NEUTRINO STUDIES IN NUCLEI AND NUCLEAR RESPONSES FOR NEUTRINOS*

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Fundamental properties of neutrinos(ν) are studies in nuclei as micro-laboratories. Here nuclear responses for ν's are crucial. The present report reviews briefly recent studies of nuclear responses for ν's and ν studies by double beta decays($\beta\beta$) and inverse β decays induced by solar and supernova ν's. Nuclear responses for charged-current neutrino interactions are mostly given by nuclear isospin–spin responses. They are well studied by charge-exchange reactions with medium energy projectiles. It has been found that ^{100}Mo has large spin isospin response for ν's. Thus ^{100}Mo isotopes are used as excellent micro-laboratories for spectroscopic studies of $\beta\beta$ decays with a sensitivity on $\langle m_\nu \rangle \sim 0.03$ eV and realtime studies of low energy solar ν's.

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1. Neutrino studies in nuclear micro-laboratories

Nuclei are quantum systems of nucleons in good quantum states of energies, spins, parities, isospins, baryon numbers, and so on. Then nuclei are used as excellent micro-laboratories for studying low energy neutrinos and fundamental weak interactions. Here nuclei are used to select and even enhance particular weak processes relevant to neutrino properties beyond the standard theory and to reduce other background ones.

Neutrinos (ν) and weak interactions are of great interest for new physics beyond the standard electroweak theory of SU$(2)_L\times$ U(1). Fundamental properties of ν's and weak interactions studied in nuclei as micro-laboratories are Majorana ν masses, Mojoron-ν and SUSY-ν couplings, right-handed ν's

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and weak bosons, ν oscillations and others. They are well studied in nuclear micro-laboratories by investigating double beta ($\beta\beta$) decays in nuclei, solar- and supernova-ν interactions(inverse β decays) in nuclei, supernova-ν interactions in nuclei, and other low energy ν processes in nuclei.

The present report is a summary of the lecture on neutrino studies in nuclei and nuclear responses with emphasis on the recent works of ν mass studies by $\beta\beta$ decays in nuclei and solar and supernova ν studies in nuclei. MOON for spectroscopic studies of $\beta\beta$ decays and solar ν's is also discussed. Some parts of the present work have been partially presented at recent symposia/conferences [2, 3].

2. Nuclear responses for low energy neutrinos

Nuclear weak responses for ν's are crucial for ν studies in nuclei. Nuclear isospin and spin–isospin responses are relevant to vector and axial-vector weak interactions [1]. The nuclear response is given as

$$R(\alpha) = (2J_i + 1)^{-1} |M(\alpha)|^2 \,, \tag{1}$$

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),

$$M(TSLJ) = G(\alpha)\tau[\sigma^S \times Y_L f_L(r)]_J \,, \tag{2}$$

where $\alpha = TSLJ$ stands for isospin (T), spin (S), orbital angular momentum (L), and total angular momentum (J). $G(\alpha)$ is the coupling constant for α mode.

Nuclear spin–isospin interactions give rise to spin–isospin giant resonances at the high excitation region of $E_{\rm ex} = 10 \sim 40$ MeV, and spin isospin core polarizations at the low excitation region of $E_{\rm ex} = 0 \sim 5$ MeV. Consequently nuclear spin isospin responses for weak, electro-magnetic and strong processes are modified much in nuclei.

Fundamental properties of ν's and astronuclear processes of ν productions are studied currently by investigating solar-ν, supernova-ν, and $\beta\beta$-ν 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 neutrino-less double beta decays ($0\nu\beta\beta$) are mostly due to a virtual ν exchange between two nucleons in a nucleus. Then the momentum of the virtual ν is necessarily of the order of $q = \hbar/R \sim 50$ MeV/c.

Nuclear responses for these low energy ν's are spin isospin responses in the low excitation region of 1-50 MeV, where the nuclear responses are much modified by the nuclear spin isospin correlation. It is of great interest for ν nuclear responses to study the nuclear spin isospin responses in a wide excitation region of $E_{\mathrm{ex}} = 0 \sim 50$ MeV [1].

3. Nuclear probes for spin–isospin responses

Nuclear spin isospin responses for low energy ν's in the region of 0–50 MeV are studied mainly by using nuclear reactions with weak, electro-magnetic and strong probes.

Weak probes are straightforward to give directly nuclear responses for ν's. Beta decay rates, however, give nuclear responses only for ground state transitions in β unstable nuclei. Medium energy lepton probes such as ν, μ, and e are in principle used for studying nuclear responses in a wide excitation region.

Nuclear reaction cross sections with these weak probes, however, are extremely small. They are of the order of $10^{-16\sim-20}$b. Thus studies with weak probes require high intensity lepton beams and large detectors. One exception is the μ^- capture process with a large cross section.

In general, electro-magnetic interactions have similar spin–isospin operators as weak interactions. Therefore electro-magnetic probes are used for getting nuclear spin–isospin responses relevant to nuclear ν responses. Nuclear reactions with electro-magnetic probes are (e,e'), (γ,X), and Coulomb excitation.

Nuclear responses studied by using these electro-magnetic probes are neutral-current (τ_3) responses. Electro-magnetic interactions include isoscalar and orbital-magnetic components in addition to the isovector spin term relevant to ν responses. They have to be corrected for in order to extract the isovector spin term.

The orbital-magnetic term is effectively included in the spin term in case of spin-stretched transitions with $J_i = L \pm J_f$. The spin matrix element is expressed by the corresponding M1 γ one as

$$\langle\sigma_i\rangle = (g_M)^{-1}\langle \mathrm{M1}\rangle \,, \tag{3}$$

where the effective g factor is given by

$$g_M = \frac{e\hbar}{2M}\left(\frac{3}{4\pi}\right)^{1/2}(g_s - g_l)\,. \tag{4}$$

Hadrons such as nucleons, light nuclei and mesons are used for studying nuclear spin–isospin responses in a wide excitation region. The reaction cross-section is large because of the strong interaction. The strong interaction, however, includes not only central spin–isospin interactions relevant to weak interactions, but also other types of interactions such as tensor interactions, isoscalar interactions and others. Charged-current responses are studied by charge-exchange reactions, while neutral-current ones by inelastic scatterings.

4. Isospin spin responses and charge-exchange spin-flip nuclear reactions

Nuclear reactions are used to study nuclear spin–isospin responses in a wide excitation region. Charge-exchange spin-flip reactions by medium energy nuclear probes have been shown to be quite powerful for studying spin–isospin responses for charged-current weak interactions. Spin–isospin modes are preferentially excited by medium energy light ions with $E_A/A \sim$ 100–300 MeV, since the central spin–isospin interaction of $V_{\tau\sigma}$ is relatively large in the medium energy region and the volume-type interaction of V_0 is small there. Charge-exchange reactions used extensively are (p,n), (n,p), $(d,^2\mathrm{He})$, $(^3\mathrm{He},t)$, $(t,^3\mathrm{He})$, $(^6\mathrm{Li}, {}^6\mathrm{He})$ $(^7\mathrm{Li}, {}^7\mathrm{Be})$ and other light ion reactions. It is noted that $(^3\mathrm{He}, t)$ and $(t,^3\mathrm{He})$ reactions are very useful since the projectile and outgoing nuclei are simple nuclei with $A = 3$ and high energy-resolution studies for these charged particles can be made by means of magnetic spectrometers.

Extensive studies of $(^3\mathrm{He}, t)$ reactions at $E(^3\mathrm{He}) = 450$ MeV have been made to investigate spin–isospin responses relevant to solar-ν, supernova-ν, and $\beta\beta$-ν [4–6]. Tritons have been analyzed by means of the high energy-resolution spectrograph. Recently a lateral and angular dispersion matching system between a new WS beam line and the spectrograph has been completed at RCNP. The system gives an extremely high resolution of $\Delta E/E = 4 \times 10^{-5}$ for inelastic proton scatterings at $E_p = 300$ MeV. Then the $(^3\mathrm{He},t)$ reaction with the new system is very powerful for studying axial charged-current responses in the τ_- mode for individual low-lying states.

Axial charged-current responses in the τ_+ mode have been studied by $(t,^3\mathrm{He})$ reactions at MSU. Medium energy tritons with $E(t) = 380$ MeV have been obtained by fragmentation of α particles from the MSU cyclotron, and ^{3}He particles have been analyzed by the A1200 beam line and K800 spectrograph [7].

Cross sections of the charge-exchange reactions at forward angles are proportional to $B(\mathrm{GT})$ values (GT responses) derived from β decay rates for strong GT states with $B(\mathrm{GT}) \geq 0.1$.

The cross section of the charge-exchange reaction with low momentum transfer is related to the isospin spin response on the basis of the major central isospin spin interaction. In the framework of the direct reaction process with the distorted Born approximation (DWBA), the cross section at low momentum and low energy transfers is expressed as [8],

$$\sigma_\alpha(q,\omega) = K(E_i,\omega)(\exp(-\tfrac{1}{3}q^2r^2))N_\alpha^{\mathrm{D}}(q,\omega)|J_\alpha|^2 B(\alpha)\,, \tag{5}$$

$$K(E_i,\omega) = \frac{k_i E_i E_f}{k_i(\hbar^2 c^2 \pi)^2}\,, \tag{6}$$

where $\alpha = \tau$ and $\tau\sigma$ denote Fermi isospin and GT isospin spin channels, and q and ω are the momentum and energy transfers. $K(E_i,\omega)$ is the kinematical factor, and $N_\alpha^{\mathrm{D}}(q,\omega)$ is the distortion factor. The distortion factor is given by the ratio of the DWBA cross section to the PWBA cross section at $\theta = 0$ deg. The nuclear responses $B(\alpha)$ with $\alpha = \tau$ and $\tau\sigma$ are $B(\mathrm{F})$ and $B(\mathrm{GT})$, respectively. They are derived from the cross sections at forward angles with low momentum transfers.

It is important to find how one can extract GT (spin–isospin) responses from charge-exchange reactions for weak GT states, and spin dipole responses of

$$|M(111J)|^2 = |G(111J)\tau[\sigma \times Y_1 f_1(r)]_J|^2 \tag{7}$$

from charge-exchange reactions for spin dipole states with S=1, $L = 1$ and $J = 0,1,2$.

GT and spin dipole giant resonances produced by charged- and neutral-current interactions of ^{8}B solar-ν and supernova-ν decay by emitting γ rays, protons and neutrons. These γ rays and particles are used to measure the spin isospin strength distribution, which reflects the ν energies. Charged-current (ν, e) reactions populate primarily one proton-particle one neutron-hole states, which decay partly by direct proton emission and partly by statistical neutron evaporation through spreading process. The excitation energy of the GT and spin dipole states can be determined by measuring these decay particles. Then the ν energy may be evaluated from the excitation energy.

5. Solar-ν's and spin–isospin responses

Solar ν's provide one with unique opportunities to study ν oscillation in vacuum and matter and ν production rates in the Sun [9]. Solar-ν's consist mainly of very low energy components of *pp*-ν, ^{7}Be-ν and other CNO ν's. They include a small component of ^{8}B-ν with energy up to 14 MeV.

The low energy solar ν's have been studied by inclusive measurements of charged-current interactions (charge-exchange reactions) of (ν, e) in nuclei [10]. The ^{8}B ν's are studied by neutral- and charged-current interactions in light and heavy water Cerenkov detectors [11, 12].

Nuclear spin–isospin responses for solar-ν's were studied for ^{71}Ga ^{100}Mo and ^{176}Yb by means of the (^{3}He, t) reactions at RCNP [4–6]. The GT strengths were obtained from the forward angle cross-sections. The charge-exchange ν reaction rates for individual solar ν sources [9] are derived from the measured B(GT) values, as shown in Table I. Here reaction rates for other nuclei are also shown.

TABLE I

Solar-ν capture rates in units of SNU [1, 9].

Nucleus	$-Q$(MeV)	pp	^{7}Be	^{13}N	pep	^{15}O	^{8}B	Total
^{2}H	1.442	0	0	0	0	–	6	6
^{37}Cl	0.814	0	1.1	0.1	0.2	0.3	6.1	7.9
^{40}Ar	>1.505	0	0	0	0	0	7.2	7.2
^{71}Ge	0.236	70.8	35	3.7	2.9	5.8	12.9	132
^{100}Mo	0.168	639	206	22	13	32	27	965
^{115}In	0.120	468	116	13.6	8.1	18.5	14.4	639
^{127}I	0.789	0	9.4	–	–	–	13	24.6

^{37}Cl and ^{71}Ga have been used to measure mainly ^{7}Be-ν and ^{8}B-ν, and pp-ν and ^{7}Be-ν, respectively [10]. The measurements are non-realtime and inclusive ones, and thus do not identify individual solar-ν sources.

It is interesting to find that ^{100}Mo has very large reaction rates for all solar-ν sources. This is due to the low threshold energy and the large GT strength of B(GT) = 0.33 for the ground state in ^{100}Tc. Thus ^{100}Mo is used for real-time spectroscopic studies of the individual solar-ν sources [13]. This nucleus is used also for studying supernova-ν's and $\beta\beta$-ν, as discussed in Sections 6 and 7. Neutrino studies in ^{100}Mo are discussed in detail in Sections 8 and 9.

^{176}Yb has two low-lying 1^{+} states at 195 keV and 339 keV with B(GT) = 0.11 and 0.20, respectively, and thus this nucleus is used to study pp and ^{7}Be ν's by $\beta\gamma$ delayed coincidence [6].

6. Supernova-ν's and spin–isospin responses

The gravitational energy released by the supernova core collapse is carried away by all kinds of ν's. The energy spectrum is given by

$$S(E_\nu) = k\ T_\nu^{-1} \frac{(E_\nu/T_\nu)^2}{\exp(E_\nu/T_\nu - a) + 1}\,, \tag{8}$$

where T_ν and a are the temperature of the ν sphere and the degeneracy parameter, respectively. The temperature and the average ν energy are

$$\begin{array}{ll} T_\nu \sim 3.5\mathrm{MeV}, & \langle E_\nu \rangle \sim 11\mathrm{MeV\ for}\ \nu_e, \\ T_\nu \sim 5\ \mathrm{MeV}, & \langle E_\nu \rangle \sim 16\mathrm{MeV\ for}\ \bar{\nu_e}, \\ T_\nu \sim 8\ \mathrm{MeV}, & \langle E_\nu \rangle \sim 25\mathrm{MeV\ for}\ \nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\,. \end{array}$$

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-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) [4, 5, 7]. It is noted that the (^{3}He, t) reaction at 0^0 shows the IAS (τ) and GT ($\tau\sigma$) giant resonances, while the reaction at 1^0 shows the spin dipole ($\tau\sigma Y_1$) giant resonances as well as IAS and GT ones.

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, and ν_x's excite the IAS, GT and spin dipole giant resonances by charge-exchange (ν_e, e) reactions via $\nu_x \to \nu_e$ oscillation.

7. Neutrino studies by $\beta\beta$ decays in nuclei and nuclear responses

Double beta decays, which are second order weak processes in nuclei, have been extensively used to study fundamental properties of neutrinos. Double beta decays with two ν's are within the standard electroweak model (SM), while those without ν are beyond SM. They are denoted as $2\nu\beta\beta$ and $0\nu\beta\beta$, respectively. The transition rates are given as [14, 15]

$$T^{2\nu} = G^{2\nu}\ |M^{2\nu}|^2\,, \tag{9}$$
$$T^{0\nu} = G^{0\nu}\ |M^{0\nu}|^2\ [\langle m_\nu \rangle + c_\lambda \langle \lambda \rangle + c_\eta \langle \eta \rangle]^2\,, \tag{10}$$

where $G^{2\nu}$ and $M^{2\nu}$ are the phase space factor and the nuclear matrix element for $2\nu\beta\beta$, and $G^{0\nu}$ and $M^{0\nu}$ are those for $0\nu\beta\beta$. $\langle m_\nu \rangle$ is the effective

Majorana ν mass term, and $\langle\lambda\rangle$ and $\langle\eta\rangle$ are the right-handed current terms. They are written as [14,15]

$$\langle m_\nu \rangle = \left| \sum m_j U_{ej}^2 \right| , \tag{11}$$

$$\langle\lambda\rangle = \lambda \left| \sum U_{ej} V_{ej} \right|, \qquad \lambda = \left(\frac{M_{\mathrm{WL}}}{M_{\mathrm{WR}}} \right)^2 , \tag{12}$$

$$\langle\eta\rangle = \eta \left| \sum U_{ej} V_{ej} \right|, \qquad \eta = -\tan\ \delta\, , \tag{13}$$

where U_{ej} and V_{ej} are coefficients for left-handed and right-handed neutrinos and M_{WL} and M_{WR} are masses of left-handed and right-handed weak bosons, and δ is the mixing angle. $M^{2\nu}$ is given mostly by the double GT$(\tau\sigma)$ matrix element,

$$M^{2\nu} = \sum \frac{M(\tau\sigma)_i M(\tau\sigma)_i}{\Delta_i} , \tag{14}$$

where the summation is over all intermediate 1^+ states.

$M^{0\nu}$ is given by the double GT matrix elements with neutrino potential terms and the ratio of the Fermi to GT matrix element. The matrix element is expressed as

$$M^{0\nu} = \sum \langle h_+(r, E_i)\tau\tau\sigma\sigma \rangle (1 - f_{\mathrm{F}})\, , \tag{15}$$

where h_+ is the neutrino potential term and f_{F} is the ratio of the Fermi to GT matrix elements.

The ν's emitted in $2\nu\beta\beta$ are low-energy s-wave real ν's. The $0\nu\beta\beta$ process is mainly a virtual ν exchange between two nucleons in a nucleus, and thus includes large angular momenta L up to $5 \sim 6$.

The value for $|M^{2\nu}|^2$ is obtained experimentally from the $2\nu\beta\beta$ transition rate. The $0\nu\beta\beta$ transition rate is very sensitive to the ν Majorana mass and the right-handed current. The $0\nu\beta\beta$ process is caused also by the ν-Majoron coupling, ν-SUSY coupling, and others. Then the nuclear response $|M^{0\nu}|^2$ are crucial for getting the Majorana ν mass and other ν interactions and couplings, which are beyond SM. Here $M^{2\nu}$ obtained experimentally can be used to evaluate nuclear interaction parameters to be used for estimating $M^{0\nu}$.

It is found theoretically and experimentally that the $2\nu\beta\beta$ process is expressed as the successive single β processes through a few low-lying single particle-hole state $|S\rangle$ in the intermediate nucleus [16]. Thus $M^{2\nu}$ is written as

$$M^{2\nu} = \sum_S \frac{M_S^\nu M_{S'}^\nu}{\Delta_S} , \tag{16}$$

where M_S^ν and $M_{S'}^\nu$ are the GT matrix elements for the single β decays of $|i\rangle \to |S\rangle$ and $|S\rangle \to |f\rangle$, respectively, and Δ_S is the energy denominator. The GT giant resonance in the intermediate nucleus dose not contribute to the $2\nu\beta\beta$ process. Experimental values for $M^{2\nu}$ are shown to be consistent with the theoretical prediction [16].

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. (16). In fact, M_S^ν and $M_{S'}^\nu$ are reduced by a factor $g_A^{\rm eff}/g_A \sim 0.3$ with respect to the single particle value, and accordingly $M^{2\nu}$ is reduced by a factor $(g_A^{\rm eff}/g_A)^2 \sim 0.01$. Theoretical calculations of $M^{2\nu}$ are difficult. Thus experimental evaluation by using Eq. (16) is very useful.

Nuclear matrix elements $M^{0\nu}$ include the ν potential term for a virtual ν exchange. Then $M^{0\nu}$ for the ν-mass term is written as

$$M^{0\nu} = M^{0\nu}_{\rm GT} + M^{0\nu}_{\rm F}\,. \tag{17}$$

The GT and F matrix elements are $M^{0\nu}_{\rm GT} = g_A\langle f|h_+(r_{nm},E)\tau_n\sigma_n\tau_m\sigma_m|i\rangle$, and $M^{0\nu}_{\rm F} = g_A\langle f|h_+(r_{nm},E)\tau_n\tau_m|i\rangle$, where the ν potential term $h_+(r_{nm},E)$ is approximately given by the Coulomb term of $R/|\boldsymbol{r_n} - \boldsymbol{r_m}|$. Here r_n and r_m are radii for nucleons associated with $0\nu\beta\beta$. They are confined between the nucleon and nuclear radii of r_0 and R. The Coulomb term for the confined r_n and r_m is found to be given by a separable form [1]. Then $M^{0\nu}$ may be expressed as a separable form as

$$M^{0\nu} \sim \sum_J \left[\frac{M_S(J)M_{S'}(J)}{\Delta_J^S} + \frac{M_G(J)M_{G'}(J)}{\Delta_J^G}\right]. \tag{18}$$

Here $M_S(J)$ and $M_{S'}(J)$ are single β matrix elements through the intermediate single particle-hole states $|S_J\rangle$ with spin J and $M_G(J)$ and $M_{G'}(J)$ are those through the giant resonance $|G_J\rangle$. Δ_j^S and Δ_J^G are the denominators for the single particle–hole state and the giant resonances, respectively. Since the second (giant resonance) term is considered to be small, $M^{0\nu}$ is expressed as

$$M^{0\nu} \sim \sum_J \left[\frac{M_S(J)M_{S'}(J)}{\Delta_J^S}\right]. \tag{19}$$

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. (19), as in case of $2\nu\beta\beta$.

Double charge-exchange reactions are very interesting to study the $\beta\beta$ responses. They provide one with double isospin and double spin–isospin responses relevant to $\beta\beta$ decays. A double charge-exchange reaction of

(^{11}B, ^{11}Li) at medium energy of $E/A \sim 100$ MeV may populate double IAS, double GT and double spin-dipole giant resonances, and low-lying double spin-isospin states. The experimental studies are in progress at RCNP Osaka University.

8. Spectroscopy of $\beta\beta$ and inverse-β decays from ^{100}Mo for ν studies in nuclei

Neutrino mass and flavor mixing are key issues of current neutrino physics. Recent ν oscillation experiments strongly suggest ν oscillations due to non-zero ν-mass differences and flavor mixings [11, 12]. The experimental data suggest that ν's have mass, and that some mass eigenvalues are approximately of the order of $0.01\sim 0.1$ eV.

The relationship between the ν oscillation and $0\nu\beta\beta$ has been studied in several articles [17]. Recently detailed discussions have been made by combining different oscillation solutions for the solar ν data with a future signal from a $0\nu\beta\beta$ experiment [18].

Thus it is of great importance to study ν mass with sensitivity in the 0.01 eV $\sim$ 0.1 eV range. Double beta decay may be the only probe presently able to access such small ν masses.

The oscillation survival probability of solar ν's shows a strong change with energy below 1 MeV for all the solutions of LMA, SMA, and LOW [9].

It has recently been found that ^{100}Mo with large neutrino responses are used for both spectroscopic study of $\beta\beta$ decays with the sensitivity of the order of $\langle m_\nu \rangle \sim 0.03$ eV, and realtime exclusive study of low energy solar ν [13]. The isotope ^{100}Mo is just the one that satisfies the conditions for the $\beta\beta$-ν and solar-ν studies as shown in Fig. 1. The unique features of ^{100}Mo are as follows:

1. The Q value for the $\beta\beta$ decays is as large as 3.034 MeV. Thus the large phase space factor $G^{0\nu}$ enhances the $0\nu\beta\beta$ rate and the large energy sum of $E_1 + E_2 = Q_{\beta\beta}$ places the $0\nu\beta\beta$ energy signal well above most BG. The transition rate for the possible ν-mass of $\langle m_\nu \rangle = 0.02 \sim 0.03$ eV is of the order of 50×10^{-36}/sec with nuclear matrix elements [19]. This is of the same order as the solar-ν capture rate.

2. The threshold energy for the solar-ν absorption into ^{100}Mo is as low as 0.168 MeV. Thus it is possible to observe low energy sources such as *pp*-ν and ^{7}Be-ν. The strong GT strength to the 1^+ ground state of ^{100}Tc is measured by charge-exchange reaction. The strength can also be experimentally measured by electron capture precisely [20]. The large capture rates are also compared with the other target nuclei in Table I.

3. 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. Neutrino captures are tagged by the subsequent β decay of the ^{100}Tc with 16 s halflife to reduce correlated and accidental BG by factors $10^{-5} \sim 10^{-6}$. The energy and angular correlations for the two β-rays identify the ν-mass term in the $0\nu\beta\beta$.

4. It is noted that supernova (SN) ν's are studied also in ^{100}Mo by measuring inverse β decays [21]. SN-ν_e with the average energy of 11 MeV excites the GT giant resonance. If SN-ν_μ and SN-ν_τ with the average energy of 25 MeV oscillate into electron neutrinos (SN-$\nu_{\rm ex}$), they excite the GT giant resonance and the isospin and spin–isospin dipole resonance's. Since SN-$\nu_{\rm ex}$ is higher in energy than SN-ν_e, the cross section and the inverse β energy for SN-$\nu_{\rm ex}$ are much larger than those for SN-ν_e. Thus, they are very sensitive to the possible oscillation from SN-$\nu_{\rm ex}$ to SN-ν_e.

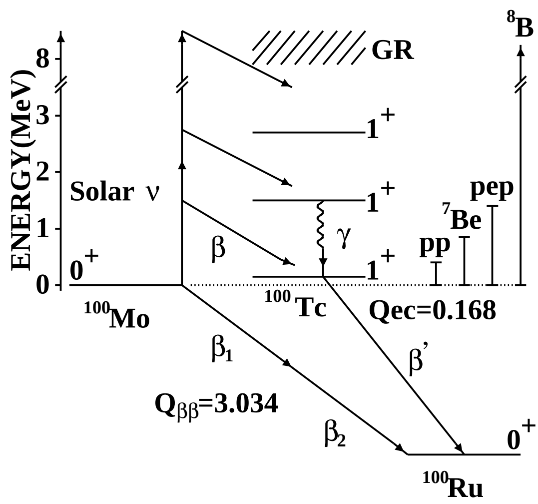

Fig. 1. Level and transition schemes of ^{100}Mo for double beta decays ($\beta_1\beta_2$) and two beta decays ($\beta\beta'$) induced by solar-ν absorption. GR is the Gamow–Teller giant resonance. $Q_{\beta\beta}$ and $Q_{\rm ec}$ are given in units of MeV.

9. Molybdenum Observatory Of Neutrinos (MOON)

MOON is a "hybrid" $\beta\beta$ and solar ν detector with sensitivity to Majorana mass of the order of $\langle m_\nu \rangle \sim 0.03$ eV as well as capability of charged-current neutrino spectroscopy of low energy solar ν's down to 168 keV. The fine localization in time and in space is crucial for reducing BG rates in realistic detectors.

Several options are under investigation for the MOON detector, (a) super modules of Mo and scintillators with WaveLength-Shifter (WLS) fiber read-out, (b) scintillator-fiber detection and readout, (c) liquid scintillators, and, (d) cryogenic calorimetric readout. Simulation spectra of $\beta\beta$ decays and inverse β decays induced by low energy solar-ν's are shown for a possible scintillator/Mo detector in Fig. 2.

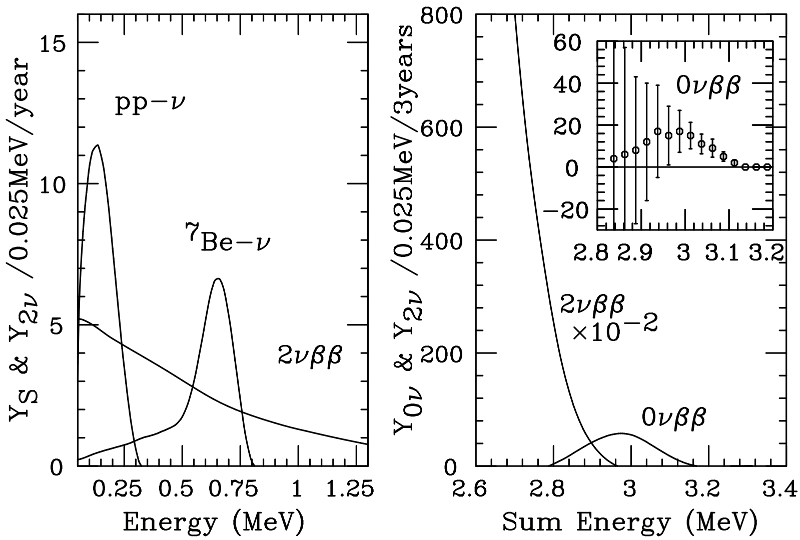

Fig. 2. Schematic energy spectra for a possible detector with 3.3 tons of ^{100}Mo (see text). Right-hand side: Sum energy spectra for 3 year measurement of $2\nu\beta\beta$ and $0\nu\beta\beta$ for $\langle m_\nu \rangle = 0.1$ eV with $M^{0\nu}$ in [15]. The inset shows the $0\nu\beta\beta$ spectrum with $\langle m_\nu \rangle$=0.05 eV after correction for $2\nu\beta\beta$ with statistical errors. Left-hand side: Inverse β spectra for ^{7}Be ν and $pp\,\nu$ on the basis of SSM [9], and possible $2\nu\beta\beta$ backgrounds. The detector threshold is set at 50 keV.

A test of prototype detector for (a) is in progress at RCNP/OULNS, Osaka. It is composed of 8 layers of plastic and WLS-fiber ensembles; each 4-layer group is covered by a different type of reflector for comparison. One layer has the dimension of 20 × 20 × 0.25 cm. Light outputs are collected by a 16-anode PMT through 64 WLS fibers with 2.5 cm interval for the x direction at the front side of the plane and the same for y at the back side, each with 1 mm square size.

An attractive approach offering higher energy resolution to reduce the intrinsic $2\nu\beta\beta$ coming into the $0\nu\beta\beta$ window is low temperature bolometry [22].

A molybdenum-loaded liquid scintillator with WLS or multi-PM read-out is also an promising approach having a lot of advantages.

The cosmogenic isotopes to be considered are the long lived ^{93}Mo, and the short lived ^{99}Nb and ^{100}Nb. Although ^{93}Mo isotopes are not removed chemically, they decay by emitting very low energy X-rays and conversion electrons. Their energies can be lower than the detector threshold. ^{99}Nb and ^{100}Nb are produced by fast neutrons at underground laboratories and decay within tens of seconds by emitting beta rays. They are estimated to give negligible contributions to the present energy and time windows. Backgrounds from U and Th chain activities must be controlled at the level of approximately $b \sim 10^{-2}$ Bq/ton. The same type of purification through the carbonyl that has been used for Ni for the SNO, and the purity level that has been achieved for Ni and other materials, can be used [23].

10. Concluding remarks

Fundamental properties of neutrinos and weak interactions are studied in nuclei as micro-laboratories. Here nuclei are used to select and enhance neutrino signals and to reduce other backgrounds. Nuclear responses for neutrinos are crucial for neutrino studies in nuclei.

Nuclear responses for neutrinos are given by vector and axial-vector type weak responses. They are expressed in general by nuclear spin–isospin responses as $R_\nu(TSLJ)$ with isospin $T = 1$, spin $S = 0{,}1$, orbital angular momentum L, total spin J and the initial state spin J_i.

Nuclear spin–isospin responses $R_\nu(TSLJ)$ are modified in nuclei by nuclear spin–isospin correlations. Actually the responses are much enhanced by spin–isospin giant resonances of $Q^+(TSLJ)$ at high excitation regions, and are reduced by the spin–isospin core polarizations due to the destructive interference with giant resonances.

Nuclear reactions with weak, electro-magnetic and hadron probes are used for obtaining R_ν in a wide excitation region. Electro-magnetic probes are used for neutral-current responses.

Nuclear weak reactions with neutrino probes are direct ways to get nuclear responses for neutrinos. Since reaction cross sections are extremely small, one needs intense ν beams and large ν detectors. High intensity proton beams from the 3 GeV synchrotron of JHF planned at Tokai Japan, and those from SNS at ORNL may provide intense ν's with intensity of the order of 10^{14} in the low energy region of $5 \sim 100$ MeV. These ν's are just adequate for nuclear response studies for solar-ν, supernova-ν and $\beta\beta$-ν. Large ν detectors such as ORLaND [24] and MOON [13] are very interesting . The low energy ν factory combined with the large ν detector is a promising project for new nuclear physics in the 21st century. Muon captures are very effective for studying spin–isospin responses in the τ_+ mode since the capture cross sections are large.

Charge-exchange nuclear reactions with medium energy hadron beams have been used extensively for studying charged-current responses in a wide excitation region. Light projectiles with energies of $E/A = 100 \sim 300$ MeV are used because of the relatively large spin-isospin interaction of $V_{\tau\sigma}$ and the small distortion potential of V_0. High energy-resolution studies of (^{3}He, t) reactions at RCNP and (t,^{3}He) reactions at MSU are powerful for studying nuclear spin–isospin responses in τ_- and τ_+ modes, respectively.

Solar-ν capture reactions in nuclei by charge-exchange (ν, e) reactions and inelastic (ν, ν') reactions are used to study weak and strong processes associated with solar-ν productions in the sun and ν oscillations. Nuclear spin–isospin responses for pp-ν, ^{7}Be-ν and other CNO ν's with energies $E_\nu < 2$ MeV are reduced by the spin–isospin core polarization, and those for ^{8}B-ν and hep-ν with $E_\nu = 5 \sim 19$ MeV are enhanced by the GT giant resonances. The charged-current responses for ^{71}Ga, ^{100}Mo, and ^{176}Yb have been studied by charge-exchange (^{3}He, t) reactions and others [4–6].

Supernova-ν capture reactions in nuclei are studied by (ν, e) , (ν_x, ν'_x) and $(\nu_x \to \nu_e, e)$ reactions with $\nu_x \to \nu_e$ standing for the neutrino flavor oscillation. Energy spectra of supernova-ν's show broad peaks with mean energies around $\langle E_\nu \rangle$ ~11 MeV for ν_e, $\langle E_\nu \rangle$ ~16 MeV for $\bar{\nu}_e$, and $\langle E_\nu \rangle$ ~25 MeV for other ν_x's, They are located in the same excitation region of the GT and spin dipole giant resonances. Consequently nuclear responses for supernova-ν are dominated by these spin–isospin giant resonances with $T = 1$, $S = 0,1$, $L = 0,1$, and $J = 0,1,2$. They are studied by measuring charge exchange and inelastic reactions with medium energy hadrons at 0° for $L = 0$, and $1^\circ \sim 2^\circ$ for $L = 1,2$. Direct proton decays and statistical neutron decays from these giant resonances are used for evaluating supernova-ν energies, which are important for ν oscillation and supernova studies.

Neutrino-less double beta decays ($0\nu\beta\beta$), which violate the lepton number conservation law by $\Delta L = 2$, are used to study the Majorana ν mass, the right-handed weak current, and other neutrino properties beyond SM. The neutrino-less decay is mainly due to a virtual ν exchange between two nucleons in a nucleus, where the neutrino momentum involved is $1 \sim 50$ MeV/c, and accordingly intermediate states with $E_{\rm ex}$ up to ~50 MeV, and L up to ~ $5\,\hbar$ are involved in the $0\nu\beta\beta$ process. Thus multi-pole spin–isospin responses with $J = 0 \sim 5$ contribute $\beta\beta$-ν responses. The nuclear matrix element is written by a separable form as $M^{0\nu} = \sum_J M_S(TSLJ) M_{S'}(TSLJ)/\Delta_S(J)$. Then $M_S(TSLJ)$ and $M_{S'}(TSLJ)$ for single particle–hole states in the intermediate nucleus are obtained from charge-exchange hadron reactions and/or single β decay rates. Double charge-exchange reactions are interesting for obtaining directly double spin–isospin responses relevant to $\beta\beta$ decays.

^{100}Mo isotopes are used as excellent micro-laboratories for neutrino studies because of the large nuclear responses for charged-current interactions of neutrinos and the unique nuclear level structures. Spectroscopic studies of two β rays from ^{100}Mo are used for investigating both the Majorana ν mass by $0\nu\beta\beta$ decays and low energy solar ν's by inverse β decays.

MOON is a realistic detector with one ton ^{100}Mo isotopes to be used for studying $0\nu\beta\beta$ decays with a sensitivity of $\langle m_\nu \rangle \sim 0.03$ eV by measuring the two correlated β rays and the pp and ^{7}Be solar ν's by measuring the inverse β decays and successive β decays from ^{100}Tc.

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