NEUTRINO NUCLEAR SPIN RESPONSES AND NUCLEAR MEDIUM EFFECTS

H. EJIRI

Research Center For Nuclear Physics, (RCNP) Osaka University, Ibaraki, Osaka 567-0047 Japan, ejiri@rcnp.osaka-u.ac.jp

Neutrinos and weak interactions have extensively been studied by measuring β, $\beta\beta$, and inverse β decays in nuclei. Here, neutrino nuclear responses, which are crucial for deducing fundamental properties of neutrinos, are mostly spin isospin responses. They are modified in the nuclear medium by nuclear spin isospin correlations. This report describes briefly 1)neutrino studies in nuclei and nuclear spin responses, 2)neutrino studies by $\beta\beta$ decays and nuclear spin isospin responses, and 3)solar neutrino studies by inverse β decays and nuclear spin responses.

1 Neutrino Studies in Nuclei and Nuclear Spin Responses

1.1 Neutrino Studies in Nuclear Microlaboratories

Nuclei, which consist of nucleons in good quantum states of E, J^π, T, and others, are used as good microlaboratories for studying elementary particles and fundamental interactions[1]. Merits of nuclear microlaboratories are selectivity and enhancement of particular processes of interest and rejection of other background processes.

Neutrino studies in nuclear double beta decays ($\beta\beta$) are good examples of nuclear particle studies in nuclear microlaboratories. Nuclear $\beta\beta$ decays are studied in nuclei, where single β, electromagnetic and strong decays are energetically forbidden. Thus one can measure selectively ultra-rare $\beta\beta$ decays without disturbance of single β, electromagnetic γ and strong nuclear decays. The neutrino-less $\beta\beta$ decay ($0\nu\beta\beta$), which is relevant to the physics beyond the standard theory, is a ν-exchange process between two nucleons in a small nucleus. Thus, the $0\nu\beta\beta$ process is enhanced by an order of $10^6 \sim 10^8$ in comparison with normal two neutrino $\beta\beta$ process. Here the nucleus acts as a micro-laboratory with a large enhancement factor for the ν process of the particle physics interest and with a large filtering power to eliminate other background processes.

Precision studies of neutrinos provide one with stringent verifications of the standard electro-weak theory of $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)$ and with possible evidences for physics beyond the standard theory. Fundamental questions of ν relevant to physics beyond the standard theory are studied by investigating nuclear single and double beta decays, nuclear ν scatterings and other nuclear weak processes in nuclear microlaboratories. High precision studies of energy spectra and longitudinal polarizations for single β decays are sensitive to the electron ν-mass and the right-handed component of ν_e, respectively. High sensitive studies of nuclear rare $\beta\beta$ decays are used to investigate fundamental properties of neutrinos and weak interactions and the nuclear response for $\beta\beta$-ν. Inverse β decays are used to measure the solar-ν flux. Accurate measurements of the solar-ν flux are important for studies of the solar-ν problem associated with solar-ν production rates and ν-oscillations.

Neutrinos are also very interesting in views of astroparticle physics and cosmology. The mass of the universe is considered to be mainly due to invisible dark matters (DM). Light neutrinos and heavy neutrinos are possible candidates for hot and cold dark matters, respectively. The heavy neutrinos are studied by measuring elastic and inelastic scatterings of them from nuclei.

1.2 Neutrino Nuclear Spin Responses and Nucelar Medium Effects

It is crucial for β-ν, $\beta\beta$-ν and solar-ν studies in nuclear microlaboratories to get reliable nuclear responses for these nuclear-ν processes. The ν nuclear responses are deduced by measuring charge-exchange spin-flip nuclear reactions. The ν-production rates in the sun are studied by investigating cross-sections of the relevant nuclear processes at low energies.

Here the ν responses in nuclei are modified much from the single- nucleon ν resoponses because of nucelar medium effects. The β and $\beta\beta$ decays are due to charged vector and charged axial-vector weak currents. Thus the ν-nuclear responses involved in the β and $\beta\beta$ processes are isospin and isospin-spin responses. They are modified in the nuclear medium by the nuclear isospin and spin correlations.

The isospin and isospin-spin nuclear responses are studied by investigating charge-exchange spin-nonflip and charge-exchange spin-flip reactions. They are shown in Fig. 1. The isospin strengths for low-energy nuclear weak processes

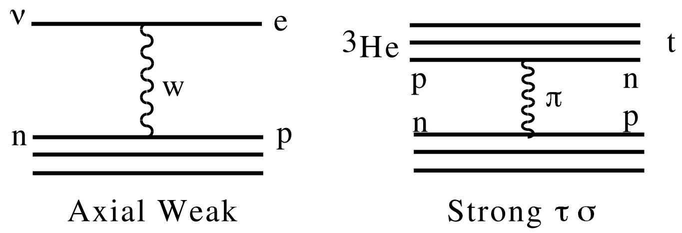

Figure 1: Nuclear spin isospin responses for axial charged weak processes and those for spin-flip charge-exchange strong processes.

are concentrated in the isobaric analogue state (IAS) because of the isospin symmetry in nuclei. On the other hand, the isospin spin strengths are spreaded in a wide excitation region. Thus the nuclear ν responses are mostly isospin spin responses.

The RCNP (Rerearch Center for Nuclear Physics) ring cyclotron provides one with medium energy (0.1∼0.4 GeV/A) light ions. They are just adequate for studying nuclear isospin-spin responses.

2 Neutrinos Studied By Double Beta Decays and Nuclear Spin Responses

2.1 Neutrino Studies By Double Beta Decays

Double beta decays ($\beta\beta$) are quite interesting from both astroparticle physics and nuclear physics view points [1-7]. Astroparticle physics aspects are concerned with fundamental properties of neutrinos and weak interactions, and nuclear physics aspects with nuclear medium effects on nuclear spin isospin responses.

In the framework of the minimal $\mathrm{SU(2)_L}\times$ U(1) standard theory, the double beta decays are followed by 2 neutrino(ν) emission, and the lepton number (L) is conserved. It is written as

$$A \to B + \beta + \beta + \nu + \nu. \tag{1}$$

Here ν is the electron anti-neutrino in case of the electron (β^-) decay and is the electron neutrino in case of the positron (β^+) decay. This process is called the two neutrino double beta decay ($2\nu\beta\beta$). The double beta decay without neutrino emission violates the lepton number conservation by $\Delta L = 2$. This is called the neutrino-less double beta decay ($0\nu\beta\beta$). It is written as

$$A \to B + \beta + \beta. \tag{2}$$

The $0\nu\beta\beta$ process is indeed a very sensitive probe for studying such quantities as the Majorana neutrino mass $\langle m_\nu \rangle$, the right handed weak current $\langle$RHC$\rangle$, the Majoron $-\nu$ coupling, the R-parity violating coupling with SUSY (super symmetry) particles, and others, which are beyond the standard $\mathrm{SU(2)_L}\times$ U(1) theory [1-9]. The $2\nu\beta\beta$ and $0\nu\beta\beta$ processes are schematically shown in Fig 2.

The transition rate $T^{0\nu}$ for $0\nu\beta\beta$ (Fig. 2 B) is given in terms of $\langle m_\nu \rangle$ and $\langle$RHC$\rangle$ as follows [2-7].

$$\begin{aligned} T^{0\nu} = G^{0\nu} \mid M^{0\nu} \mid^2 [\langle m_\nu \rangle^2 + C_{\lambda\lambda}\langle\lambda\rangle^2 + C_{\eta\eta}\langle\eta\rangle^2 + \\ C_{m\lambda}\langle m_\nu\rangle\langle\lambda\rangle + C_{m\eta}\langle m_\nu\rangle\langle\eta\rangle + C_{\lambda\eta}\langle\lambda\rangle\langle\eta\rangle], \end{aligned} \tag{3}$$

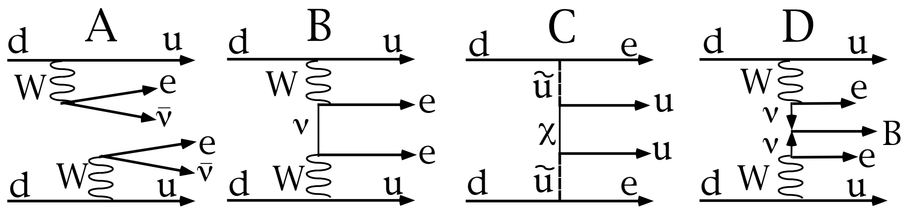

Figure 2: Schematic diagrams of $\beta\beta$ decay processes: A, two-neutrino process, B, neutrino-less process with the Majorana neutrino exchange; C, neutrino-less process in the SUSY model; and D, neutrino-less process followed by the Goldstone boson B (Majoron).

where $\langle\lambda\rangle$ and $\langle\eta\rangle$ are the <RHC> terms. λ is written as $(M_W^L/M_W^R)^2$ with $M_W^L(M_W^R)$ being the mass of the left-handed (right-handed) weak boson, and η is the coupling of left and right weak bosons. $G^{0\nu}$ is the phase space factor, $M^{0\nu}$ is the nuclear matrix element for the mass term, and C_{ij} is the matrix element for the relevant term in unit of $M^{0\nu}$. Actually, $M^{0\nu}$ and $C_{ij}M^{0\nu}$ represent the spin isospin nuclear responses.

The transition rates for the gluino ($\tilde{g}$) exchange process (Fig. 2C), the Majoron emitting process ($0\nu\beta\beta$B, Fig. 2D), with $\langle g_B\rangle$ being written as $g_B\Sigma U_{ej}U_{ei}$, and for double Majoron emitting one ($0\nu\beta\beta$BB) are discussed in refs. [1-9].

The $0\nu\beta\beta$, $0\nu\beta\beta$B and $2\nu\beta\beta$ are studied by measuring sum energy spectra of $E_\beta + E_{\beta'}$. Individual terms of $\langle m_\nu\rangle, \langle\lambda\rangle$ and $\langle\eta\rangle$ of $0\nu\beta\beta$ are determined by studying energy and angular correlations of two β rays [10].

The transition rate $T^{2\nu}$ for $2\nu\beta\beta$ (Fig. 2A) is written as

$$T^{2\nu} = G^{2\nu} \mid M^{2\nu} \mid^2, \tag{4}$$

where $G^{2\nu}$ and $M^{2\nu}$ are the phase space factor and the nuclear matrix element, respectively. Thus observed $2\nu\beta\beta$ halflives give $2\nu\beta\beta$ matrix elements $M^{2\nu}$. They are used to verify nuclear structure calculations for $M^{2\nu}$ and parameters for spin-isospin interactions. They are used also for calculating $M^{0\nu}$.

The $2\nu\beta\beta$ process for the $0^+ \to 0^+$ ground state transition in even even nuclei proceeds mostly via intermediate states with spins $J^\pi \leq 1^+$ because the real β and ν are mostly of s-wave. The $0\nu\beta\beta$ process associated with the virtual ν-exchange between two nucleons in the nucleus involves large momentum transfers of $q = 0.2 \sim 0.4$ GeV/c, and accordingly large angular momenta J^π up to $6^\pm$.

Experimental studies of $\beta\beta$ have been carried out by means of indirect geochemical and radiochemical methods and direct counting methods. They are given in review articles [1-7] and references therein. These indirect methods are inclusive measurements of all kinds of $\beta\beta$ decays to ground and excited states.

High sensitive detector systems, ELEGANT's [ELEctron GAmma-ray Neutrino Telescopes] have been developed by the Osaka Group to study $\beta\beta$ decays and dark matters. EL. V consists of two drift chambers for β-ray trajectories, 16 modules of plastic scintillators for β-ray energies and times, and 20 modules of NaI detectors for X and γ-rays [11]. The $2\nu\beta\beta$ matrix elements were obtained from the $2\nu\beta\beta$ halflives [11, 12] as 0.09 for ^{100}Mo and 0.069 for ^{116}Cd. They are indeed one tenth of the single particle value. The ^{100}Mo run gave most stringent limits on halflives for the $0^+ \rightarrow 0^+$ $0\nu\beta\beta$ and $0\nu\beta\beta$B processes. The energy spectrum for ^{100}Mo is shown in Fig. 3. The upper limits in the $\langle m_\nu \rangle$, $\langle \lambda \rangle$ and $\langle \eta \rangle$ space were obtained by using nuclear matrix elements in ref. 13.

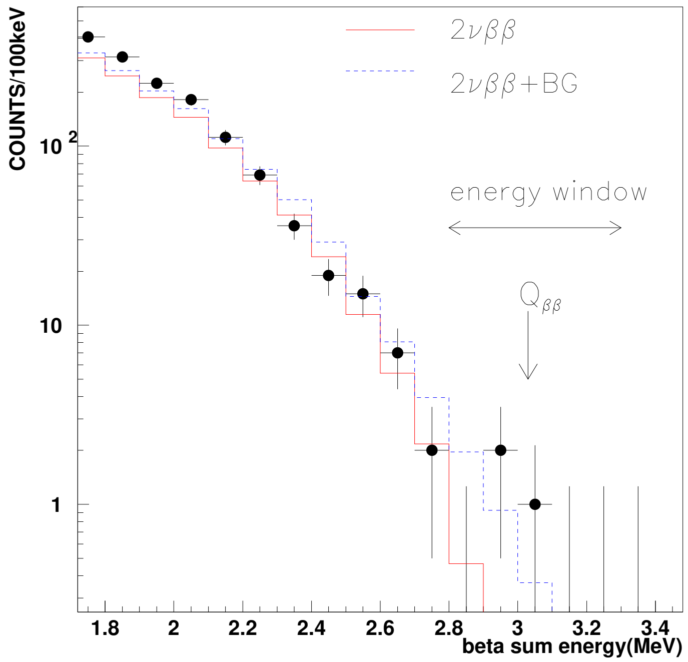

Figure 3: Sum energy spectrum of $E_\beta + E^{'}_\beta$ for $\beta\beta$ decays of ^{100}Mo (left-hand side). The Monte Carlo simulation with $T^{2\nu}_{1/2} = 1.15 \cdot 10^{19} y$ is shown [10].

The obtained limits with 68% CL are as follows.

$0\nu\beta\beta$	$\langle m_\nu \rangle$	$T_{1/2} > 5.2 \cdot 10^{22} y$	$\langle m_\nu \rangle$	< 2.2 eV
$0\nu\beta\beta$	$\langle \lambda \rangle$	$T_{1/2} > 3.9 \cdot 10^{22} y$	$\langle \lambda \rangle$	$< 4.3 \cdot 10^{-6}$
$0\nu\beta\beta$	$\langle \eta \rangle$	$T_{1/2} > 5.1 \cdot 10^{22} y$	$\langle \eta \rangle$	$< 2.5 \cdot 10^{-8}$
$0\nu\beta\beta$B	$\langle g_{\mathrm{B}} \rangle$	$T_{1/2} > 0.54 \cdot 10^{22} y$	$\langle g_{\mathrm{B}} \rangle$	$< 7.3 \cdot 10^{-5}$

Limits on supersymmetric parameters [14] are derived from the limit on $0\nu\beta\beta$ as

$$\lambda'_{111} \leq 6.9 \cdot 10^{-9} (m(\tilde{q}))^2 (m(\tilde{g}))^{1/2}, \tag{5}$$

where $m(\tilde{q})$ and $m(\tilde{g})$ are the squark and gluino masses, in unit of GeV, respectively, and λ'_{111} is the R-parity violating (lepton-number non-conserving) coupling. The $0\nu\beta\beta$ limit gives a limit on the mass of the excited neutrino in the framework of the composite neutrino model [15]. The limit obtained from the ^{100}Mo $0\nu\beta\beta$ limit is

$$m(\nu^*) > 5.9 \cdot 10^4 \mathrm{TeV}. \tag{6}$$

EL. VI consists of 25 modules of CaF_2 scintillators surrounded by 3π CsI detectors [16]. Because of the large Q value of 4.27 MeV, one may study well both $0\nu\beta\beta$ and $2\nu\beta\beta$ of ^{48}Ca.

EL.V and EL.VI are installed at the new underground lab. of Ohto Cosmo Observatory with around 1500 m w.e. It is located at about 100 Km south from Osaka Univ. Background levels at the new lab. are $4 \cdot 10^{-3}/\mathrm{m}^2/\mathrm{sec}$ for cosmic muons, $4 \cdot 10^{-1}/\mathrm{m}^2/\mathrm{sec}$ for neutrons, and 10 $\mathrm{Bq/m}^3$ for Rn. These are satisfactory small.

Stringent lower limits on $0\nu\beta\beta$ halflives have been obtained for ^{76}Ge, ^{136}Xe, and others, as reported in recent conferences [17]. They give upper limits on $\langle m_\nu \rangle$, $\langle$RHC$\rangle$, $\langle g_{\mathrm{B}} \rangle$, SUSY-couplings, and other neutrino properties. These data, together with the present Osaka data, lead to stringent limits of $\langle m_\nu \rangle < 1 \sim 3$eV, and $\langle g_\beta \rangle < 1 \sim 2 \cdot 10^{-4}$. The electron Majorana neutrino by itself may not be the major DM component.

It is important to get limits on neutrinos and weak currents from several high-precision data such as ^{76}Ge, ^{100}Mo, ^{136}Xe , and so on because of the possible uncertainties in the nuclear spin isospin responses (matrix elements) involved.

2.2 Neutrino Nuclear Responses and Charge Exchange Nuclear Reactions

Nuclear $\beta\beta - \nu$ responses are given by the nuclear matrix elements of $M^{2\nu}$ and $M^{0\nu}$. They depend largely on nuclear spin-isospin ($\sigma\tau$) interactions used for nuclear structure calculations. Recent QRPA (Quasiparticle Random Phase Approximation) calculations indicate that $M^{2\nu}$ is quite sensitive to the particle-particle interaction [18-22].

The $2\nu\beta\beta$ nuclear matrix elements are as small as $M^{2\nu} = 10^{-1} \sim 10^{-2}$ in unit of $(m_e c^2)^{-1}$. $M^{2\nu}$ for $0^+_i \to 0^+_f$ ground state $\beta\beta$ decays of even-even nuclei consists of $M^{2\nu}(1^+)$ and $M^{2\nu}(0^+)$ for intermediate 1^+ and 0^+ states, respectively. $M^{2\nu}(0^+)$ is considered to be much smaller than $M^{2\nu}(1^+)$, because the Fermi strength with the isospin operator τ_- is entirely absorbed into the double isobaric analogue state (IAS) in the high excitation region.

$M^{2\nu}(1^+)$ for the ground state transition $|0_i\rangle \to |0_f\rangle$ is written as

$$M^{2\nu}(1^+) = \sum_k \frac{M^\nu_k M^\nu_{k'}}{\Delta_k}, \tag{7}$$

where M^ν_k and $M^\nu_{k'}$ stand for the single β matrix elements for the successive β transitions from the initial $0^+(\mid 0_i\rangle)$ to the final $0^+(|0_f\rangle)$states through the k-th intermediate 1^+ state. The energy denominator Δ_k is given as $\Delta_k = E_k - E_i + Q_{\beta\beta}/2$, where $Q_{\beta\beta}$ is the Q-value for the ground state $\beta\beta$ transition and E_k is the excitation energy of the k-th state.

There exists one single particle-hole 1^+ state $\mid S\rangle$ with $[j_p \cdot j_n^{-1}]$ in most medium-mass nuclei. The observed values for $M^{2\nu}$ are found to be reproduced by the one major component of $M^\nu_S M^\nu_{S'}/\Delta_S$ through the SP 1^+ intermediate state in eq. (7). Thus it is written as [23].

$$M^{2\nu} \approx M^\nu_S M^\nu_{S'}/\Delta_S, \tag{8}$$

The GT strengths are indeed concentrated mostly in the single particle-hole 1^+ state $(\mid S\rangle)$ and the GT giant resonance state $(\mid G\rangle)$. The GT component of the $2\nu\beta\beta$ matrix element is evaluated by assuming, for simplicity, two intermediate states, $\mid S\rangle$ and $\mid G\rangle$, as follows:

$$M^{2\nu}(1^+) = \frac{M^\nu_S M^\nu_{S'})}{\Delta_S} + \frac{M^\nu_G M^\nu_{G'}}{\Delta_G}. \tag{9}$$

Introducing the $\tau\sigma$-type interaction H_I between $\mid S\rangle$ and $\mid G\rangle$, one gets mixing between them. The similar mixing exists between the final state $\mid S'\rangle$ and the giant GT resonance $\mid G'\rangle$. Then, the contribution through the GT giant resonance given in the second term is shown to be negligible because of the cancelation between the two mixing terms. Consequently, the $2\nu\beta\beta$ matrix element is approximately expressed by eq.(9). The giant resonance $\mid G\rangle$ does not contribute much to $M^{2\nu}(1^+)$.

It is very interesting to extend the present analysis for $J^\pi = 1^+$ to higher multipole states with $J^\pi \neq 1$, which are relevant to $0\nu\beta\beta$. Studies of both τ_- type (^{3}He, t) and (p,n) reactions and τ_+ type (t,^{3}He) and (d, ^{2}He) reactions are important in order to obtain intermediate GT strengths experimentally.

The nuclear response for $0\nu\beta\beta$, where one neutrino is exchanged between two nucleons in the nucleus, is given by the neutrino potential of the Coulomb type. It is written as $\upsilon_0/\mid \mathrm{r}_1\text{-}\mathrm{r}_2 \mid$ with r_1 and r_2 being the cordinates of the two nucleons. It has recently been shown that the Coulomb type neutrino potential is expressed by the separable form of $f(r_1)\cdot f(_2)$ [24]. Then the $0\nu\beta\beta$ response $M^{0\nu}$ may be also expressed as the product of the matrix elements for successive β decays.

2.3 Nuclear Spin Responses Studied By Nuclear Charge-Exchange Reactions

Nuclear isospin spin responses associated with the charged axial weak processes are investigated by means of charge-exchange spin-flip nuclear reactions, as illustrated in Fig. 1.

The charge exchange (^{3}He, t) reaction on the stable isotope of ^{100}Mo was studied [25]. The 450 MeV ^{3}He beam was provided from the RCNP Osaka ring cyclotron. The observed energy spectrum of the (^{3}He, t) reaction shows discrete states at the low excitation region, the sharp IAR (isobaric analogue resonance), and the broad GTR (GT giant resonance), as shown in Fig. 4. The

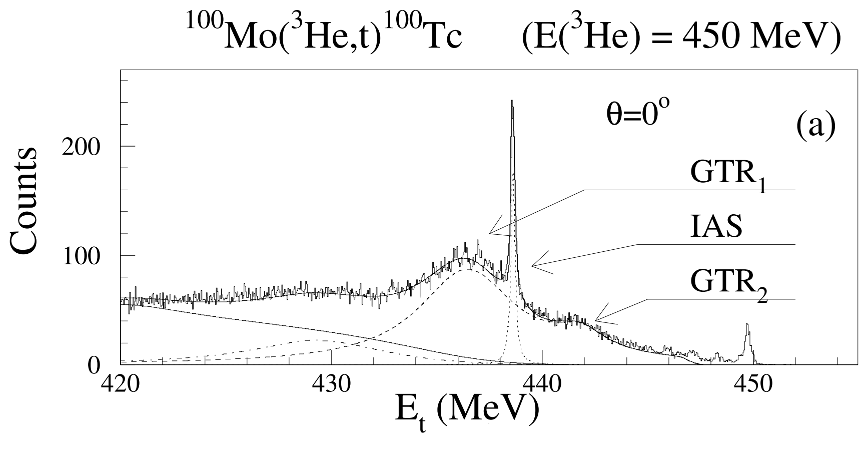

Figure 4: Energy spectrum for ^{100}Mo (^{3}He, t) ^{100}Tc. IAS(dotted line) and GTR(dashed line) are the isobaric analogue state and GT giant resonances, respectively [25].

matrix element $M_S^\nu(0_i \to 1)$ obtained by the (^{3}He, t) reaction and the matrix element $M_{S'}^\nu(1 \to 0_f)$ obtained from the known $\log(ft)$ are used to estimate the $2\nu\beta\beta$ matrix element $M_S^\nu M_{S'}^\nu/\Delta_S$ through the 1^+ ground state in the intermediate nucleus. The estimated value reproduces the observed value $M^{2\nu}$ obtained from the $2\nu\beta\beta$ halflife [11]. The strong GTR, which absorbs a large fraction of the single GT strength, does not contribute to $2\nu\beta\beta$. This supports the simple expression of eq.(8) derived by the experimental and theoretical analyses [23].

3 Nuclear Spin Responses for Solar Neutrinos Studied By Inverse Beta Decyas

Solar-ν problems involve current subjects of particle-physics, astrophysics and of nuclear physics, as discussed in various review articles [26, 27] and references therein. Solar neutrinos provide one with a very sensitive probe for the neutrino oscillation [27] because of the long distance between the sun and the earth, the strong solar neutrino flux, and of the large volume of the solar matter. The astrophysics aspect is neutrino production rates [26].

The nuclear physics aspect includes the neutrino production processes in the sun. Nuclear reaction rates (cross-sections) at the low energy region of the solar system are very small. They are studied by using high-intensity low-energy beams at underground laboratories.

The solar-ν flux has been studied by inverse beta decays and electron scattering [28-30]. Inverse beta decays (neutrino absorptions) of nuclei with low Q values are effective for studying major components of the solar - -ν. Recent measurements of the solar neutrino flux indicate shortage of the solar neutrino flux, which are hardly explained by conventional solar models [28-30].

Spin isospin responses (strengths) for the solar neutrino give directly the absorption (inverse beta decay) rates, which are crucial for the solar neutrino problem.

The major component of the pp solar neutrino has been studied by

$$\nu + {}^{71}\mathrm{Ga} \to \beta^- + {}^{71}\mathrm{Ge} \quad \text{and} \tag{10}$$

$$\beta^- + {}^{71}\mathrm{Ge}^* \to \beta^- + {}^{71}\mathrm{Ge} + \gamma. \tag{11}$$

The number of ^{71}Ge isotopes are counted to extract the solar neutrino flux.

The spin isospin strengths for ν+^{71}Ga have been investigated by means of the (^{3}He, t) reaction on ^{71}Ga [31]. The energy spectrum at $\theta = 0^o$ is shown in Fig. 5. The spectrum consists of the single particle-hole strengths for low lying discrete states, the isobaric analogue state, and the GT giant resonances. GT strengths for states below the neutron threshold energy of 7.4

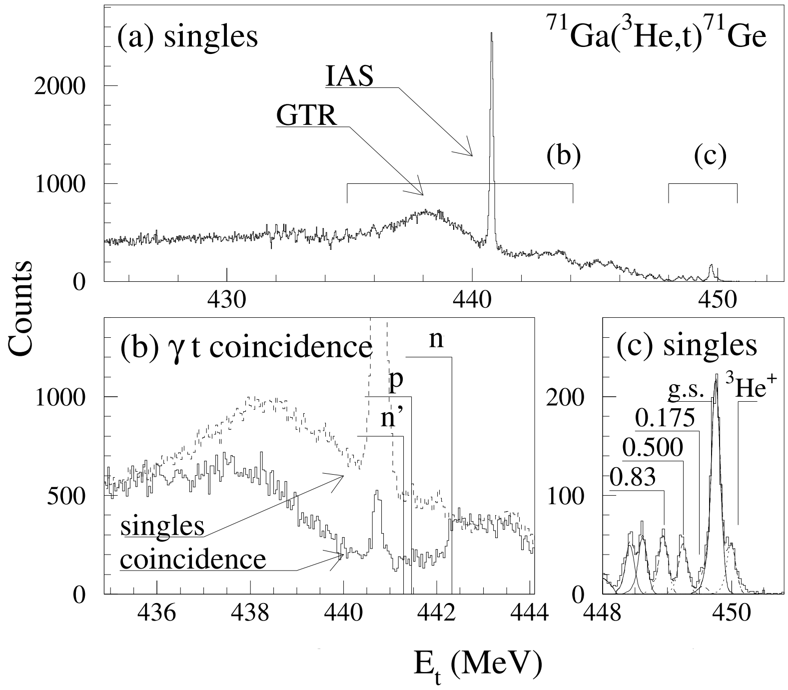

Figure 5: A zerp-degree ^{71}Ga(^{3}He, t)^{71}Ge spectrum at E(^{3}He)=450 MeV [31]. (a) Singles spectrum, (b) coincidence spectrum gated by γ-rays, and (c) enlarged spectrum for low lying states. The energies are given in unit of MeV.

MeV are derived. The total GT strength of 3.07 $\pm$ 0.11 was found for ^{71}Ge up to the particle threshold energy of 7.4 MeV. On the basis of the standard solar model (SSM), capture rates of the solar neutrino are deduced from the observed B(GT) values, as shown in Table 1. They are given in unit of solar neutrino unit of SNU. The present value supports the calculated value [26]. In fact the solar-ν absorption is investigated by measuring the daughter nuclei of ^{71}Ge produced by the ^{71}Ga $(\nu, e\gamma)$ ^{71}Ge. The corresponding reaction is studied by measuring the ^{71}Ga $(^{3}\mathrm{He}, \mathrm{t}\gamma)$ ^{71}Ge process. It is interesting to note that the levels above the neutron threshold energy by a couple of hundred keV feed the ground state by γ-dacays, producing the ^{71}Ge nuclei, as shown in Fig. 5. The contribution is 0.3 SNU, which is about 2.5% of the ^{8}B-ν absorption rate [31].

neutrino source	present result (SNU)	Bahcall (SNU)
pp	$70.8 \pm 0.2 \pm 1.4$	70.8
^{8}B	$12.6 \pm 0.4 \pm 4.7$	14.0
hep	$(5.34 \pm 0.15) \times 10^{-2}$	0.06
^{13}N	$3.74 \pm 0.07 \pm 1.87$	3.8
^{15}O	$5.81 \pm 0.14 \pm 3.37$	6.1
^{17}F	$(6.01 \pm 0.15 \pm 2.76) \times 10^{-2}$	0.06
pep	$2.94 \pm 0.09 \pm 0.15$	3.0
^{7}Be	$35.0 \pm 0.7 \pm 5.3$	34.3
total	$130.3 \pm 1.57 \pm 16.8$	132^{+20}_{-17}

Table 1: Neutrino capture rate for individual neutrino sources. The values are obtained with the assumption of the neutrino flux given by the standard solar model by Bahcall [26]. The uncertainties of the present results are caused by those from the experimental B(GT) values and from the standard solar model,respectively.

The present work has partly been given in the recent review article [1] and in the recent report [32].

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