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NEUTRINOS AND SYMMETRIES STUDIED BY NUCLEAR DOUBLE BETA AND RARE DECAYS *

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Nuclei, which consist of nucleons in good quantum states, are good micro-laboratories for studying fundamental interactions and elementary particles. In particular, nuclear double beta decays and nuclear rare decays are used to study neutrinos (ν) and symmetries in nuclear microlaboratories. Subjects discussed include (*i*) ν-masses and weak interactions studied by nuclear double beta decays ($\beta\beta$), (*ii*) neutrino nuclear responses for solar-ν and $\beta\beta - \nu$, (*iii*) strange-quark weak processes studied by hyperon weak decays in nuclei, and (*iv*) nucleon decays studied by nuclear rare deexcitations. All these subjects are associated with neutrinos and symmetries beyond the standard theory.

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1. Nuclear microlaboratory for symmetry studies

Nuclei are ultra-cold quantum systems of interacting nucleons. Major interactions there are electro-weak and strong interactions. Here nucleons are in low energy quantum states with good quantum numbers of energy E and spin J, which are associated with symmetries in time transfer and space rotation, respectively.

Symmetries are broken in nuclei except for symmetries associated with these time and space transformations. Fundamental interactions in nuclei are not symmetric, but electromagnetic, weak and strong interactions are quite different in strength. There are quite distinct differences between quarks and leptons, and between fermions and boson. They don't mix with each other, and thus the baryon number B and the lepton number L are

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extremely good quantum numbers. The properties of particles depend on their generations and/or flavours. Neutrino masses are nearly zero, but other particles have finite and different masses. The left-right asymmetry in the weak interaction is almost maximum. Thus the parity is completely violated in the weak interaction but no P violation is found in the electromagnetic and strong interactions. On the otherhand, the CP violation is small in the weak process of quark sectors. So far, the T violation is not found in any interactions within experimental limits.

The standard theory (ST) is formulated on the basis of theoretical considerations on these experimental observations. Thus ST includes partially symmetric and partially asymmetric features, depending on interactions and particles.

Nuclei as broken symmetry nucleon systems, however, show partial/asymptotic symmetries. Nuclear states in nuclei have approximately good quantum numbers. Parities(π), flavours($s, c, \cdots$) and nucleon numbers(B) are fairly good quantum numbers in bound nuclei, where nucleons are stable against strong interactions. This is because weak interactions are much weaker than strong interactions in cold nuclei. Isospins T are approximately good quantum numbers in low excitation states because the short range nuclear interactions are nearly isospin-independent and the Coulomb interaction is of long range.

Nuclei with fairly good quantum numbers are used as microlaboratories for studying fundamental interactions and elementary particles. In particular, symmetries are studied effectively in nuclear microlaboratories by searching for small deviations from broken symmetries towards symmetries and unifications. Then the symmetry studies may provide one with stringent verifications of ST and with evidences for unified symmetric theories beyond ST.

Nucleons in nuclei are in states with quite good quantum numbers of E, J^{π}, T, B, L and so on. Then one can select specific types of interactions, $H(E, J^{\pi}, T)$, to be studied in nuclear processes. Nuclear processes to be studied are written as

$$M_{\alpha} = \langle E_i J_i^{\pi} T_i \alpha_i | H | E_f J_f^{\pi} T_f \alpha_f \rangle, \tag{1}$$

where i and f stand for initial and final nuclear states, respectively. It is even possible to enhance specific interaction processes of particle physics interests, and to hinder other background processes by selecting particular nuclear states and transitions as shown in case of double beta decays.

Neutrinos and symmetries have extensively been studied by investigating nuclear double beta decays and nuclear rare decays at nuclear microlaboratories. Here nuclear responses are crucial for extracting physics quantities of particle physics interests [1]. Nuclear weak processes for axial-vector interactions are associated with spin isospin responses. The isospin spin responses are studied by investigating charge exchange spin flip nuclear reactions such as (p, n), (^{3}He, t), (d, ^{2}He) and (t, ^{3}He). The proton and ^{3}He beams with 0.5-0.2 GeV energies, which are provided from the RCNP cyclotron, are used for preferencial excitations of nuclear spin isospin modes.

This report describes briefly recent works at RCNP Osaka on neutrino masses and weak interactions studied by nuclear double beta decays, nuclear neutrino responses studied by charge-exchange nuclear reactions, strange-quark weak processes studied by hyperon weak processes, and nucleon decays studied by nucleon-hole deexcitations. These are all associated with symmetry studies in nuclear microlaboratories. A short note is given on a new underground laboratory of Oto Cosmo Observatory for studies of neutrinos and dark matters.

2. Neutrinos and weak interactions studied by double beta decays

2.1. Double beta decays and neutrinos

Neutrinos (ν) are quite asymmetric and stable particles in the framework of the standard electroweak theory of $\mathrm{SU(2)_L \times U(1)}$. Pure left-handed neutrinos are considered to be mass-less leptons with no flavour mixings. The lepton number is conserved.

Extensive studies are under progress on unified symmetric theories to include possible finite components of ν-mass, right-handed helicity, lepton number violation and others, which are beyond the standard theory. Double beta decays provide one with very sensitive probes for studying these fundamental properties of neutrinos and symmetries. Double beta decays are indeed very interesting from both astroparticle physics and nuclear physics view points.

The neutrino-less double beta decay ($0\nu\beta\beta$) is given by A(2n)$\rightarrow$ B(2p)+$2\beta^-$. It violates the lepton number conservation law by $\Delta L = 2$. The $0\nu\beta\beta$ is 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.

Masses of light and heavy neutrinos are very interesting in views of possible candidates of these neutrinos for hot and cold dark matters, respectively.

The two neutrino double beta decay ($2\nu\beta\beta$) is given by A(2n)$\rightarrow$B($2p$) $+2\beta^- + 2\overline{\nu}$. It is the process within the standard theory. The $2\nu\beta\beta$ and $0\nu\beta\beta$ processes are schematically shown in Fig. 1. They have extensively been discussed in review articles [1-6] and references therein.

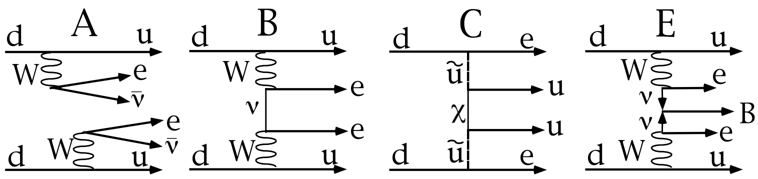

Fig. 1. Schematic diagrams of $\beta\beta$ decay processes. A: two-neutrino process, B: neutrino-less process with the Majorana neutrino exchange; C: neutrino-less process with the SUSY particles, and D: neutrino-less process followed by the Goldstone boson (Majoron). d and u are d- and u-quarks, respectively, and n and p are neutron and proton, respectively.

The transition rate $T^{0\nu}$ for $0\nu\beta\beta$ (Fig. 1 B) is given in terms of $\langle m_\nu \rangle$ and $\langle \text{RHC} \rangle$ as follows [1-6].

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

where $\langle \lambda \rangle$ and $\langle \eta \rangle$ are the $\langle \text{RHC} \rangle$ 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.

The transition rate for the gluino ($\tilde{g}$) exchange process (Fig. 1 C) is given as [1-6.7]

$$T_S(\tilde{g}) = G^S(f^2 M_{\tilde{g}} A(M_{\tilde{g}})/M_{\tilde{u}}^4)^2, \tag{3}$$

where G^S and $A(M_{\tilde{g}})$ are the phase space factor and the nuclear form factor, respectively. $M_{\tilde{g}}(M_{\tilde{u}})$ and f are the gluino (squark) mass and the R-parity violating interaction. The transition rate $T^{0\nu}$ for the Majoron emitting process ($0\nu\beta\beta B$, Fig. 1 D) is written as [1-6]

$$T^{0\nu B} = G^B \mid M^B \mid^2 \langle g_B \rangle^2, \tag{4}$$

where G^B, M^B and $\langle g_B \rangle$ are the phase space factor, the matrix element and the Majoron-ν coupling, respectively. The double Majoron emitting process ($0\nu\beta\beta BB$) is discussed in ref.8.

The $0\nu\beta\beta$, $0\nu\beta\beta B$ and $2\nu\beta\beta$ are studied by measuring sum energy spectra of $E_\beta + E_{\beta'}$, as shown in Fig. 2. 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.

The transition rate $T^{2\nu}$ for $2\nu\beta\beta$ (Fig. 1 A) is written as

$$T^{2\nu} = G^{2\nu} \mid M^{2\nu} \mid^2, \tag{5}$$

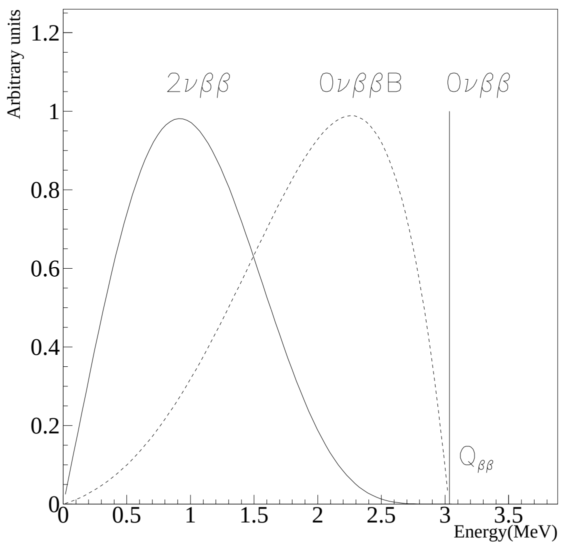

Fig. 2. Sum energy spectra $E = \varepsilon_1 + \varepsilon_2$ for $\beta\beta$ decays from ^{100}Mo(0^+) to the 0^+ ground state of ^{100}Ru. The solid lines show the calculated shapes on an arbitrary scale.

where $G^{2\nu}$ and $M^{2\nu}$ are the phase space factor and the matrix element, respectively. Thus observed halflives give $2\nu\beta\beta$ matrix elements $M^{2\nu}$. They are used to check nuclear structure calculations for $M^{2\nu}$ and parameters for spin-isospin interactions. The interactions are used also for calculating $M^{0\nu}$. The $2\nu\beta\beta$ process proceeds mostly via 1^+ intermediate states. The $0\nu\beta\beta$ process associated with the ν-exchange between two nucleons in a nucleus involves large momentum transfers of $q = 0.2 \sim 0.4$ GeV$/c$, and accordingly many intermediate J^π states up to $J^\pi \approx 6^\pm$.

Hadron currents associated with $0\nu\beta\beta$ and $2\nu\beta\beta$ processes include nucleon, meson, and isobar currents. Among them two nucleon processes are dominant.

Neutrino-less double beta decays($0\nu\beta\beta$) are enhanced by a factor $\sim 10^7$ in a nucleus, since they are ν-exchange processes between two nucleons (quarks) in a nucleus (baryon). The phase space factor $G^{0\nu}$ and the nuclear matrix element $M^{0\nu}$ become much larger than those for two neutrino double beta decays ($2\nu\beta\beta$). Studies of $\beta\beta$ in nuclei, where intermediate nuclei are heavier than initial nuclei, get feasible because strong single β decays to intermediate nuclei are energetically forbidden. Thus the nucleus, being used for studying the rare $0\nu\beta\beta$ process, acts as an excellent telescope with a large enlargement for $0\nu\beta\beta$ and with a large filtering power for rejecting single β rays and other backgrounds.

Double beta decays are second-order weak processes. Therefore their decay rates are extremely small. The half-lives for $2\nu\beta\beta$ decays are of the orders of $10^{19} \sim 10^{24}$y, and those for the $0\nu\beta\beta$ decays with $\langle m_\nu \rangle \approx 1$eV are of the orders of $10^{22} \sim 10^{26}$y.

2.2. ELEGANT's for $\beta\beta$ of ^{76}Ge, ^{100}Mo and ^{116}Cd

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. III, IV and V were used at the Kamioka underground laboratory with 2700 m w.e(water equivalent). EL. III, consists of a pure Ge detector surrounded by a $4\pi\cdot$ NaI detector array [9]. It was used for studying $\beta\beta$ of ^{76}Ge. A limit on the $\beta\beta$ of ^{76}Ge to the 2^+ excited state was derived by requiring coincidence with the $2^+ \rightarrow 0^+$ γ-ray signal from the NaI detector array. EL. IV consists of a set of 11 Si-detector disks [10]. It was used for the $2\nu\beta\beta$ of ^{100}Mo.

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].

EL. V was used for measuring $\beta\beta$ decays of ^{100}Mo and ^{116}Cd. The first ^{100}Mo run with the 104 gr ^{100}Mo foils gave for the first time a finite $2\nu\beta\beta$ halflife of $1.15 \cdot 10^{19} y$ for the ^{100}Mo $0^+ \rightarrow 0^+$ decay [11].

The ^{116}Cd run with the 91 gr ^{116}Cd gave for the first time a finite $2\nu\beta\beta$ halflife of $2.6 \cdot 10^{19} y$ for the ^{116}Cd $0^+ \rightarrow 0^+$ [12]. The $2\nu\beta\beta$ matrix elements are 0.09 for ^{100}Mo and 0.069 for ^{116}Cd. They are indeed one tenth of single particle values.

The second ^{100}Mo run with 179 gr ^{100}Mo foils was carried out [13]. Here the background rate was reduced by introducing a new central drift chamber [14]. The result gave most stringent limits on halflives for the $0\nu\beta\beta$ and $0\nu\beta\beta$B processes, as shown in Fig. 3.

The obtained limits on the $0^+ \rightarrow 0^+$ $0\nu\beta\beta$ for ^{100}Mo 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	$\langle g_B \rangle$	$T_{1/2} > 0.54 \cdot 10^{22} y$	$\langle g_B \rangle$	$< 7.3 \cdot 10^{-5}$

Here the limits are the on-axis values with nuclear matrix elements in Ref. [15].

EL. V and EL. VI consists of 25 modules of CaF_2 scintillators surrounded by 3π CsI detectors [16], as shown in Fig. 4. The CaF_2 module consists of a

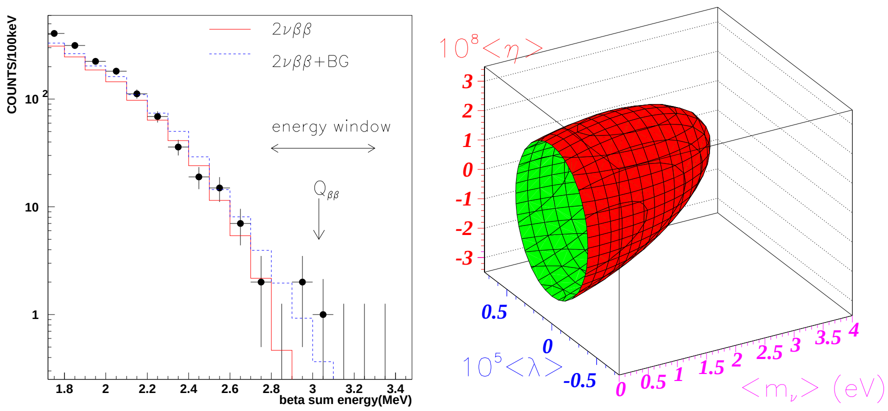

Fig. 3. Double beta decays of ^{100}Mo. (a) Energy spectrum of $\beta_1 + \beta_2$ (b) Limits on $\langle m_\nu \rangle$, $\langle \lambda \rangle$ and $\langle \eta \rangle$.

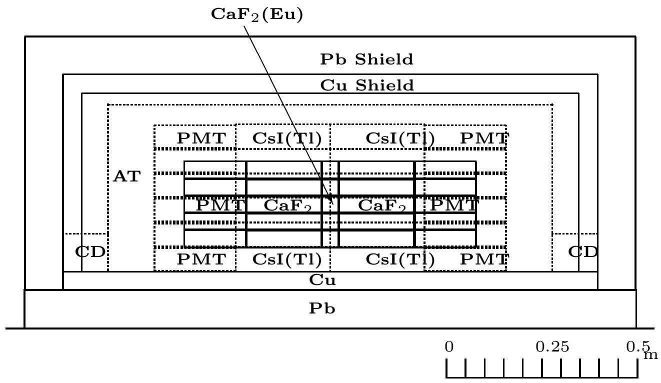

Fig. 4. Schematic view of ELEGANT VI with CaF_2 (Eu) to search for dark matters. The central 45mm long CaF_2 (Eu) are replaced by the 200 mm long CaF_2 (pure) for $\beta\beta$ of ^{48}Ca.

central CaF_2 crystal with $45 \times 45 \times$ 200mm^3 and a pair of side CaF_2 crystals with $45 \times 45\times$ 75mm^3, each at both sides of the central crystal. The total ^{48}Ca content in the 25 central detectors is 31 gr. 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.VI will be installed at the new underground laboratory of Oto Cosmo Observatory with around 1400 m w.e. It is located at about 100 Km south from Osaka Univ. Background levels there are small, $4 \cdot 10^{-3}/m^2/sec$ for cosmic rays, $4 \cdot 10^{-1}$/m^2/sec for neutrons, and 10 Bq/m^3 for Rn.

2.3. Nuclear matrix elements

Nuclear matrix elements $M^{2\nu}$ deduced from the observed halflives are one or two orders of magnitudes smaller than single particle values. $M^{2\nu}$ is approximately given by the product of the successive single-β matrix elements M_S^ν and $M_{S'}^\nu$ through the single particle-hole 1^+ state at the low excitation region [17], as shown in Fig. 5. Single β matrix elements are smaller by factors $(g_A/g_A^0) = 0.3$ than single particle values and $\beta\beta$ matrix elements are smaller by $(g_A/g_A^0)^2 \sim 0.1$.

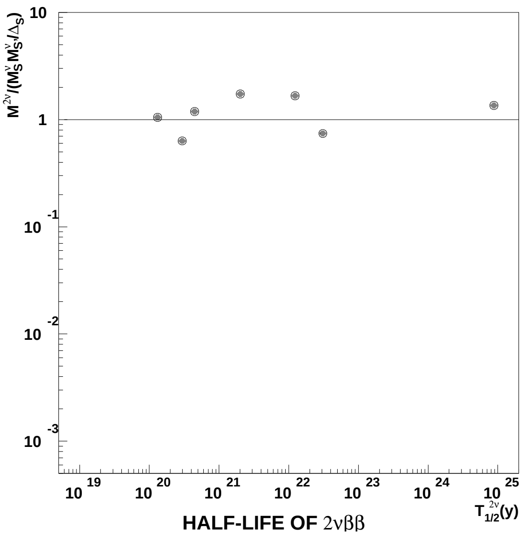

Fig. 5. Ratio of the $2\nu\beta\beta$ matrix elements $M^{2\nu}$ and the product of the matrix elements of successive single β decays through the single particle-hole 1^+ state at the intermediate nucleus[17].

3. Nuclear spin isospin responses for $\beta\beta$-ν and solar-ν

3.1. Nuclear spin isospin responses for axial-vector weak processes

Charged axial-vector weak processes involve nuclear isospin (τ) spin(σ) responses. They are investigated by charge-exchange (τ) spin-flip (σ) nuclear reactions, as shown in Fig. 6.

Spin isospin responses for ^{100}Mo were studied to investigate axial-vector weak responses relevant to $\beta\beta$ [18]. The ^{100}Mo (^{3}He, t) ^{100}Tc was measured by the high resolution spectrometer GRAND RAIDEN. The 0.45 GeV ^{3}He beam obtained from the RCNP cyclotron was used. The $\tau\sigma$ strengths are concentrated, as shown in Fig. 7, into three states (resonances), the single particle-hole 1^+ state($\mid S\rangle$) at the low excitation region, the isobaric analogue state ($\mid$ IAS$\rangle$) and the GT giant resonance $\mid G\rangle$.

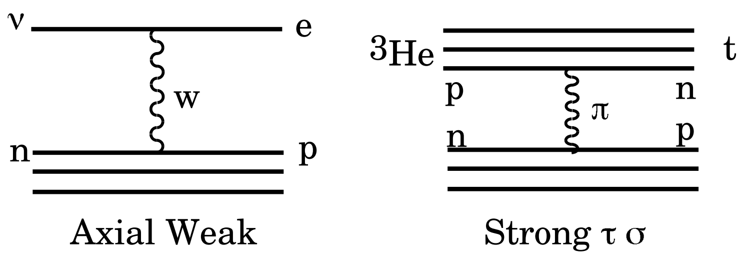

Fig. 6. Nuclear spin isospin responses for axial charged weak processes and those for spin-flip charge-exchange strong processes.

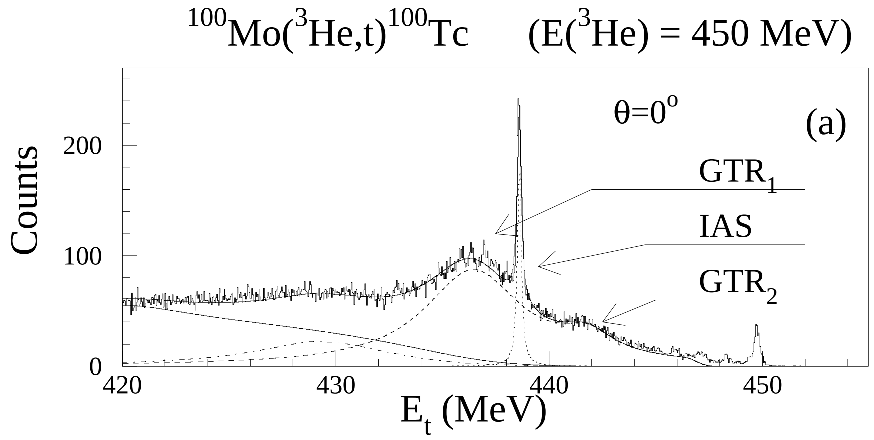

Fig. 7. Energy spectrum for ^{100}Mo (^{3}He, t) ^{100}Tc. IAS(dotted line) and GTR(dashed line) are the isobaric analogue state and GT giant resonances, respectively [18].

The $2\nu\beta\beta$ matrix element is analyzed, for simplicity, in terms of the couplings of two GT(1^+) states of $\mid S\rangle$ and $\mid G\rangle$ in the intermediate nucleus and those of $\mid 0_f\rangle$ and $\mid G'\rangle$ in the final nucleus [17]. Then the $2\nu\beta\beta$ matrix element is written as

$$M^{2\nu} = \frac{M^{\nu}_{S}M^{\nu}_{S'}}{\Delta_S} + \frac{M^{\nu}_{G}M^{\nu}_{G'}}{\Delta_G}, \tag{6}$$

where the first and the second terms stand for the products of the matrix elements for the successive single β decays through $\mid S\rangle$ and $\mid G\rangle$ in the intermediate nucleus, respectively. It is shown that the second term in Eq. (6) vanishes because of the cancellation between the contributions from the admixture of $\mid S\rangle$ into the $\mid G\rangle$ and the admixture of $\mid G'\rangle$ into $\mid 0_f\rangle$. Consequently one gets $M^{2\nu} \approx M^{\nu}_{S}M^{\nu}_{S'}/\Delta_S$, just as found empirically.

3.2. Nuclear spin isospin responses for solar-ν

The solar-ν, which is mainly the low energy pp neutrino, is studied by the inverse β decay of the ^{71}Ga (ν, β^-) ^{71}Ge process. The $\tau\sigma$ responses for ^{71}Ga were studied by measuring the ^{71}Ga (^{3}He, t) ^{71}Ge reaction [19,20]. 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 was studied by measuring the ^{71}Ga $(^3\mathrm{He}, \mathrm{t}\gamma)$ ^{71}Ge process.

The energy spectra of the (^{3}He, t γ) reactions are shown in Fig. 8. Particle-unbound states with excitation energies up to 1 MeV above the neutron threshold contribute to the ^{71}Ge population through γ transitions to low-lying states.

The total GT strength of 3.07 $\pm$ 0.11 was found for ^{71}Ge up to the neutron threshold energy. It gives the solar-ν absorption rate of 130.3$\pm$ 1.6 SNU. The contribution from the unbound states is 0.3 SNU which is about 2.5% of the total rate for ^{8}B-ν[20].

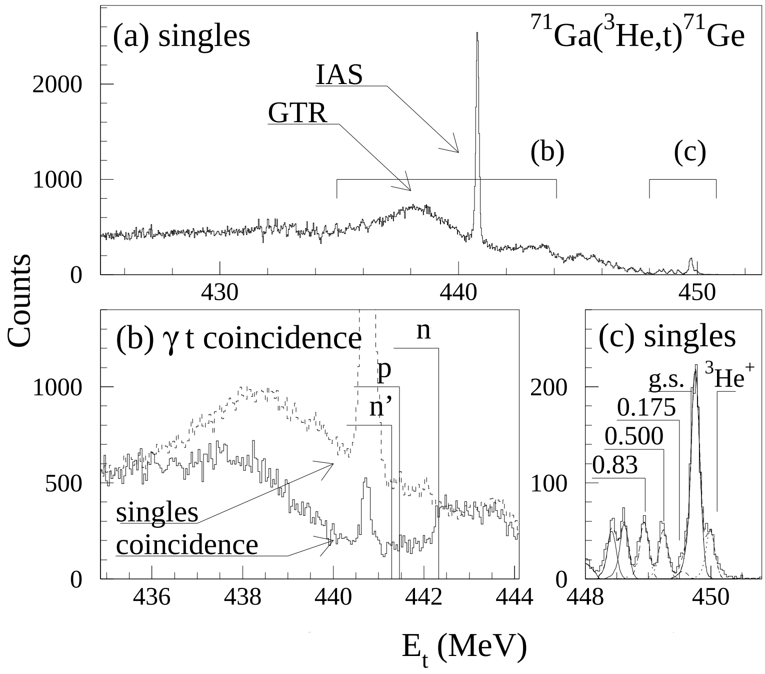

Fig. 8. Energy spectra for ^{71}Ga (^{3}He, t) and (^{3}He, t γ) (a) Singles spectrum. (b) Coincidence spectrum gated by γ-rays, where n and p indicate the neutron and proton threshold energies. (c) Enlarged singles spectrum for low lying states.

4. Strange-quark weak processes studied in hyperon nucleon systems

Hypernuclei, which are quantum systems of hyperons and nucleons, are used for studying strangeness nuclear physics in hypernuclear microlaboratories. Weak processes and symmetires associated with strange quarks are studied by investigating hypernuclear weak processes. Weak decays of Lambda (Λ) proceed through the mesonic decay of $\Lambda \rightarrow \mathrm{N} + \pi$ and the non-mesonic decay of $\Lambda + \mathrm{N} \rightarrow \mathrm{N} + \mathrm{N}$. The non-mesonic process, which is unique of the hypernuclear decay, gives weak processes of the quark sector as shown in Fig. 9. Non-mesonic decays of spin-polarized Λ hypernuclei

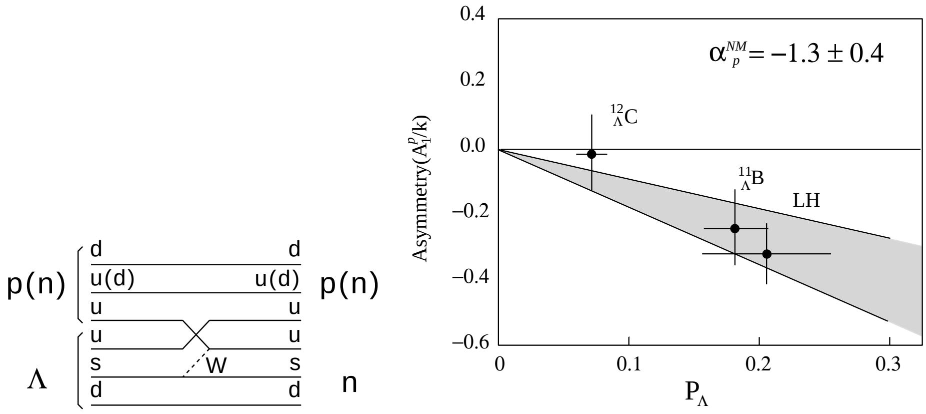

Fig. 9. Non-mesonic weak decay of a Λ hyperon in a hypernucleus. (a) Quark diagrams. (b) asymmetries of protons from Λn→ pn against Λ spin polarization P_Λ [21].

were studied by using (π^+, K^+) reactions on ^{12}C [21]. Non-mesonic decay protons from $\Lambda + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{n}$ show asymmetric distributions with respect to the Λ polarization P_Λ. The proton distribution is expressed as

$$W(\theta) = W_0(1 + AP\ \cos\theta), \tag{7}$$

where P is the Λ polarization, A is the asymmetry parameter, and θ is the angle with respect to the Λ polarization axis. The observed asymmetry of $A \approx -1$ shows a large parity violation for the quark sector weak process.

Inverse weak processes of p + n→ Λ+n are studied by using 0.41 GeV polarized protons from the RCNP ring cyclotron [22]. Here P and T symmetries are investigated by observing the P-odd $J_p \cdot k_p$ and T-odd $(J_p \times k_P) \cdot J_\Lambda$ terms, where J_p, k_p and J_Λ are the proton spin, the proton momentum and the Λ spin, respectively.

5. Nuclear decays and nuclear stabilities

The stability of nucleos in a nucleus is based on the following three laws(facts); (*i*) the baryon number is conserved so that neucleons (baryons) can not decays into non-nucleonic (baryonic) particles. (*ii*) nucleon as a fermion with the fermi statistics cannot decay into a state occupied by other nucleons by the Pauli principle, and (*iii*) nucleon is the lightest baryon in a free space as well as in a nucleus.

Non-Paulian nuclear transitions, which were associated with nucleon instability and the admixture (δ^2) of non-fermion statistics, were studied by observing energy spectra of decay particles from stable Na and I nuclei in the large NaI detector [23]. It gives an upper limit $\delta^2 \leq 1.4 \times 10^{-53}$ on the relative strength of the non-Paulian transition.

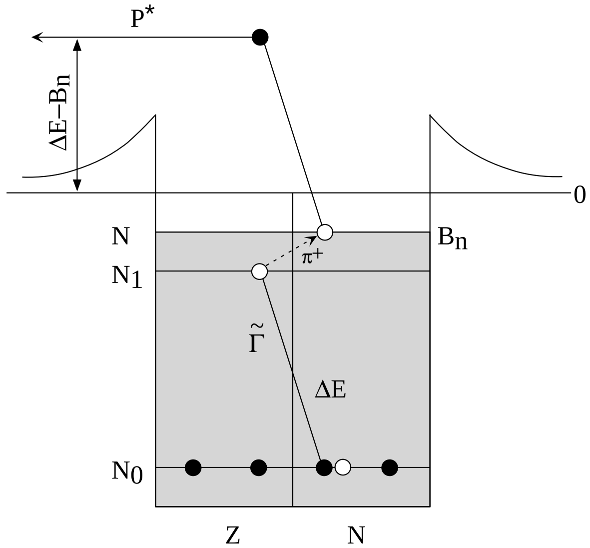

Fig. 10. Nucleon decay in a nucleus and deexcitation of a nucleon hole.

Nucleon decays can also be studied by investigating the nuclear deexcitation followed by the nucleon hole produced by the nucleon decay in a nucleus, as shown in Fig. 10 [24]. This method is applied for decay modes with unknown and /or neutral (ν) decay products since direct measurements of them are difficult.

Baryon-number-violating nucleon decays were studied by searching for X and γ rays associated with radioactive residual nuclei produced by single- and multi-nucleon decays in ^{127}I [25]. New lower limits of $\tau(n) > 4.7\times10^{24}$yr, and $\tau(p) > 3.0 \times 10^{24}$yr, $\tau(nn) > 2.1 \times 10^{24}$yr, $\tau(nnn) > 1.8 \times 10^{23}$yr, and $\tau(nnnn) > 1.4 \times 10^{23}$yr were deduced on the mode-independent mean lives for single and multi-nucleon decays in ^{127}I [25].

A search was made for anomalous γ-rays associated with the deep s hole in ^{16}O in the large underground water Cherenkov detector Kamiokande [26]. The result was used to set a limit of $\tau_{\mathrm{B}} = 4.9 \times 10^{26}$ yr (90% CL) on invisible nucleon decay through $n \to \nu_\mu \nu_\mu \overline{\nu}_\mu$, $n \to \nu_e \nu_e \overline{\nu}_e$ and $n \to \nu_\tau \nu_\tau \overline{\nu}_\tau$.

6. Concluding remarks

1. Nuclei, as ordered systems of nucleons with good quantum numbers of E, J^π, T and so on, are used as excellent nuclear microlaboratories to study fundamental symmetries of particles and interactions.

2. Neutrino-less double beta decays ($0\nu\beta\beta$) are sensitive to neutrino physics beyond the standard theory. The limits on the $0\nu\beta\beta$ of ^{100}Mo studied by EL V, together with those on other nuclei set upper limits of $\langle m_\nu \rangle < 1 \sim 2$ eV, $\langle \mathrm{RHC} \rangle < 10^{-6}$, $\langle g_\beta \rangle < 1 \sim 2 \cdot 10^{-4}$.

3. Finite halflives for two neutrino double beta decays ($2\nu\beta\beta$) of ^{100}Mo and ^{116}Cd were obtained. The observed values for $M^{2\nu}$ are shown to be written as $M^{2\nu} \approx M_S^\nu \cdot M_{S'}^\nu / \Delta_S$, where M_S^ν and $M_{S'}^\nu$ are matrix elements of successive single β decays through the single particle-hole 1^+ state ($\mid S \rangle$) in the intermediate nucleus, and Δ_S is the energy denominator. This is theoretically explained in terms of the coupling of $\mid S \rangle$ with the GT giant resonance.

4. Nuclear spin (σ) isospin (τ) responses for axial-vector charged-current weak processes were studied by investigating spin-flip charge-exchange nuclear reactions.

5. Non-mesonic Lambda decays of Λp$\to$ np show large asymmetries with respect to the Λ spin polarization, suggesting the large P violation. Inverse processes of pn$\to$ Λp are studied by using polarized protons from the RCNP cyclotron to investigate P and T symmetries associated with strange quark sectors.

6. Studies of rare nuclear processes are extended to investigate conservation laws and exotic transitions. Nuclear/nucleon stabilities in nuclei and the Pauli-principle for composite particles are studied by measuring exotic γ and nucleon decays of stable nuclei.

7. Nucleon decays and baryon number non-conservations are studied by measuring nuclear deexcitations of the nucleon-hole produced after the nucleon decay in a nucleus. This methods give most stringent limits on nucleon decays into invisible particles (neutrinos, etc) and on multi-nucleon decays.

8. The new underground laboratory (Oto Cosmo Observatory), together with the ELEGANT's series of high-sensitive detectors, is useful for studying neutrinos and symmetries. Here the accelerator laboratory with strongly interacting probes plays a crucial role by providing one with relevant nuclear responses.

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