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The MOON project and DBD matrix elements

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Abstract. This is a brief report on experimental studies of double beta decays (DBD) in Japan, the MOON project for spectroscopic studies of neutrino-less DBD ($0\nu\beta\beta$) and on experimental studies of DBD nuclear matrix elements. Experimental DBD studies in Japan were made by geochemical methods on ¹³⁰Te,¹²⁸Te and ⁹⁶Zr and by a series of ELEGANT(EL) counting methods, EL III on ⁷⁶Ge, EL IV, V on ¹⁰⁰Mo, ¹¹⁶Cd, and EL VI on ⁴⁸Ca. Future counter experiments are MOON, CANDLES, XMASS and DCBA. The MOON project, which is based on EL V, aims at studies of the Majorana nature of the neutrino (ν) and the ν -mass spectrum by spectroscopic $0\nu\beta\beta$ experiments with the ν -mass sensitivity of $< m_{\nu}^{m} >=$ 100–30 meV. The MOON detector is a super ensemble of multi-layer modules, each being composed by PL scintillator plates and position-sensitive detector planes. DBD nuclear matrix elements have been studied experimentally by using charge exchange reactions. The 2-neutrino DBD matrix elements are expressed by successive single- β matrix elements through low-lying intermediate states.

1. Introduction

Double beta decay (DBD) have been studied experimentally by indirect geochemical methods and direct counting methods. Geochemical experiments are integral measurements of both 2-neutrino double beta decay $(2\nu\beta\beta)$ and neutrino-less double beta decays $(0\nu\beta\beta)$. In fact $2\nu\beta\beta$ rates are in most cases much larger than $0\nu\beta\beta$ rates, and thus observed rates by geochemical methods are $2\nu\beta\beta$ rates. On the other hand direct counting experiments are exclusive measurements for individual $2\nu\beta\beta$ and $0\nu\beta\beta$ rates.

The $0\nu\beta\beta$ is a sensitive and realistic probe for studying the Majorana nature of the neutrino (ν) , the lepton number non-conservation, the ν -mass spectrum and the absolute mass scale. They are discussed in recent review articles and references therein [1, 2, 3, 4, 5, 6].

Nuclear matrix elements for $2\nu\beta\beta$ and $0\nu\beta\beta$ are very interesting, as discussed in review articles and references therein [7, 8]. Experimental $2\nu\beta\beta$ rates give $2\nu\beta\beta$ matrix elements, which are used to evaluate $0\nu\beta\beta$ matrix elements, while $0\nu\beta\beta$ matrix elements are crucial for extracting neutrino properties from $0\nu\beta\beta$ rates.

The present paper reports briefly (1) geochemical and counter DBD experiments in Japan, (2) the outline of the MOON (Majorana/Mo Observatory Of Neutrinos) project for spectroscopic $0\nu\beta\beta$ experiment, and (3) experimental studies of DBD nuclear matrix elements.

DBD experiments in Japan were carried out by the geochemical methods for ¹³⁰Te, ¹²⁸Te, and ⁹⁶Zr since the 1960's [9, 10, 11], and also by direct counter experiments with a series of

ELEGANT(ELEctron GAmma rays and Neutrino Telescope EL) detectors since the 1980's. They are EL III on ⁷⁶Ge [12, 13, 14], EL IV, V on ¹⁰⁰Mo, ¹¹⁶Cd [15, 16, 17, 18, 19, 20, 21] and EL VI on ⁴⁸Ca [22]. Meanwhile, DBD theories have been developed by the theory group in Japan [23]. The counter experiments have been extended to MOON [24, 25, 26, 27] and CANDLES [28] in Osaka. XMASS and DCBA are future DBD plans at ICRR and KEK [29, 30].

The MOON project is based on the ELEGANT V experiments with $\beta\beta$ sources \neq detectors [24, 25, 26]. The MOON detector sensitivity is enlarged by orders of magnitudes in order to study the ν -mass in the QD-IH mass region and to observe the low-energy solar- ν as well. MOON is a project for spectroscopic studies of $\beta\beta$ rays from ¹⁰⁰Mo, ⁸²Se and other $\beta\beta$ isotopes.

Nuclear matrix elements are very sensitive to nuclear spin-isospin correlations and nuclear structures, and thus theoretical evaluations of them are hard [7, 8]. Experimentally, properties of intermediate states are studied by charge exchange reactions, and are used to evaluate nuclear matrix elements [8, 25, 31, 32]. In fact, $2\nu\beta\beta$ matrix elements are well expressed by using experimental single- β matrix elements through low-lying intermediate states [1, 8, 33, 34].

This report is based partly on the recent reviews on MOON and DBD experiments [26, 27].

2. DBD experiments in Japan

DBD geochemical experiments in Japan were carried out first in the 1960's by Takaoka and Ogata at Osaka Univ. [9]. They measured the integrated half-life of ¹³⁰Te. The obtained value of $T_{1/2} = 8.2 \pm 0.6 \ 10^{20}$ y agrees with later measurements. In the 1990's, Takaoka et al. and Kawashima et al. measured by geochemical methods integrated half-lives for ¹²⁸Te and ⁹⁶Zr [10, 11].

Direct counting experiments were made first by the DBD pioneer, Prof. E. Fiorini and his collaborator in the early 1970's [35]. They studied ⁷⁶Ge $\beta\beta$ decays by using Ge detectors.

Counter experiments in Japan were started in the early 1980's by the Ejiri's group at Osaka, Extensive experiments on $0\nu\beta\beta$ and $2\nu\beta\beta$ were performed by a series of ELEGANT (EL) detectors. EL III, which was a high-purity Ge detector surrounded by NaI detectors, was used to study the ground and excited state $0\nu\beta\beta$ decays from ⁷⁶Ge [12, 13, 14]. Meanwhile, the ambitious experiment IGEX with enriched ⁷⁶Ge detector was proposed by Prof. F. Avignone and his collaborator, which gave a very stringent limit on the $0\nu\beta\beta$ halflife [36].

EL IV was composed of multilayer Si disks and ¹⁰⁰Mo foils, with NaI active shields, and was used to study $2\nu\beta\beta$ from ¹⁰⁰Mo.

EL V is a detector complex of drift chambers for 2 β ray tracking, PL plates for β ray energies and times, and NaI detector arrays for γ and X-rays [16]. It started operation in 1989, and gave the first results of the $2\nu\beta\beta$ decays from ¹⁰⁰Mo and ¹¹⁶Cd [15, 19], and most stringent limits on $0\nu\beta\beta$ decays from them [20, 21].

EL VI, which consists of CaF detectors surrounded by CsI detectors, is for studying the $0\nu\beta\beta$ from ⁴⁸Ca. It gave the most stringent limits on $0\nu\beta\beta$ from ⁴⁸Ca [22].

It is noted that the neutrino masses to be studied using the present detectors are limited by their mass sensitivity of 0.2-1 eV. Among them, CUORICINO [37] and NEMO III [38] are expected to reach the mass region of 0.2-0.5 eV in the near future.

Experimental proposals for future $\beta\beta$ experiments with the QD-IH mass sensitivity have been made on $\beta^{-}\beta^{-}$ isotopes. Some of the future experiments in Japan are as given below.

NOON is a spectroscopic experiment with multi-layer scintillation plates and tracking detector planes [24, 25, 26]. It is based on the ELEGANT V [15, 16]. It aims at studies of QD-IH mass region. Details are given in section 3.

CANDLES (CAlcium fluoride for studies of Neutrinos and Dark matter by Low Energy Spectrometer) is an array of CaF₂ crystals in liquid scintillator to study $\beta\beta$ decays of ⁴⁸Ca and dark matter [28]. It is based on ELEGANT VI with CsI active shields [22]. Water buffers are

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used as passive shields. It is noted that the natural abundance of the 48 Ca isotope is only $0.2\,\%$ and the enrichment process is very difficult.

XMASS uses a large liquid Xe scintillator to study 136 Xe double beta decays and search for DM [29]. A prototype detector is now under progress. A one year run with 10 kg will cover the 0.1 - 0.2 eV QD region.

DCBA (Drift Chamber Beta-ray Analyzer) uses a tracking chamber to study ¹⁵⁰Nd $\beta\beta$ decays [30]. Tests are under progress by using DCBA-T2 and DCBA-T3. The energy resolution is crucial to reduce the background (BG) contribution from $2\nu\beta\beta$. The half-life sensitivities are 10^{25} y and 10^{26} y with natural and enriched ¹⁵⁰Nd sources, respectively.

3. MOON for high-sensitivity $0\nu\beta\beta$ spectroscopy

MOON is a $\beta\beta$ spectroscopic experiment to study the Majorana ν -mass in the QD–IH mass region of 100–30 meV, which corresponds to the half-life of 10^{26-27} y for ⁸²Se and ¹⁰⁰Mo [24, 25, 26]. The MOON-type spectroscopic experiment has several unique features.

i. MOON uses external $\beta\beta$ sources, which are separated from $\beta\beta$ detectors. Thus the $\beta\beta$ nuclides are selected in views of the large signal rate (i.e. the large phase space volume, the large nuclear matrix element, and the large number of the $\beta\beta$ isotopes) and the small BG rate (i.e. the large $Q_{\beta\beta}$ value and the small $2\nu\beta\beta$ rate). ⁸²Se, ¹⁰⁰Mo and ¹⁵⁰Nd are possible candidates.

ii. The $\beta\beta$ event can be confirmed by measuring at least two $\beta\beta$ isotopes with different nuclear matrix elements and different $0\nu\beta\beta$ peak energies. Energy and angular correlations for two β -rays are measured. The $0\nu\beta\beta$ decays to both the ground and excited 0^+ states are also measured. These measurements are important for identifying the ν -mass process among other processes (right-handed week currents, heavy ν , SUSY and others).

iii. Using $0\nu\beta\beta$ isotopes with large $Q_{\beta\beta} \approx 3$ MeV, the signal can be placed well above most RI $\beta - \gamma$ rays to avoid the RI BGs. Two β -ray spectroscopy by tracking detectors make it possible to get required S/N (signal to BG) ratios.

iv. Major BGs from the high energy tail of the $2\nu\beta\beta$ spectrum in the $0\nu\beta\beta$ window can be reduced to the level required for the mass sensitivity by using detectors with realistic energy resolution of around $\sigma = 2.0\%$.

v. The multi-layer structure of detector modules makes the detector quite compact. It is possible to expand a small-scale detector for the QD mass study to a large-scale one for the IH mass study by increasing the number of modules. Actually MOON is an extension of the ELEGANT experiments with two detector layers [16]. Accordingly the basic concept and detector components have been well proved.

3.1. MOON and Majorana neutrino mass

The light Majorana ν -mass sensitivity of the $0\nu\beta\beta$ experiment is given by the minimum effective ν -mass to be observed. It is given as

$$\langle m_{\nu}^{m} \rangle = (S_{N})^{-1/2} (N_{\beta\beta})^{-1/2} \delta^{1/2},$$
(1)

where $N_{\beta\beta}$ is the effective number of $\beta\beta$ isotopes and δ is the number of $0\nu\beta\beta$ signals required for the 90% CL. Using practical units, $S_N = 6 \cdot 10^{15} G^{0\nu} |M^{0\nu}|^2 (A)^{-1} m_e^{-2}$ with the phase space volume of $G^{0\nu}$ in units of $10^{-14} y^{-1}$ and the mass number A. $N_{\beta\beta} = \epsilon^{0\nu} N T$ with $\epsilon^{0\nu}$: the signal efficiency, N: the weight of $\beta\beta$ isotopes in units of ton, T: the run live-time in units of year. δ is given as $\delta \approx 1.6 + 1.7 (BT)^{1/2}$ with B being the BG rate per ton per year.

The nuclear matrix element $M^{0\nu}$ is crucial for the mass sensitivity as discussed in reviews [1, 5, 7, 8] and references [39, 40, 41]. It is found that nuclear matrix elements by recent QRPA calculations [40, 41] are approximately expressed as $M^{0\nu} \approx 18A^{-1/3}$. By using this approximate value, one gets the nuclear sensitivity coefficient in equ. (1) as $(S_N)^{-1/2} \approx 10 \text{ meV}$ for ⁸²Se and ¹⁰⁰Mo. The sensitivity coefficient for the excited 0⁺ state in ¹⁰⁰Mo is around 20 meV.

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The MOON detector with $N \approx 0.1, B \approx 4, \epsilon^{0\nu} \approx 0.25$ is required to get the QD mass sensitivity of around 100 meV in the T = 2 year run, and that with $N \approx 0.5, B \approx 1.5, \epsilon^{0\nu} \approx 0.25$ for the IH mass sensitivity of around 30 meV in the T = 4 year run.

3.2. MOON detector

The MOON detector is a high-sensitivity hybrid detector ensemble to measure individual $\beta\beta$ ray energies, their emission points and their angles as well as γ rays [24, 25, 26]. The MOON detector consists of multi-layer detector modules, as shown in Fig. 1. One unit of the detector consists of 17 modules. Each module is composed by 3 kinds of detector layers and the source films.

i. Six plastic scintillator plates (PL) for $\beta\beta$ energy and time. Scintillation photons are collected by photo-multiplier tubes (PMT) around the plastic-scintillator plate.

ii. Five sets of up and down thin position-sensitive detector (PL-fiber or Si-strip) planes for $\beta\beta$ vertex position and the emission angle. Each set of the position-sensitive detector planes is inserted between the PL plates.

iii. One thick NaI detector array for X and γ rays.

iv. Five thin $\beta\beta$ source films are interleaved between the position-sensitive detector planes.

Two β -rays from a $\beta\beta$ source film are measured in coincidence by up and down positionsensitive detector planes and up and down PL plates. All other position detector planes and PL plates in the module are used as active shields to reject BG γ rays and BG neutrons. The thick NaI plate is for measuring γ rays following $\beta\beta$ decays to the 0⁺ excited states. All other modules are used as active shields.

Each PL plate is around $1.25 \text{ m} \times 1.25 \text{ m} \times 0.015 \text{ m}$ and each PL/Si-detector plane is around $0.9 \text{ m} \times 0.9 \text{ m} \times 0.3 \text{ mm}$, while each source film is around $0.85 \text{ m} \times 0.85 \text{ m}$ with 0.05 gr/cm^2 . The total $\beta\beta$ source is 0.36 kg per film, 1.8 kg per module and 30 kg per unit of the detector.



Figure 1. MOON detector. One unit with 17 modules, and 1 module with 6 PL plates and 5 sets of up and down position-sensitive detector planes.

The energy resolution is crucial for reducing the BG contribution from the high energy tail of the $2\nu\beta\beta$ spectrum into the $0\nu\beta\beta$ window. So far $\sigma \approx 2.1$ % is achieved at 3 MeV ($Q_{\beta\beta}$ value of ¹⁰⁰Mo) for a small PL plate with 6 cm × 6 cm × 1 cm. Good resolution is expected also for larger PL plates by correcting for the position dependence of the light collection in PL plates. This resolution is just what is required to reduce the $2\nu\beta\beta$ BG contribution and to achieve the

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IH mass sensitivity of the order of 50–30 meV. Improvement of the resolution to $\sigma \approx 1.7\%$ is under progress for the higher sensitivity experiment by using better PL plates and PMTs.

The position-sensitive detector planes are used for identifying the $\beta\beta$ vertex point within 10-20 mm², and also for particle identification, i.e. selection of β rays and rejection of γ and α rays. Two options of the position-sensitive detector planes are under consideration, one is a PL fiber plane and the other is a Si-strip plane.

The $\beta\beta$ source film is interleaved between the X-type and Y-type detector planes, each with $90 \text{ cm} \times 90 \text{ cm} \times 300 \,\mu\text{m}$. The PL scintillator fibers with $300 \,\mu\text{m}$ square cross section are stretched to X direction in case of the X-type plane and to Y direction in case of the Y-type plane. Photons from the fibers are collected by multi-anode photomultipliers.

The overall E-resolution of the PL plate and the fiber plane is expected to be $\sigma \approx 2.3\%$. This is good enough to achieve the ν - mass sensitivity to study the ν -mass in the QD and IH mass regions. In case of the Si-strip detector plane, one expects a similar resolution.

The multi-layer module structure with good energy and position resolutions is very powerful for selecting $0\nu\beta\beta$ signals and for rejecting RI-background signals. This makes it realistic to build a compact detector of the order of 0.4 m^3 per kg $\beta\beta$ isotopes. The detector is smaller in volume than the SuperNEMO by orders of magnitude [42].

The enriched ⁸²Se and/or ¹⁰⁰Mo isotopes are used for the $\beta\beta$ source. Enrichment to 85% of each isotope is made by using the centrifugal separation. The ¹⁰⁰Mo isotope separation is made by the centrifugal separation of MoF₆ gas. Using 6000 centrifuges and 40 separation steps, ¹⁰⁰Mo isotopes are obtained with a rate of 350 gr per day, and a half ton in 5 years.

Isotope separation and purification of ⁸²Se and ¹⁰⁰Mo isotopes are done as in NEMO III [38]. The purity of the enriched isotopes is required to be around 300–100 mBq per ton or less for U and Th radioactive isotopes in order to achieve the QD-IH mass sensitivity.

3.3. Selection of DBD signals and the Majorana mass sensitivity

The $0\nu\beta\beta$ signal is identified by observing two β rays by a set of the up and down positionsensitive ΔE -detector planes and PL E-detector plates, each at the same point within 0.1-0.2 cm². All PL detector plates and position-sensitive detector planes other than the relevant set of the up and down detector plates and detector planes are used as active shields. No pre- and post-decay signals before and/or after the signal are observed at the same position of the detector set.

The energy spectra around the $0\nu\beta\beta$ peak region are evaluated by Monte Carlo simulations [43], as shown in Fig. 2 for ⁸²Se and ¹⁰⁰Mo with 50 mg/cm. Counting rates equivalent to 0.6 t y run with the signal condition mentioned above are shown, while the simulation was made for 10^6 events to get good statistics. The $0\nu\beta\beta$ efficiency is obtained as $\epsilon^{0\nu} \approx 0.25$.

The low energy tail of the $0\nu\beta\beta$ spectrum reflects the dependence of the energy loss on the emission angle. Thus the $0\nu\beta\beta$ signal efficiency decreases as the source thickness increases.

It is very important to note that the high energy slope of the $2\nu\beta\beta$ spectrum for the 50 mg/cm² is same as that for the 10 mg/cm^2 . Thus the contribution of the $2\nu\beta\beta$ tail into the $0\nu\beta\beta$ window is mainly due to the energy resolution and the source thickness effect is not appreciable.

Natural RI BGs at the $0\nu\beta\beta$ E-window are mainly from ²⁰⁸Tl and ²¹⁴Bi isotopes with $Q_{\beta} > Q_{\beta\beta} \approx 3$ MeV. BGs rate from ²⁰⁸Tl and ²¹⁴Bi impurities in the Mo source films were evaluated by Monte Carlo simulations [43].

There are various kinds of backgrounds from cosmic ray origins even at underground laboratories. Charged muons are rejected by passive shields and multi-layer PL plates and PL-fiber/Si-strip planes. The cosmic muon BG is less than 1/t y.

Cosmic neutrons, which are produced by cosmic- μ capture reactions around the detector, are major BG sources. Energetic γ rays with E > 3 MeV, which follow inelastic scatterings of neutrons and neutron capture reactions, are potential BG sources at the $0\nu\beta\beta$ window. They are evaluated by Monte Carlo simulations [43]. Actually, the neutrons are also rejected by the active

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Figure 2. Sum energy spectra of $0\nu\beta\beta$ and $2\nu\beta\beta$ rays in the $0\nu\beta\beta$ peak region for 0.6 ton year run with $50 \text{ mg/cm}^2 \beta\beta$ sources. Left: ⁸²Se with $< m_{\nu} >= 75 \text{ meV}$. Right: ¹⁰⁰Mo with $< m_{\nu} >= 250 \text{ meV}$. Top: E-resolution $\sigma = 2.2 \%$. Bottom: $\sigma = 1.7 \%$. Ref. Shima[43].

shields of the PL plates, and the experiment is carried out at a deep underground laboratory of around 2500 m water equivalent (w.e). Then the rate is estimated to be B = 1/t y.

The high energy part of the $2\nu\beta\beta$ spectrum in the $0\nu\beta\beta$ window is the major BG in the MOON type detector with moderate energy resolution. The $2\nu\beta\beta$ BG rate is given as

$$B(2\nu\beta\beta) = 4.2 \ \epsilon^{2\nu} \ (t_{1/2} \ 0.01 \ A)^{-1}, \tag{2}$$

where $t_{1/2}$ is the $2\nu\beta\beta$ half-life in units of 10^{20} y, $\epsilon^{2\nu}$ is the $2\nu\beta\beta$ efficiency (probability of $2\nu\beta\beta$ events at the $0\nu\beta\beta$ window) in units of 10^{-7} . The $2\nu\beta\beta$ efficiency was evaluated for the 3σ E-window as $\epsilon^{2\nu} = 0.8$ and 0.3 in units of 10^{-7} for $\sigma = 2.2\%$ and 1.7\%, respectively.

The MOON experiment will be carried out in three phases, phase I with 1 detector unit (0.03 ton $\beta\beta$ source) to search for the Majorana ν -mass in the 150 meV QD mass region and phase II with 4 units (0.12 ton) for the ν -mass in the lower QD mass region of around 100–70 meV. Phase III with 16 units (0.48 ton) is for the IH mass region of around 30–40 meV.

The E-resolution of $\sigma = 2.2 \%$ and 1.7 % and the source impurities of 60 and 20 mBq for ²⁰⁸Tl isotopes and 300 and 100 mBq for ²¹⁴Bi isotopes are assumed for the phase I-II and the phase III experiments, respectively, at the underground laboratory of 2450 m w.e. The ²⁰⁸Tl and ²¹⁴Bi impurities for the phase I-II are the values in the NEMO III experiment [38] and those for the phase III are 1/3 of the values of NEMO III. The BG rates per ton year (/t y) are 4.2 and 1.6 for the $2\nu\beta\beta$ contributions, 0.9 and 0.3 for ²⁰⁸Tl and 0.03 and 0.01 for ²¹⁴Bi, respectively, for the phase I-II and the phase III experiments. The BG rates from natural and cosmogenic RI isotopes are much less than the $2\nu\beta\beta$ rate, and well below 1/t y.

The $0\nu\beta\beta$ half-life sensitivity and the ν -mass sensitivity for each phase are evaluated for the

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⁸²Se and ¹⁰⁰Mo by using $M^{0\nu} = 18 \ A^{-1/3} = 4.2$ and 3.9 for ⁸²Se and ¹⁰⁰Mo. The evaluated half-lives and the ν -mass sensitivities are given in Table 1.

Table 1. Half-life sensitivities $(t_{1/2})$ and ν - mass sensitivities $(\langle m_{\nu}^m \rangle)$ for the phases I, II, and III experiments with N=1, 4,and 16 detector units, respectively.

Phase	$N_{\beta\beta}$	$\Sigma N_{\beta\beta}T$	$t_{1/2}\ ^{82}\mathrm{Se}$	$t_{1/2}$ ¹⁰⁰ Mo	$< m_{\nu}^m >^{82} \mathrm{Se}$	$< m_{\nu}^m >^{100} \mathrm{Mo}$
Ι	$0.03\mathrm{t}$	0.06 t y	$0.32 \ 10^{26} \ y$	$0.15 \ 10^{26} \ y$	$134\mathrm{meV}$	$161\mathrm{meV}$
II	$0.12\mathrm{t}$	0.30ty	$1.12 \ 10^{26} \ y$	$0.41 \ 10^{26} \ y$	$70\mathrm{meV}$	$98\mathrm{meV}$
III	$0.48\mathrm{t}$	$1.92~{\rm t}~{\rm y}$	$5.9 10^{26} \text{ y}$	$2.0 10^{26} \text{ y}$	$31\mathrm{meV}$	$44\mathrm{meV}$

3.4. Detector research and development

Photon responses of PL and NaI scintillators to be used for MOON were studied by using the detector test bench CROSS (Correlation Response Observatory for Scintillation Signals) at NIRS (National Institute for Radiological Sciences) [44].

One PL scintillator plate with $6 \text{ cm} \times 6 \text{ cm} \times 1 \text{ cm}$ was set at CROSS. The scintillation photons were collected by 2 inch ϕ H6410 photomultiplier tubes with 25% photo-electron efficiency at the 4 sides of the plate. The energy resolution was found to be given by $\sigma \approx 3.7 E^{-1/2}$ %, and the expected resolution at $Q_{\beta\beta} \approx 3 \text{ MeV}$ is $\sigma = 2.1$ %.

A prototype MOON-1 detector was constructed to prove feasibility of MOON with the IH mass sensitivity [26, 45, 46, 47]. It consists of 6-layer plastic-scintillator (PL) plates, each with $53 \times 53 \times 1 \text{ cm}^3$. RP-408 (BC-408 equivalent) PL.

The 94.5 % enriched ¹⁰⁰Mo films with 40 mg/cm^2 are interleaved between the PL plates in the MOON-1 detector. The 6-layer PL plates are viewed by 56 6×6 cm² square-type photo-multiplier tubes (PMT) R6236-01-KMOD provided by Hamamatsu Photonics. One PMT collects photons from 3 PL plates and the hit PL plate is identified by the PMT hit pattern.

Photon response for the same PL plate as used for the MOON-1 detector was studied using the 976 keV K conversion electron from a ²⁰⁷Bi RI source at the centre of PL. The number of total photo-electrons is 1830 ± 35 for the 976 keV electron line. The energy resolution is found to be $\sigma = 4.8 \pm 0.2 \%$, which corresponds to $\sigma = 2.7 \%$ at 3 MeV.

The MOON-1 detector was set in the active and passive shields of ELEGANT V [16]. The measured energy resolution is found to be well reproduced by $\sigma = 5.0 \ E^{-1/2} \%$ with E in units of MeV. This leads to the energy resolution of $\sigma = 2.9 \%$ at 3 MeV, as required for the half-life sensitivity of 2.3 10^{26} y (QD-IH mass of 50 meV) for ⁸²Se. The resolution of around $\sigma = 2.2 \%$ is expected by correcting for the position dependence of the photon collection.

4. DBD matrix elements

Nuclear $\beta\beta$ responses are evaluated by using relevant β matrix elements for intermediate states. The $0\nu\beta\beta$ matrix element is expressed in terms of the single- β matrix elements as

$$M^{0\nu}(\tau\sigma) \approx \Sigma_J \left[\frac{M_S(J)M_{S'}(J)}{\Delta_S(J)} \right],\tag{3}$$

where $M_S(J)$ and $M_{S'}(J)$ are single- β matrix elements through the low-lying (single particlehole) states $|S_J\rangle$ in the intermediate nuclei [8, 33]. Extensive studies of charge exchange reactions have been made to get $GT(1^+)$ responses with $\tau^{\pm}\sigma$. The reactions studied are (p,n), (n,p), (d,²He), (³He, t) (t,³He), (⁷Li, ⁷Be), and others [8, 25, 48, 49].

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Recently it has been pointed out that low energy photons are used to study nuclear weak responses relevant to $\beta\beta$ decays. Nuclear matrix elements from intermediate 1⁺ and 1⁻ states to the final 0⁺ state are studied by investigating M1 and E1 photon absorptions into IAS (Isobaric Analog States) of the intermediate states [25].

One direct way to get the weak (neutrino) nuclear responses is to use ν -beams. Low energy ν -beams with $E \leq 100 \text{ MeV}$ can be obtained from pion decays. Intense pions are produced by nuclear Macro 6interaction with GeV protons. The J-PARC booster synchrotron provides high energy 3 GeV protons with $1.2 \cdot 10^{15}$ per sec, and the expected ν intensity is $3 \cdot 10^{14}$ per sec. These low energy neutrinos are very interesting for studying neutrino nuclear response [31]. NuSNS uses low energy neutrinos from stopped pions produced by intense SNS protons in order to study neutrino nuclear responses [50, 51].

Then $M_S(J)$ and $M_{S'}(J)$ are obtained experimentally from the charge exchange reactions and/or single β decay rates [8]. Then $2\nu\beta\beta$ matrix elements derived from $2\nu\beta\beta$ half-lives are well reproduced by using single- β GT matrix elements through low-lying 1⁺ states in the intermediate nucleus [33, 34]. Thus $0\nu\beta\beta$ matrix elements may be evaluated from single- β matrix elements through low-lying 0[±], 1[±], 2[±], 3[±], ... in the intermediate nucleus.

5. Concluding remarks

DBD experiments in Japan have been carried out by using the geochemical methods at the Ogata lab. Osaka Univ. since the 1960's, and by the ELEGANT series counter experiments at the Ejiri lab. Osaka Univ. since the early 1980's. The counter experiments have been extended to the future MOON experiments and others.

MOON is the high-sensitivity spectroscopic $0\nu\beta\beta$ experiment with detector $\neq \beta\beta$ source. ⁸²Se and/or ¹⁰⁰Mo with the large $Q_{\beta\beta}$ are used. Energy and angular correlations for 2–3 kinds of $\beta\beta$ nuclei and for both the ground and excited states are useful to identify the light ν -mass $0\nu\beta\beta$ process.

The MOON detector consists of multi-layer scintillator plates and position sensitive detector planes. Good energy and position resolutions, together with the compact multi-layer structure of the detector, make it realistic to study the QD and IH mass regions.

DBD matrix elements are given in terms of single- β matrix elements through low-lying states in intermediate nuclei. Charge exchange reactions are used to get the single- β matrix elements.

It is noted that MOON can be used for real-time studies of solar and supernova neutrinos since ¹⁰⁰Mo has large charged-current responses for both solar and supernova neutrinos [8, 52].

Low-energy solar neutrinos are studied by observing the inverse β decays from ¹⁰⁰Mo in delayed coincidence with the successive β decay from ¹⁰⁰Tc to reduce BGs. The good position resolution is crucial to reduce the $2\nu\beta\beta$ accidental coincidence rate. All Mo isotopes have large responses for supernova neutrinos. Thus a MOON-type detector can be used to study supernova neutrinos by using thick natural Mo plates of the order of 100 tons in place of thin ¹⁰⁰Mo foils.

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