\alpha=\text{F}$ for isospin Fermi and $\alpha=\text{GT}$ for spin-isospin GT.

Charge-exchange ($^3\text{He}, \text{t}$) reactions relevant to the $\beta\beta$ decays of ^{100}Mo have been studied at RCNP [1]. Charge exchange reactions of ($^3\text{He}, \text{t}$) and (t, ^3He) at finite angles are interesting to study 2^- and higher-multipole strengths relevant to $0\nu\beta\beta$ decays.

4.2. γ -probes

Medium energy γ -rays produced by inverse Compton scattering of laser photons off GeV electrons are realistic probes for studying nuclear spin isospin responses. Then β decay matrix elements can be studied by using photo-nuclear reactions through isobaric analogue states (IAS). The β and γ matrix elements are related to the β matrix element as [17]

$$< f | g_\nu m^\beta | i > = \frac{g_\nu}{e} < f | [e m^\gamma, T_-] | i > \approx \frac{g_\nu}{e} (2T_0)^{1/2} < f | m^\gamma | \text{IAS} >, \quad (4)$$

where $|\text{IAS} > = (2T_0)^{-1/2} T_- | i >$, and m^β and m^γ are analogous β and γ transition operators. Thus one can obtain the β matrix element for $|i > \rightarrow |f >$ by observing the analogous γ absorption $|f > \rightarrow |\text{IAS} >$ through the IAS of $|i >$, where $|f >$ and $|i >$ are the final state and the intermediate state in the $\beta\beta$ decay. It is noted that these photo-nuclear reactions through IAS are used to get the β matrix elements to excited states in the intermediate nucleus.

In medium heavy nuclei, IAS is located on the E1 giant resonance (GR). Accordingly IAS shows up as a sharp isobaric analogue resonance (IAR) [17]. Then one can get the phase of the matrix element from the interference pattern of the IAR and GR. The polarization of the incident γ -rays can be used to study E1 and M1 matrix elements separately.

HI γ S (High Intensity γ -ray Source) provides intense γ rays with $E_\gamma = 2\text{--}70$ MeV, $\Delta E_\gamma/E_\gamma \approx 1\%$, and $\Phi \approx 10^7/\text{MeV}/\text{s}$. They are obtained by intra-cavity Compton backscattering of FEL photons off 1.2 GeV electrons at Duke Strage Ring. The photon intensity will increase by 2 orders of magnitude in future. The laser-backscattered γ source at New SUBARU in the SPring-8 campus provides γ rays with $E_\gamma = 17\text{--}40$ MeV, $\Delta E_\gamma/E_\gamma \approx 2\%$, and $\Phi \approx 10^6/\text{s}$.

4.3. Neutrino probes

One direct way to get weak responses relevant to $0\nu\beta\beta$ decays is to use ν beams [18,19]. Since ν nuclear cross-sections are as small as $\sigma = 10^{-40\sim 42} \text{ cm}^2$, one needs high flux ν -beams and large detectors. Low energy ν -beams with $E \leq 100$ MeV are obtained from weak decays of pions produced by nuclear interaction with GeV protons as

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow \nu_e + \bar{\nu}_\mu + e^+, \quad (5)$$

where ν_μ and $\nu_e, \bar{\nu}_\mu$ are well separated by the decay time.

Intense 1 GeV protons with 6×10^{15} per sec are obtained from SNS at ORNL, and ν 's with intensity of 9×10^{14} per sec can be obtained. NUSNS for various kinds of particle and astrophysics with the intense ν 's is under progress [19]. The J-PARC booster synchrotron provides higher energy 3 GeV protons with 1.2×10^{15} per sec. The ν 's with 3×10^{14} per sec are possible [18].

- [1] Ejiri H, 2000 *Phys. Rep. C* **338** 265; Ejiri H 2005 *J. Phys. Soc. Japan* **74** 2101
- [2] Vergados D, 2002 *Phys. Rep.* **361** 1
- [3] Elliott S and Vogel P, 2002 *Annu. Rev. Nucl. Par. Sci.* **52** (2002) 115
- [4] Suhonen J.D. and Civitarese O. 1998 *Phys. Rep.* **300** 123
- [5] Avignone F, 2005 *Nucl. Phys. Proc. Suppl. Neutrino 2004 B* **143** 233
- [6] Aalseth C.E et al. 1999 *Phys. Rev. C* **59** 2108; **D 65** 092007
- [7] Arnaboldi C et al. CUORICINO coll. 2004 *Phys. Lett. B* **584** 260;
Fiorini E. CUORICINO CUORE coll. 2005 *Nucl. Phys. Proc. Suppl. B* **143** 225
- [8] Sarazin X et al. 2004 *Proc. neutrino conference ν 2004*
Arnord D et al. 2005 *Phys. rev. Lett.* **95** 182502
- [9] Klapdor Kleingrothaus H. V et al. 2002 *Mod. Phys. Lett. A* **16** 2409; 2004 *Phys. Lett B* **586** 198
- [10] Umehara S et al. 2003 *Proc. NDM03* eds. Ejiri H and Ogawa I,
<http://ndm03.phys.sci.osaka-u.ac.jp/proc/index.htm>
- [11] Avignone F et al. 2003 *Proc. Dubna 03*; 2002 hep-exp/0201038; Aalseth C.E. 2004 *Yad. Fiz.* **67** No. 11
- [12] Scheonert S 2005 Private communication; Klapdor-Kleingrothaus H.V. 2001 hep-ph/0103074
- [13] Danilov M et al. 2000 *Phys. Lett. B* **480** 12; Akimov D et al. *Proc. NDM03, eds. H. Ejiri and I. Ogawa*,
<http://ndm03.phys.sci.osaka-u.ac.jp/proc/index.htm>.; Conti E et al. 2003 *Phys. Rev. B* **68** 054201.
- [14] Ishihara N et al. 2001 *Nucl. Instr. Meth. A* **443** 101
- [15] Ejiri H, et al. 1991 *Phys. Lett. B* **258** 17; *NIM* **302** 304
- [16] Ejiri H, et al. 2000 *Phys. Rev. Lett.* **85** 2917; Ejiri H 2006 *Prog. Part. Nucl. Physics* **57** 153
Doe P, et al. 2003 *Nuclear Physics A* **721** 517c
Ejiri H, et al., 2004 *Czechoslovak Journal of Physics B* **54** 317
Nomachi M, et al, 2005 *Nucl. Phys. Proc. Suppl. B* **143** 507
Nakamura H et al. 2005 *Proc. TAUP2005, Zaragoza, Spain* <http://ezpc00.unizar.es/taup2005/> ; Nakamura H 2006 *Dr.thesis, Osaka Univ.*
- [17] Ejiri H, et al. 1968 *Phys. Rev. Lett.* **21** 373; *Nucl. Phys.* **128** 388; *Phys. Lett.* **28B** 304
- [18] Ejiri H 2003 *Nucl. Instr. Meth. Phys. Research* **503** 276
- [19] Hungerford Ed 2005 *Proc. NNR05, SPring-8* ed. Ejiri H,
<http://www.spring8.or.jp/ext/en/appeal/nnr05>