DOUBLE BETA DECAYS OF ^{100}Mo AND DOUBLE WEAK DECAYS WITH $\Delta S=-2$*

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Double beta decays of ^{100}Mo have been studied by ELEGANTS (EL) IV and V. The data of EL IV show the half-life of $T^{2\nu}_{1/2} > 6\cdot10^{18}$y (a probable value may be around $7\cdot10^{18}$y). ELEGANTS V with drift chambers has been constructed. Monte-Carlo calculations, being combined with test run data, show sensitivity up to $\tilde{T}_{1/2} \sim 2.8\cdot10^{23}$y for the neutrino-less double β decays. Double weak decays of two nucleons to the H dihyperon have been studied. The data exclude the light H with the mass below 1.875 GeV.

§1 Introduction

Low-background spectrometers ELEGANTS (ELEctron GAmma-ray NeuTrino Spectrometer) have been developed to study low-energy rare nuclear processes. We report briefly recent works on the two-neutrino double beta decay (2νββ) of ^{100}Mo with ELEGANTS IV,$^{1)}$ on the neutrino-less (oν) and two neutrino (2ν) ββ decays of ^{100}Mo with ELEGANTS V,$^{2)}$ and on double weak decays of two nucleons to the H dihyperon, with ELEGANTS III.$^{3)}$

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The $0\nu\beta\beta$ is very sensitive to the Majorana neutrino mass, right-handed weak current and other fundamental properties of the weak interactions. They reflect physics at TeV region, and thus the $0\nu\beta\beta$ provides information complementary to the high energy physics. The $2\nu\beta\beta$ provides very important information on the nuclear matric elements involved in the $2\nu\beta\beta$ and also inthe $0\nu\beta\beta$. The H particle mass is related to the QCD evaluation of the six quark (uuddss) symmetric system and to possible strange matter.

§2 Two neutrino double β decays of ^{100}Mo with ELEGANTS IV

The double β decays accompanied by two neutrinos is a second order weak process with very long halflives of the order of $10^{18}\sim 10^{26}$y. Experimental observation of the $2\nu\beta\beta$ rate is very important because it gives the $2\nu\beta\beta$ nuclear matrix element $M^{2\nu}_{\beta\beta}$, the major component ($M^{0\nu}_{\beta\beta}(1^+)$) of the $0\nu\beta\beta$ matrix element $M^{0\nu}_{\beta\beta}$ and the test example of measuring low-energy rare process$^{4-7)}$. The value $M_{\beta\beta}$ reflects the spin isospin ($\tau^-\sigma$ and $\tau^+\sigma$) response in β^- and β^+ processes in nuclei$^{4-6)}$.

The $2\nu\beta\beta$ decay rate is written in terms of the phase space factor $G_{2\nu}$ and the $\beta\beta$ matrix element $M^{2\nu}_{\beta\beta}$ as

$$t_{2\nu} = \ln 2 (T^{2n}_{1/2})^{-1} G_{2\nu} |M^{2\nu}_{\beta\beta}|^2. \qquad (1)$$

Here $G_{2\nu}$ gives a nuclear sensitivity S_N for measuring $|M^{2\nu}_{2\beta}|^2$. ^{100}Mo has a large Q value of $Q_{\beta\beta}$=3.034 MeV. Thus it has a very large nuclear sensitivity $G_{2\nu}$ since $G_{2\nu}$ is proportional to $Q^{11}_{\beta\beta}$.

The $2\nu\beta\beta$ decay of ^{100}Mo has been studied by means of ELEGANTS IV at the KAMIOKA underground laboratory$^{1)}$. ELEGANTS IV consists of 11 Si detectors, each with 43 mm $\phi \times 4$ mm. The Si detector array is surrounded by a 4π NaI detector. These detectors are shielded by OFHC cupper bricks, and Pb bricks. The Si detectors are used to measure β-rays from Mo source disks interleaved between the detectors. The NaI detector is used to detect γ rays. Signals from the γ detector are used to identify true events by β-γ coincidence and anti-coincidence measurements.

Enriched ^{100}Mo source disks with 30mmϕ × 78mg/cm^2 and natural ^{nat}Mo ones with the same diameter and thickness have been prepared from chemically purified ^{100}Mo and ^{nat}Mo powders. Contamination of radioactive elements in the ^{100}Mo and ^{nat}Mo sources has been examined. U. Th and K contents in the ^{100}Mo are 1.3ppb,<0.5ppb, and 3.5ppm, respectively, while those in the ^{nat}Mo are <0.5ppb, <0.5ppb, and <0.5ppm, respectively.

The first run was made by using the five ^{100}Mo source disks and the five ^{nat}Mo ones for 2490 hrs, and the second run by interchanging positions of the ^{100}Mo and ^{nat}Mo sources with respect to the Si detectors for 2317hrs. The change of the source position is made to cancel out the position dependence. The spectum is obtained by summing coincidence signals from the two adjacent Si detectors. The measured spectum for the ^{100}Mo, being subtracted by that for the ^{nat}Mo, is shown in Fig.1. Here β-ray signals beyond 0.15MeV are used to avoid low energy noise signals and low energy background signals. The total number of the counts in the 0.3-2MeV region, where the $2\nu\beta\beta$ events of ^{100}Mo are localized, is 343 for the ^{100}Mo source disks and 294 for the ^{nat}Mo one, leading to 49 excess counts for the ^{100}Mo in the first run, while it is 449 for the ^{100}Mo and 345 for the ^{nat}Mo, leading to 104 excess counts. Thus the total excess counts are 153 ± 38. This corresponds to the half-life of $7.1 \cdot 10^{18}$y, provided that the excess count is entirely due to the $2\nu\beta\beta$ of ^{100}Mo. Monte Carlo calculation shows that the possible counts due to the excess radioactive elements in the ^{100}Mo source with respect to those in the ^{nat}Mo source can hardly be more than 10% of the observed excess counts. Definite conclusion on the $T^{2\nu}_{1/2}$ should be made after fine Monte Carlo calculation on the shape of the spectra due to the possible radioactive contaminants in the source disks

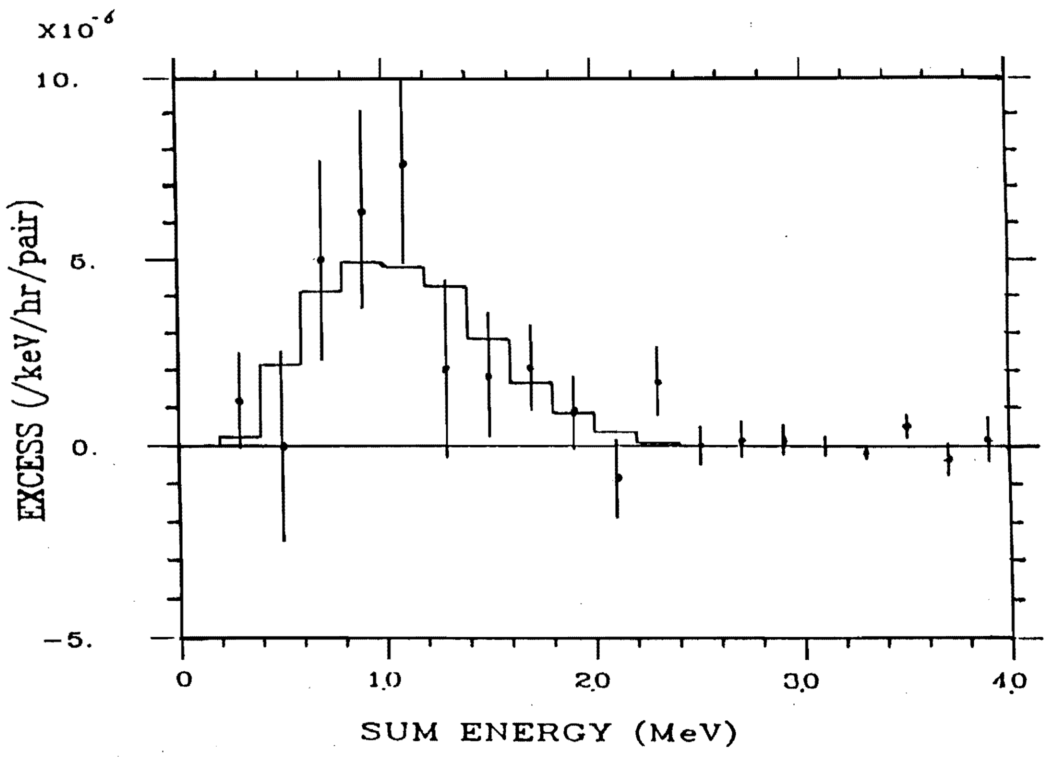

Fig. 1. Energy spectrum of $E_{\beta 1}+E_{\beta 2}$ for ^{100}Mo, being substracted by that for ^{nat}Mo. The solid line show a Monte Carlo calculation for $T_{1/2}=7.1 \cdot 10^{18}$y (Watanabe et al. (1))

and the detectors. The upper limit for the $T_{1/2}^{2\nu}$ is $6.4 \cdot (5.4) 10^{18}$y with 68% (90%) CL. The present result indicates the observed value of $|M_{\beta\beta}^{2\nu}|^2$ is at least one order of magnitude smaller than the calculation including the large cancellation$^{4-6)}$.

§3 ELEGANTS V for ^{100}Mo ββ Decays

ELEGANTS V has been developed to study 0νββ and 2νββ decays of ^{100}Mo and other nuclei. The 0νββ decay gives the most sensitive and direct evidence for the lepton number nonconservation and the finite Majorana neutrino mass. The oνββ process requires the helicity mixing of the electron neutrino. Thus the 0νββ Hamiltonian includes the Majorana mass term $<m_\nu>$

and the right-handed current terms with j_R and J_R. The 0νββ decay rate due to the mass term $<m_\nu>$ is written as

$$t_{o\nu}=\ln2(T^{o\nu}_{1/2})^{-1}=G_{0\nu}|<m>_\nu|^2, \tag{2}$$

where $G_{o\nu}$ is the phase space factor, corresponding to the nuclear sensitivity S_N. $G_{o\nu}$ is proportional to $Q^5_{\beta\beta}$. Thus nuclei with large $Q_{\beta\beta}$ have large nuclear sensitivity. The detection limit is given as $N_t/\sqrt{N_{BG}}>1$, where N_t is the number of true events and $\sqrt{N_{BG}}$ is the fluctuation of the background events. Thus the detector sensitivity is given as

$$S_D=N_t/\sqrt{N_{BG}}=N_0\ k/\sqrt{n_{BG}}\cdot\Delta E. \tag{3}$$

ELEGANTS V is designed so as to have a large detector sensitivity S_D as well as a large nuclear sensitivity S_N[8,9]. It uses an external source, and thus one can select ββ source nuclei with large $Q_{\beta\beta}$ (i.e. large S_N). First we study 0νββ and 2νββ decays of ^{100}Mo A large S_D is realized by employing a large source (large N_0) and by using drift chambers to reduce background rates (N_{BG}) by identifying tracks of two β rays. Fig. 3 shows schematic views of ELEGANTS V. The ^{100}Mo source consists of two ^{100}Mo source sheets of 70 cm × 70 cm × 20 mg/ cm^2. The total number of ^{100}Mo nuclei is 1.2×10^{24}. The drift chamber consists of fifteen layers with 993 sense wires for tracking β rays as well as α rays. Detection of α rays from ^{214}Po is used to reject background events due to ^{214}Bi. Sixteen plastic scintillators, each being 100 cm × 12 cm × 1.5 cm, are used to measure the energy of the β rays. Twenty NaI(Tl) scintillator modules, each with 100 cm × 10 cm × 10 cm, are used for measuring γ rays, X rays and cosmic rays in order to identify true and background event. The solid angle covered by these NaI detectors is 85% of 4π. The whole counter system is shielded by 10 cm thick

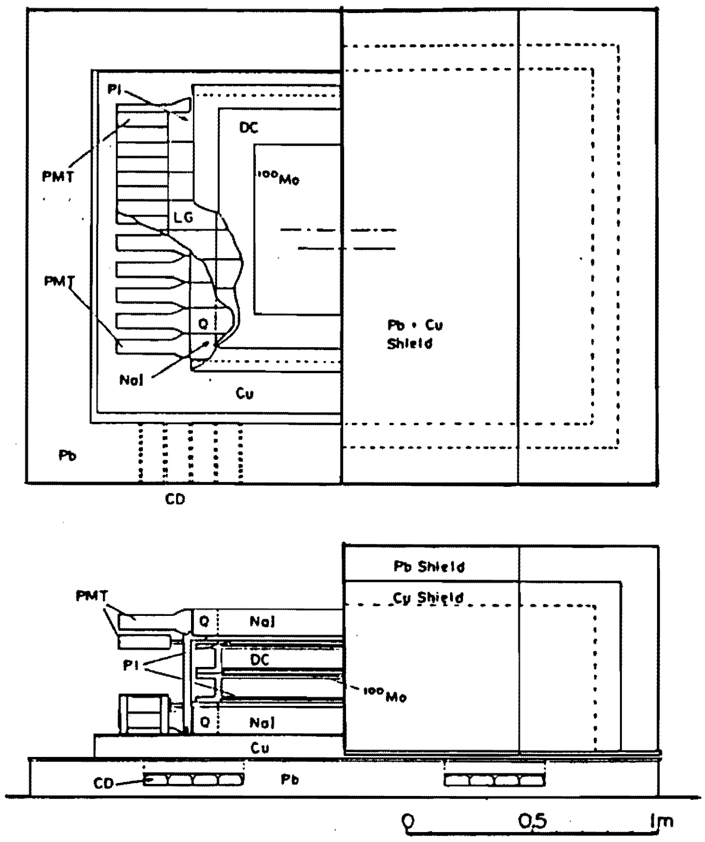

Fig. 2. schematic view of ELEGANTS V. ^{100}Mo: Mo source sheet. DC: drift chamber, NaI: NaI(Tl) crystal, Q: quatslight guid, PL: plastic scintillator, PMT: photomultiplier, Cu: OFHC cupper brick, Pb: lead brick, CD: cable duct.

OFHC (oxygen free high conductive) bricks and by 15 cm thick pure lead bricks. Light gas with mixture of 85% He and 15% CO_2 is used for the drift chamber to reduce scattering of β rays. ELEGANTS V is covered by a air tight sheet, and is filled by N_2 gas to exhaust active radon gas.

Detection efficiencies for the $0\nu\beta\beta$ mode due to the m_ν term, that due to the right-handed current $\lambda j_R J_R$, and the $2\nu\beta\beta$ mode are evaluated by Monte Carlo calculations to be ε= 0.35, 0.2 and 0.13, respectively.

The test run was carried out at the Osaka University sea-level lab. and at the Kamioka underground lab. Background rates at around 2 MeV, which are mainly due to radioactivities, are reduced much by requiring i) two fires (two coincident signals) in the plastic scintillators, ii) anti-coincidence with signals from the NaI detectors, and iii) presence of track(s) in the drift chamber. The reduction factor at the sea-level lab. is about 10^3. Background events at the higher energy region, which are mainly due to cosmic rays, are reduced by a factor 10^4 by requiring anticoincidence with signals from the NaI detectors. Severe selection of true events are made by measuring flight times of two β rays, angles of two β rays, and checking of α and X rays accompanied by electron (β) events. These requirements will reduce the background rates due to radioactive contaminants. Cosmic rays are reduced by a factor $3 \cdot 10^{-5}$ at the underground lab.

The background rates evaluated from the measured data are as small as expected. Thus background events due to the possible U and Th contents in the source will be considered to remain finally. The purified ^{100}Mo powder is measured to have the U and Th contents less than 0.5 ppb. A Monte Carlo calculation based on these U and Th contents in the source gives the following upper limits $\tilde{T}$ on the measurable half-lives. $\tilde{T}^{o\nu}_{1/2}(m_\nu)=2.8 \cdot 10^{23}$y, $\tilde{T}^{2\nu}_{1/2}=1.7 \cdot 10^{23}$y, $\tilde{T}^{2\nu}_{1/2}=1.8 \cdot 10^{21}$. The limit for the $0\nu\beta\beta(m_\nu)$ mode corresponds to the lower limit of m_ν around 0.3eV to be measured by ELEGANT V. A run with a dummy source is under progress, and a run with ^{100}Mo and ^{nat}Mo will start this fall, 1989.

§4 Search for the H Dihyperon by Double Weak Decay of Nuclei

Since Jaffe$^{11)}$ has predicted the existence of a flavor singlet six quark state, the so called H particle, such exotic stable particle has been discussed much from view points of elementary particle theory and astrophysics. H is a dihyperon with spin party $J^\pi=0^+$, isospin I=0 and strangeness S= -2. Several groups studied the possible mass range of the H particle by using various theoretical models. Recently Iwasaki et al. have calculated the H particle mass in terms of the lattice QCD12). It is shown that the case where the H particle mass is slightly below the NN threshold for the weak decay,i.e. $M_H<2M_N$, is consistent with the numerical lattice QCD results12).

The present work aims at studying the existence of the light H particle in the mass region below the two nucleon mass, $M_H<2M_N$ by investigating double weak decays of two nucleons in nuclei to the H particle3,10). The relevant masses are shown in Fig. 3.

The Hamiltonians involved in double weak decays are H_L for the leptonic process and H_{NL} for the non-leptonic process. They are written as

$$H_L=\frac{G_F}{\sqrt{2}}\cdot\sin\theta_c\cdot\bar{\nu}\gamma^{\mu}(1-\gamma_5)eJ_{\mu}, \quad (4)$$

$$H_{NL}=G_F\cdot m_{\pi}^{2}\cdot H_I, \quad (5)$$

where G_F is the Fermi coupling constant, θ_c is the Cabibbo angle, J_{μ} denotes the hadron current with the strangeness changing of $\Delta S=-1$, and H_I is the non-leptonic weak Hamiltonian with $\Delta S=-1$.

In case of $nn\to H$, data of the double beta decay experiment using a Ge detector13)are used to evaluate double weak decays of $^{74}Ge\to{}^{72}Ge(2^+)+H$ and $^{72}Ge\to{}^{70}Ge(2^+)+H$. Lower limits on halflives of the ^{74}Ge and ^{72}Ge decays are calculated as a function of M_H by the second order purturbation of H_{NL}. Measured lower limits on halflives are much longer than calculated values. The mass region below 1861.4 MeV and 1859.9 MeV, which correspond to threshold masses of the decays, are excluded from the data of ^{74}Ge and ^{72}Ge,respectively.

Halflives of known radiative nuclei provide lower limits on M_H. The nucleus ^{10}Be with halflife of $1.62\cdot10^6$ year has the largest mass difference M(N,Z)-M(N-2,Z)=1870.7 MeV, where M(N,Z) represents the mass of the nucleus with neutron number N and

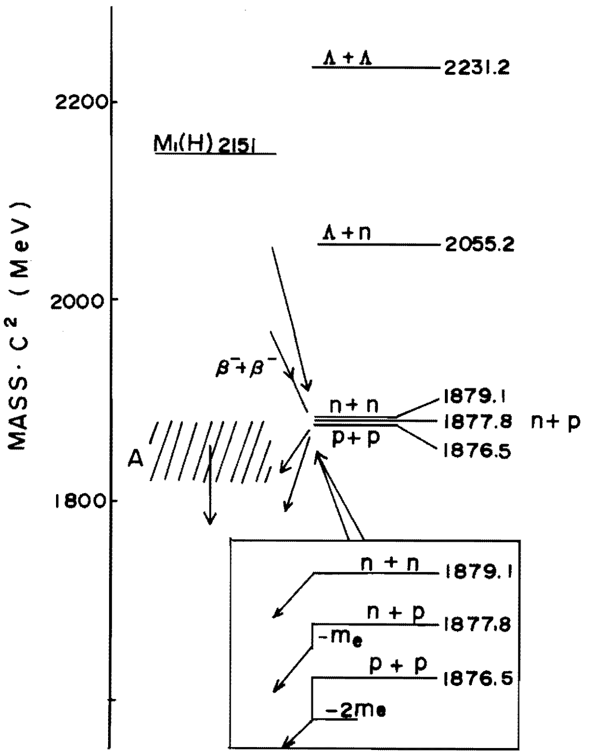

Fig. 3. Masses of ΛΛ, Λn, nn, np, and possible H.

proton number Z. Since the observed halflife of ^{10}Be is still much longer than the calculated values, the mass region below of 1870.7 MeV is excluded.

The decay of $pn \to H+e^+ +\nu$ was studied by observing e^+. The large NaI detector HERMES[14)] was used to study the decay of $^{127}I \to {}^{125}I+H+e^+ +\nu$. The halflife of the decay is calculated by the second order purturbation of H_L and H_{NL}. Since the measured lower limit of the halflife is much longer than the calculated values, the mass region below 1862 MeV is excluded.

The stable isotope of deuteron, which has the least binding energy of the nucleon, excludes the region below 1875.1 MeV. Similarly, the existence of the stable nucleus ^{6}Li with the threshold mass of 1873.6 MeV excludes the region below 1873.6 MeV. Here the emitted H particle is assumed to be in the unbound(B_H<0) region. If the H particle can be bound to the

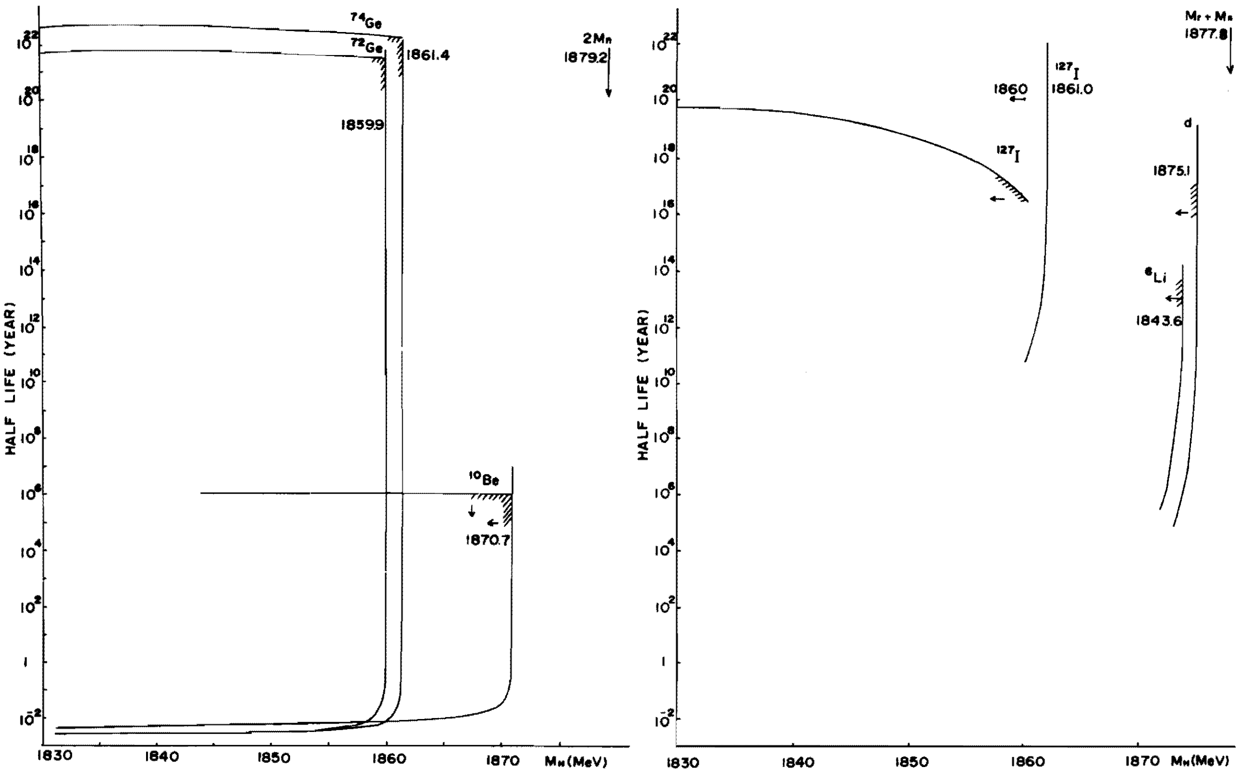

Fig. 4.

Fig. 4. Half-lives of the double weak decays as a function of M_H.
Left: nn→H process for ^{10}Be, ^{72}Ge and ^{74}Ge.
Right: pn→H+β^++ν process for d, ^{6}Li, and ^{127}I.
M_H denotes the threshold energy of the double weak decays.

residual nucleus ^{4}He with a binding energy B_H the mass region below 1873.6 MeV + B_H is excluded. Thus the whole region below the nucleon mass might be excluded if B_H would be only a few MeV. The half-lives are shown as a function of M_H in Fig. 4.

In short the light mass H dihyperon with M_H<1875.1 MeV (2.7MeV below M_p+M_n) is excluded from the double weak decay rates. It is very interesting to search for H in the heavier mass region of $2M_N < M_H < M_N + M_\Lambda$. We note that the H particle in this mass region can be studied by measuring double weak decay of H → N + N in a H nucleus provided that H is bound in the H nucleus.

The main part of this report is essentially the same as given at the preceeding meetings, Yamada Conference on Nuclear Weak Process and Nuclear Structure[15] and Franco Japonais Colloque on Intermediate Nuclear Physics[16].

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