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Nuclear responses for neutrinos and neutrino studies by double beta decays and inverse beta decays

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Abstract. This is a brief report on recent studies of nuclear responses for neutrinos (ν) by charge exchange reactions, ν masses by double beta ($\beta\beta$) decays and of solar and supernova ν's by inverse β decays. Subjects discussed include (1) ν studies in nuclear micro-laboratories, (2) ν masses studied by $\beta\beta$ decays of ^{100}Mo and nuclear responses for $\beta\beta - \nu$, (3) solar and supernova ν's by inverse β decays and ν responses for ^{71}Ga and ^{100}Mo, and (4) MOON (molybdenum observatory of neutrinos) for spectroscopic studies of Majorana ν masses with sensitivity of $m_\nu \sim 0.03$ eV by $\beta\beta$ decays of ^{100}Mo and real-time studies of low energy solar and supernova ν's by inverse β decays of ^{100}Mo.

Keywords. Double beta decays; neutrinos.

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1. Neutrinos studied in nuclear micro-laboratories

Nuclei with nucleons in good quantum states are used as excellent micro-laboratories for studying low energy neutrinos (ν) and fundamental weak interactions. Here nuclei are used to select and enhance particular processes relevant to ν properties beyond the standard theory of SU(2)$_L\times$ U(1). Actually Majorana ν masses, Majoron-ν and SUSY-ν couplings, right-handed ν's and weak bosons, ν oscillations and others are studied by investigating double beta ($\beta\beta$) decays in nuclei, solar-ν and supernova-ν interactions (inverse β decays) in nuclei, and other low energy ν-nuclear processes of astroparticle physics interest [1–4].

Low-energy solar ν's, which are major solar-ν components, have been so far studied by non-real-time and inclusive measurements. They do not measure the ν energies and thus do not identify the ν sources in the sun. Real-time spectroscopic studies of the low energy solar-ν are crucial for studies of the solar-ν problems. They can be carried out in nuclei by measuring inverse β decays induced by the solar ν.

Supernova ν's provide excellent opportunities for studying ν oscillations and supernova explosion mechanisms. They can be studied also by measuring inverse β decays.

Nuclear responses for ν's are crucial for studying fundamental properties of ν's and weak interactions in nuclear micro-laboratories [1]. They are given by nuclear isospin and spin-isospin responses for vector and axial-vector weak interactions. The nuclear response is given as $R(\alpha) = (2J_i + 1)^{-1}|M(\alpha)|^2$, where $M(\alpha)$ is the nuclear matrix element, and J_i is the initial state spin. The nuclear matrix element is expressed in terms of the spin (σ), isospin (τ) and spherical harmonic operator (Y_L),

$$M(TSLJ) = G(\alpha)\tau^T[\sigma^S \times Y_L f_L(r)]_J, \tag{1}$$

where $\alpha = TSLJ$ stands for isospin (T), spin (S), orbital angular momentum (L), and total angular momentum (J).

Solar-ν, supernova-ν, and $\beta\beta - \nu$ are currently used for studying fundamental properties of ν's in nuclear micro-laboratories. Energies of solar-ν's are mostly in the region of 0.1–1 MeV, and extend up to around 14 MeV. Supernova-ν's are in the region of 5–50 MeV. On the other hand virtual ν's up to around 50 MeV are involved in $\beta\beta$ processes in nuclei.

Charge-exchange spin-flip reactions by medium energy nuclear probes have been shown to be quite powerful for studying spin-isospin responses relevant to ν studies in nuclei [1]. Actually spin-isospin modes are preferentially excited by medium energy light ions with $E_A/A \sim$ 100–300 MeV, since $V_{\tau\sigma}$ is relatively large in the medium energy region and V_0 is small there. Charge exchange reactions used extensively are (p, n), (n, p), (d, ^{2}He), (^{3}He, t), (t, ^{3}He), (^{7}Li, ^{7}Be) and other light ion reactions. Among these reactions, (^{3}He, t) and (t, ^{3}He) reactions are very useful because of the simple structures of projectile and outgoing nuclei and of possible high energy-resolution studies.

Extensive studies of (^{3}He, t) reactions at $E(^3\mathrm{He}) = 450$ MeV have been made at RCNP, Osaka to investigate spin-isospin responses relevant to solar-ν, supernova-ν, and $\beta\beta - \nu$ [5].

2. Neutrino masses by double beta decays and nuclear responses

Neutrino-less double beta decays ($0\nu\beta\beta$), which violate the lepton number conservation law by $\Delta L = 2$, are caused by the Majorana ν mass, the right-handed weak current, the ν coupling with the Majoron field, the R-parity violating interaction with SUSY particles and others, which are beyond the standard electro-weak theory [2].

The $0\nu\beta\beta$ process due to the ν-mass term is mainly a ν-exchange process between two nucleons inside a nucleus. Since the distance r between them is very small, the ν exchange is significantly enhanced in the nuclei by a factor 10^{6-8}. Thus the $\beta\beta$ nucleus is regarded as a microscope with a large enlargement factor for $0\nu\beta\beta$ signals and a strong filtering power to reject huge single β background signals.

The transition rate for $2\nu\beta\beta$ is expressed as

$$T^{2\nu} = G^{2\nu}|M^{2\nu}|^2, \tag{2}$$

where $G^{2\nu}$ stands for the kinematical factor including the double weak coupling constant and the phase space volume. $M^{2\nu}$ is the nuclear matrix element. It is expressed as the sum of the Fermi and Gamow–Teller (GT) matrix elements. Since the Fermi strength is mostly absorbed into the double isobaric analogue state, $M^{2\nu}$ is mainly given by the double GT matrix element.

The $0\nu\beta\beta$ decay rate for the $0^+ \rightarrow 0^+$ ground state transition is given by [2]

$$T^{0\nu} = G^{0\nu}|M^{0\nu}(\tau\sigma)|^2 \left[(1-\chi_F)\frac{\langle m_\nu\rangle}{m_e}\right]^2 K, \tag{3}$$
$$K = [1 + (\langle m_\nu\rangle/m_e)^{-2}k],$$
$$k = C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + C_{m\lambda}m_e^{-1}\langle m_\nu\rangle\langle\lambda\rangle\cos\psi_1$$
$$+C_{m\eta}m_e^{-1}\langle m_\nu\rangle\langle\eta\rangle\cos\psi_2 + C_{\lambda\eta}\langle\lambda\rangle\langle\eta\rangle\cos(\psi_1-\psi_2).$$

Here $G^{0\nu}$ is the kinematical factor for the ν-mass term and $M^{0\nu}(\tau\sigma)$ is the nuclear spin-isospin matrix element for the ν-mass term, and χ_F is the ratio of the isospin matrix element to the spin-isospin matrix element.

The ν-mass term and the right-handed weak current terms are given by the effective values defined as $\langle m_\nu\rangle = |\sum_j m_j U_{ej}^2|, \langle\lambda\rangle = \lambda|\sum_j U_{ej}V_{ej}|$ and $\langle\eta\rangle = \eta|\sum_j U_{ej}V_{ej}|$. The $\langle m\rangle, \langle\lambda\rangle$ and $\langle\eta\rangle$ terms are obtained individually by spectroscopic studies of the two β-ray correlations.

ELEGANT detectors have been developed by the Osaka group for spectroscopic studies of $\beta\beta$ decays from ^{100}Mo, ^{116}Cd and ^{48}Ca, and of cold dark matters [6]. They are set at Oto underground lab. (Oto Cosmo Observatory). EL 5 gives most stringent limits of 10.3 (5.5) 10^{22} y and 1.5 (2.1) eV with 68 (90) % CL on the $0\nu\beta\beta$ half life and the effective ν mass, respectively [6].

The minimum ν-mass to be studied is given by the detector sensitivity. The $\langle m_\nu\rangle$ to be studied by calorimetric methods with good energy resolution ^{76}Ge and ^{130}Te detectors may be of the order of 0.4 ∼1.5 eV, while the mass by spectroscopic methods for ^{100}Mo and ^{150}Nd with the large $G^{0\nu}$ may be of the order of 1∼2 eV. They depend on $M^{0\nu}$.

Recent results with atmospheric, solar and accelerator ν's strongly suggest ν oscillations due to non-zero ν-mass differences and flavor mixings. It is of great interest to study absolute ν masses in the 0.01–0.1 eV region suggested by the ν oscillation data. Then one needs large volume detectors with high sensitivities to study the smaller $\langle m_\nu\rangle$ in the region of 0.02∼0.1 eV. MOON is developed for this purpose as discussed in §4 [7].

The $2\nu\beta\beta$ transition rate gives $M^{2\nu}$, which can be used to evaluate nuclear interaction parameters to be used for evaluating $M^{0\nu}$. $M^{2\nu}$ is given by the double GT(spin-isospin) matrix element as $M^{2\nu} \sim M^{2\nu}(1^+) = M^{2\nu}(\tau\sigma\tau\sigma)$.

The $2\nu\beta\beta$ process is found to be expressed as a successive single β process through a low-lying single particle-hole state $|S\rangle$ in the intermediate nucleus [6]. Thus $M^{2\nu}$ is written as

$$M^{2\nu} = \frac{M_S^\nu M_{S'}^\nu}{\Delta_S}, \tag{4}$$

where M_S^ν and $M_{S'}^\nu$ are the GT matrix elements for the single β decays of $|i\rangle \rightarrow |S\rangle$ and $|S\rangle \rightarrow |f\rangle$, respectively, and Δ_S is the energy denominator. The GT giant resonance in the intermediate nucleus does not contribute to the $2\nu\beta\beta$ process. Experimental values for $M^{2\nu}$ are shown to be consistent with the theoretical prediction [8].

It is important to note that the single β matrix elements of M_S^ν and $M_{S'}^\nu$ are obtained by using charge exchange reactions and/or single β decay rates. Thus the $M^{2\nu}$ matrix element can be evaluated from eq. (4).

Nuclear matrix elements $M^{0\nu}$ includes the ν potential term for a virtual ν exchange. The ν potential term $h_+(r_{nm}, E)$ is approximately given by the Coulomb term, which is written by a separable form [1]. Then $M^{0\nu}$ may be expressed by a separable form as $M^{0\nu} \sim \sum_J [M_S(J)M_{S'}(J) + M_G(J)M_{G'}(J)]$. Here $M_S(J)$ and $M_{S'}(J)$ are single β matrix elements through the intermediate single particle-hole state $|S_J\rangle$ with spin J and $M_G(J)$ and $M_{G'}(J)$ are those through the giant resonance $|G_J\rangle$. Since the second (giant resonance) term is considered to be small, $M^{0\nu}$ is expressed as

$$M^{0\nu} \sim \sum_J [M_S(J)M_{S'}(J)]/\Delta_S(J). \tag{5}$$

Then $M_S(J)$ and $M_{S'}(J)$ are obtained empirically from the charge exchange reactions and/or single β decay rates, and $M^{0\nu}$ are evaluated from $M_S(J)$ and $M_{S'}(J)$ by using eq. (5), as in case of $2\nu\beta\beta$.

3. Solar and supernova neutrinos by inverse beta decays and neutrino nuclear responses

Solar-ν's consist mainly of very low energy ν's of $pp-\nu$, ^{7}Be$-\nu$ and a small component of ^{8}B-ν. They are well studied by charged-current interactions (charge exchange reactions) of (ν, e) in nuclei. Nuclear spin isospin responses for solar-ν's were studied for ^{71}Ga and ^{100}Mo by using the (^{3}He, t) reaction at RCNP [5]. The GT strengths were obtained from the forward angle cross-sections. The charge exchange ν reaction rates for individual solar ν sources [4] were derived from the measured B(GT) values, as shown in table 1. Reaction rates for other nuclei are also shown in ref. [1]. ^{100}Mo is found to have large responses for low energy solar ν's. This is due to the low threshold energy and the large GT strengths for the ground state and excited states in ^{100}Tc.

The gravitational energy released by the supernova core collapse is carried away by all kinds of ν's. The temperatures of the ν spheres and the average ν energies are $T_\nu \sim 3.5$ MeV and $\langle E_\nu\rangle \sim 11$ MeV for ν_e, $T_\nu \sim 5$ MeV and $\langle E_\nu\rangle \sim 16$ MeV for $\bar{\nu}_e$, and $T_\nu \sim 8$ MeV and $\langle E_\nu\rangle \sim 25$ MeV for $\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$.

The supernova-ν spectrum provides important information on supernova mechanisms, ν masses, and ν oscillations. The supernova-ν's are studied in nuclei through charged-

Table 1. Solar-ν absorption rates R_ν for ^{100}Mo [7].

Source	$E_\nu^{(\max)}$ (MeV)	$E_\beta^{(\max)}$ (MeV)	R_ν/SNU^a
pp	0.42	0.25	639 ± 85
pep	1.44	1.27	13 ± 2
^{7}Be	0.86	0.69	206 ± 35
^{8}B	∼15	∼14.2	27(23)^b ± 4
^{13}N	1.20	1.03	22± 3
^{15}O	1.74	1.57	32 ± 4

$E_\nu^{(\max)}$, $E_\beta^{(\max)}$ are the maximum ν energy and maximum β-ray energy.
$^{(a)}$Standard-solar-model (SSM) capture rates based on BP98 [4] with errors from those of B(GT).
$^{(b)}$Rate for the states below the effective neutron threshold energy.

current and neutral-current reactions, i.e. charge exchange and inelastic reactions. Here GT and spin dipole giant resonances in the $5 \sim 40$ MeV region play important roles for supernova-ν nuclear responses. They are well studied by charge-exchange spin-flip reactions such as (^{3}He, t) and (t, ^{3}He). It is noted that the (^{3}He, t) reaction at $\theta = 0$ deg. shows the IAS(τ) and GT($\tau\sigma$) giant resonances, while the reaction at $\theta = 1$ deg. shows the spin dipole ($\tau\sigma Y_1$) giant resonances as well as IAS and GR ones [1].

The supernova-ν spectra overlap with the IAS, GT and spin dipole giant resonances. Thus the high energy component of ν_e excites the IAS and GT resonances via charge-exchange (ν_e, e) reactions. The cross sections and the average electron energy are small. On the other hand ν_x's excite the IAS, GT and spin dipole giant resonances by charge exchange (ν_e, e) reactions via $\nu_x \rightarrow \nu_e$ oscillation. The cross section and the average energy are large. Thus they are very sensitive to the supernova ν oscillation.

4. MOON (molybdenum observatory of neutrinos) for low energy neutrino studies in ^{100}Mo

Recently measurements of two correlated β rays from ^{100}Mo are shown to make it possible to perform both spectroscopic studies of $0\nu\beta\beta$ with a sensitivity of the order of $\langle m_\nu \rangle \sim 0.03$ eV and real-time exclusive studies of the low energy solar ν's by inverse β decays [7]. The unique features are as follows:

1. The β_1 and β_2 with the large energy sum of $E_1 + E_2$ are measured in coincidence for the $0\nu\beta\beta$ studies, while the inverse β-decay induced by the solar ν and the successive β decay are measured sequentially in an adequate time window for the low energy solar-ν studies. The isotope ^{100}Mo is just the one that satisfies the conditions for the $\beta\beta - \nu$ and solar-ν studies.
2. The large Q value of $Q_{\beta\beta} = 3.034$ MeV gives a large phase-space factor $G^{0\nu}$ to enhance the $0\nu\beta\beta$ rate and a large energy sum of $E_1 + E_2 = Q_{\beta\beta}$ to place the $0\nu\beta\beta$ energy signal well above most BG except ^{208}Tl and ^{214}Bi. The $g^{\nu}_{7/2} - g^{\pi}_{9/2}$ shell-model structure of ^{100}Mo–^{100}Tc leads to the large measured two-neutrino double beta decay ($2\nu\beta\beta$) rate [9], and the large calculated value for the $0\nu\beta\beta$ decay rate [2]. The energy and angular correlations for the two β-rays identify the ν-mass term.
3. The low threshold energy of 0.168 MeV for the solar-ν absorption allows observation of low energy sources such as pp and ^{7}Be. The GT strength to the 1^+ ground state of ^{100}Tc is measured to be $(g_A/g_V)^2 B(\mathrm{GT}) = 0.52 \pm 0.06$ by both charge-exchange reaction and electron capture [5,10]. Capture rates are large even for low energy solar ν's, as shown in table 1. The solar-ν sources are identified by measuring the inverse β-energies. Only the ^{100}Tc ground state can absorb $^{7}\mathrm{Be} - \nu$ and $pp - \nu$. Therefore the intensity ratio of the $pp - \nu$ and the $^{7}\mathrm{Be} - \nu$ is independent of the B(GT).
4. The measurement of two β-rays (charged particles) enables one to localize in space and in time the decay-vertex points for both the $0\nu\beta\beta$ and solar-ν studies. Radiations associated with BG are also measured. The tightly localized β–β event in space and time windows, together with relevant β and γ measurements, are key points for selecting $0\nu\beta\beta$ and solar-ν signals and for reducing correlated and accidental BG by factors $10^{-5} \sim 10^{-6}$ as in the case of ELEGANT [6].

The $0\nu\beta\beta$ events are identified by setting the appropriate energy window and the prompt time window for the $\beta\beta$ coincidence signals. The rate in units of 10^{-36}/sec is given as $R_{0\nu} = 6.6 \times 10^4 |\langle m \rangle|^2/(\text{eV})^2$ by RQRPA [3].

For solar ν detection, the inverse β-decay induced by the solar-ν absorption is followed by β-decay with a mean life $\tau = 23$ sec. Thus a time window can be set as $\Delta T = 30$ sec (10^{-6} y) from $t_1 = 1$ sec to $t_2 = 31$ sec. The starting time of 1 sec is long enough to reject most correlated BG such as the $2\nu\beta\beta$, β-rays followed by conversion electrons, scatterings of single β-rays, etc. The stopping time of 31 sec is short enough to limit the accidental coincidence BG. The accidental rate is further reduced by effectively subdividing the detector into K unit cells by means of position readout.

The lower limit (sensitivity) on $\langle m_\nu \rangle$ can be obtained by requiring that the number of $0\nu\beta\beta$ events has to exceed the statistical fluctuation of the BG events. The sensitivity of the order of $\langle m_\nu \rangle \sim 0.03$ eV can be achieved for three year measurement by means of a realistic detector with a few tons of ^{100}Mo and RI contents of the order of 0.1 ppt ($b \sim 10^{-3}$ Bq/ton).

Sensitivity for the solar ν is obtained similarly as in case of the $0\nu\beta\beta$. It is of the order of ~ 100 SNU for one year measurement by using the same detector with $K \sim 10^9$. In fact the $2\nu\beta\beta$ rate and the BG rate from RI at 0.1 ppt ($b \sim 10^{-3}$Bq/ton) are larger than the solar-ν rate by factors $\sim 10^7$ and $\sim 10^5$, respectively. The fine localization in time ($\Delta T = 10^{-6}$ y) and in space ($1/K = 10^{-9}$), which is possible with the present two-β spectroscopy, is crucial for reducing BG rates in realistic detectors.

One possible detector is a super-module of $\sim$1 ton of ^{100}Mo (~ 10 tons of Mo in case of natural Mo) purified to 10^{-3} Bq/ton for ^{238}U and ^{232}Th or less. This purity level has been achieved for Ni and other materials for the Sudbury Neutrino Observatory [11]. The super-module with a fiducial volume of $(x, y, z) =$ (2.5 m, 2.5 m, $1 \sim 5$ m, depending on enriched ^{100}Mo or natural Mo) is composed of $400 \sim 2000$ modules with $(x, y, z) =$ (2.5 m, 2.5 m, 0.25 cm).

The Mo foils with thickness of $0.05 \sim 0.03$ g/cm^2 are interleaved between the modules. Light outputs from each scintillator module are collected by WLS (wave length shifter) fibers. One may use only scintillation fiber arrays stretched to x and y directions in place of scintillator/WLS ensembles. Use of enriched ^{100}Mo isotopes with 85 % enrichment is very effective for reducing the detector volume and for getting the large S/N ratio.

The detector can be used also for supernova-ν studies and other rare nuclear processes, and for other isotopes. Another option is a liquid scintillator in place of the solid one, keeping similar configurations of the WLS readout [12]. The energy and spatial resolution are nearly the same. Then ^{150}Nd with the large $Q_{\beta\beta}$ may be used either in solid or solution in the liquid scintillator for $0\nu\beta\beta$. Of particular interest is ^{136}Xe because liquid Xe is a scintillator.

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