Spectroscopy of Double-Beta and Inverse-Beta Decays from ^{100}Mo for Neutrinos

H. Ejiri,[1,*] J. Engel,[2] R. Hazama,[1] P. Krastev,[3] N. Kudomi,[4] and R. G. H. Robertson[1]

[1]*Nuclear Physics Laboratory and Department of Physics, University of Washington, Seattle, Washington 98195*
[2]*Department of Physics and Astronomy, University of North Carolina, North Carolina 27599*
[3]*Department of Physics, University of Wisconsin, Wisconsin 53706*
[4]*Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan*

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Spectroscopic studies of two β rays from ^{100}Mo are shown to be of potential interest for investigating both the Majorana ν mass by neutrinoless double β decay ($0\nu\beta\beta$) and low energy solar ν's by inverse β decay. With a multiton ^{100}Mo detector, coincidence studies of correlated $\beta\beta$ from $0\nu\beta\beta$, together with the large Q value ($Q_{\beta\beta}$), permit identification of the ν-mass term with a sensitivity of $\sim$0.03 eV. Correlation studies of the inverse β decay and the successive β decay of ^{100}Tc, together with the large capture rates for low energy solar ν's, make it possible to detect, in real time, individual low energy solar ν in the same detector.

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Neutrino mass is a key issue of current neutrino (ν) physics. Recent results with atmospheric [1,2], solar [1,3], and accelerator [4] neutrinos strongly suggest ν oscillations due to nonzero ν-mass differences and flavor mixings. Neutrino oscillation measurements, however, do not give the ν masses themselves. The minimum ν mass consistent with the accelerator-ν oscillation is in the eV range [4]. The minimum mass associated with the atmospheric-ν effect is of the order of 0.05 eV [1]. Neutrino mass of astroparticle interest is in the range of $\sim$1–0.01 eV [5]. It is of great interest to study directly ν mass with sensitivity down to $\sim$0.03 eV.

Double beta decay may be the only probe presently able to access such small ν masses. Actually, observation of neutrinoless double beta decay ($0\nu\beta\beta$) would identify a Majorana-type electron ν with a nonzero *effective* mass $\langle m_\nu \rangle$ [6–9]. Calorimetric measurements of total $\beta\beta$-energy spectra have been made on ^{76}Ge, ^{130}Te, and other isotopes [6,10,11]. They give upper limits on $\langle m_\nu \rangle$ in the sub-eV to eV region. The $0\nu\beta\beta$ process is, in fact, sensitive not only to the ν mass ($\langle m_\nu \rangle$) but also to a right-handed weak current and other terms beyond the standard model [6–8]. Spectroscopic studies of the energy and angular correlations for two β rays are useful to identify the terms responsible for $0\nu\beta\beta$. Spectroscopic measurements for two β rays have been made on ^{82}Se, ^{100}Mo, ^{136}Xe, and on others [6,12–15]. They give upper limits of a few eV on $\langle m_\nu \rangle$. NEMO III will study $\langle m_\nu \rangle$ in the sub-eV region [16]. Backgrounds (BG) from radioisotope (RI) impurities make it hard to perform spectroscopic studies with sensitivities down to $\sim$0.05 eV.

Solar neutrinos have been studied for more than 30 years [17]. Low energy solar-ν studies, so far, have been carried out with ^{71}Ga and ^{37}Cl detectors [3]. They are nonreal-time and inclusive measurements that do not identify the ν sources in the sun. Real-time spectroscopic studies of low energy solar ν are important for studies of the solar-ν problems [17–20]. They require, however, extremely low RI impurities of the order of $b \sim 10^{-5}$ Bq/ton or less [19]. Delayed coincidence studies with γ rays are an excellent way to reduce BG as proposed by Raghavan [18,20].

Rates for both the $0\nu\beta\beta$ decay at $\langle m_\nu \rangle \sim 0.03$ eV and the inverse-β decay induced by solar ν are extremely small, $\sim$6–8 orders of magnitude smaller than BG rates for normal two neutrino $\beta\beta(2\nu\beta\beta)$ and RI impurities with $\sim$Bq/ton. Nuclei used for $\beta\beta$ decays have a potential for solar ν studies [20]. It is interesting and important to find nuclei with adequate $0\nu\beta\beta$ and solar-ν-capture rates, and effective ways to select the rare $0\nu\beta\beta$ and inverse β signals from much larger BG signals due to $2\nu\beta\beta$ and RI impurities.

The present Letter shows that it is possible by measuring two correlated β rays from ^{100}Mo to perform both spectroscopic studies of $0\nu\beta\beta$ with a sensitivity of the order of $\langle m_\nu \rangle \sim 0.03$ eV, and real-time exclusive studies of low energy solar ν by inverse β decay. The unique features are as follows.

(1) The β_1 and β_2 with the large energy sum of $E_1 + E_2$ are measured in coincidence for the $0\nu\beta\beta$ studies, while the inverse β-decay induced by the solar ν and the successive β-decay are measured sequentially in an adequate time window for the low energy solar-ν studies. The isotope ^{100}Mo is just the one that satisfies the conditions for the $\beta\beta - \nu$ and solar-ν studies, as shown in Fig. 1.

(2) The large Q value of $Q_{\beta\beta} = 3.034$ MeV gives a large phase-space factor $G^{0\nu}$ to enhance the $0\nu\beta\beta$ rate and a large energy sum of $E_1 + E_2 = Q_{\beta\beta}$ to place the $0\nu\beta\beta$ energy signal well above most BG except ^{208}Tl and ^{214}Bi. The energy and angular correlations for the two β rays can be used to identify the ν-mass term.

(3) The low threshold energy of 0.168 MeV for the solar-ν absorption allows observation of low energy sources such as pp and ^{7}Be. The GT strength to the 1^+ ground state of ^{100}Tc is measured by both charge-exchange reaction and electron capture [21,22]. The value is $(g_A/g_V)^2 B(GT) = 0.52 \pm 0.06$ [21]. Capture rates are

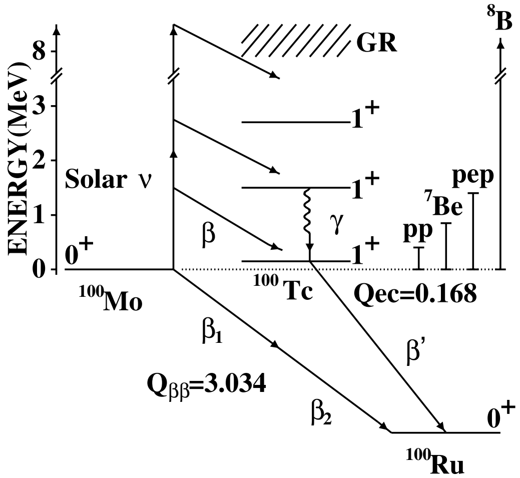

FIG. 1. Level and transition schemes of ^{100}Mo for double beta decays ($\beta_1\beta_2$) and two beta decays ($\beta\beta'$) induced by solar-ν absorption. GR is the Gamow-Teller giant resonance. $Q_{\beta\beta}$ and $Q_{\rm ec}$ are given in units of MeV.

large even for low energy solar ν's, as shown in Table I. The rates are 1.1 and 3.3 per day for ^{7}Be ν and pp ν, respectively, for 10 tons of ^{100}Mo. The solar-ν sources are identified by measuring the inverse-β energies. Only the ^{100}Tc ground state absorbs ^{7}Be ν and pp ν.

(4) The measurement of two β rays (charged particles) enables one to localize in space and in time the decay-vertex points for both the $0\nu\beta\beta$ and solar-ν studies. Radiations associated with BG are also measured. The tightly localized β-β event in space and time windows, together with relevant β and γ measurements, are key points for selecting $0\nu\beta\beta$ and solar-ν signals and for reducing correlated and accidental BG by factors of 10^{-5}–10^{-6} [13].

The $0\nu\beta\beta$ transition rate $R_{0\nu}$ for $\langle m_\nu\rangle$ is given by

$$R_{0\nu} = G^{0\nu}(M^{0\nu})^2|\langle m_\nu\rangle|^2, \quad (1)$$

where $G^{0\nu}$ is the phase-space factor and $M^{0\nu}$ is the matrix element [6–8], both relatively large for ^{100}Mo.

The $g^{\nu}_{7/2} - g^{\pi}_{9/2}$ shell-model structure of ^{100}Mo-^{100}Tc leads to the large measured $2\nu\beta\beta$ rate [6,13], and large calculated values for the $0\nu\beta\beta$ transition rate [8,9].

TABLE I. Solar-ν absorption rates R_ν in SNU (solar neutrino unit) for ^{100}Mo. $E_\nu^{(\max)}$, $E_\beta^{(\max)}$ are the maximum ν energy and maximum β-ray energy, respectively.

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

[a]Standard-solar-model (SSM) capture rates based on BP98 [17] with errors from those of $B(GT)$.
[b]Rate for the states below the effective neutron threshold energy.

The $0\nu\beta\beta$ events are identified by setting the appropriate energy window and the prompt time window for the $\beta\beta$ coincidence signals. The rate in units of 10^{-36}/s is given as $R_{0\nu} = 6.6 \times 10^4|\langle m\rangle|^2/(\text{eV})^2$ by RQRPA (renormalized quasiparticle random phase approximation) [8]. The uncertainty in calculation of the matrix element is considered to be of order 50% [9].

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

Signal and background rates for $0\nu\beta\beta$ and for ^{7}Be and pp solar ν's are summarized in Table II. There are eight efficiencies implicit in Table II. The efficiency $\epsilon_{0\nu}$ arises from the $0\nu\beta\beta$ window (cut) optimized for the ν mass term in $0\nu\beta\beta$, and is approximately 0.14. Here β_1 and β_2 are required to be oppositely directed with energies larger than 0.5 MeV. The efficiency $\epsilon_{2\nu}$ describes the degree to which 2ν events fall in the 0ν window, and is found to be 1.2×10^{-8} by Monte Carlo calculations [13] with an assumed energy resolution $\Delta E/E \sim 7\%$ in FWHM at $E_1 + E_2 = Q_{\beta\beta} = 3.034$ MeV. The efficiency $\epsilon_{\rm U} \simeq 0.6 \times 10^{-5}$ reflects the β branch of ^{214}Bi in the $0\nu\beta\beta$ window without preceding decays from ^{214}Pb being detected. The efficiency for ^{208}Tl with the effective $Q_\beta \sim 1$ MeV is negligible. It is noted that signals of γ rays following the ^{208}Tl β decay are separated in space from the β signal, and thus are rejected, and the internal conversion coefficients are very small.

The two solar neutrino efficiencies, $\epsilon_7 = 0.35$ and $\epsilon_{pp} = 0.2$, are dominated by losses in the Mo foils. The correlated BG comes mainly from the successive β decays of ^{214}Pb $\rightarrow$ ^{214}Bi $\rightarrow$ ^{214}Po for which an efficiency $\epsilon_c \simeq 27 \times \Delta T$ is estimated from the ground-state branch of ^{214}Bi. The efficiency ϵ_a for the accidental BG, which is mainly due to the $2\nu\beta\beta$, is estimated as $\epsilon_a \sim 4.3 \times 10^6 \Delta T/K$ with $1/K$ being the spatial (position) resolution (inverse of the localization factor K) for the vertex point of the two β rays.

The lower limit (sensitivity) on $\langle m_\nu\rangle$ can be obtained by requiring that the number of $0\nu\beta\beta$ events has to exceed the statistical fluctuation of the BG events. The sensitivity of the order of $\langle m_\nu\rangle \sim 0.03$ eV can be achieved for three year measurement by means of a realistic detector with a few tons of ^{100}Mo and RI contents of the order of 0.1ppt ($b \sim 10^{-3}$ Bq/ton), in contrast to $b \sim 10^{-6}$ Bq/ton for calorimetric methods. Sensitivity for the solar ν is obtained similarly as in the case of the $0\nu\beta\beta$. It is of the order of ~100 SNU for one year measurement by using

TABLE II. Expected rates for signals and backgrounds per ton of ^{100}Mo isotope (9.6% of natural Mo) in a natural Mo detector containing 15% Mo by weight. Rates for U and Th are disintegration rates for ^{238}U and ^{232}Th. [$10^{-13}(0.1ppt)$ ^{238}U $\sim 1.25 \times 10^{-3}b$(Bq/ton) for ^{214}Bi; $10^{-13}(0.1ppt)$ ^{232}Th $\sim 0.45 \times 10^{-3}b$(Bq/ton) for ^{208}Tl.]

Source	Raw rate ton^{-1} ^{100}Mo/yr	Effective ($0\nu\beta\beta$)	Effective (solar ν)
0ν, 0.05 eV	31	4.3	···
2ν, 1.15×10^{19} yr	3.6×10^8	~4.4	···
10^{-13} U w/w	2.6×10^6	~15	···
10^{-13} Th w/w	8×10^5	~0	···
^{7}Be (SSM)	39	···	~14
pp (SSM)	121	···	~26
Correlated	2.6×10^6	~0	$\sim 7 \times 10^7 \Delta T$
Accidental	3.6×10^8	~0	$\sim 1.6 \times 10^{15} \Delta T/K$

the same detector with $K \sim 10^9$. In fact, the $2\nu\beta\beta$ rate and the BG rate from RI at $0.1ppt$ ($b \sim 10^{-3}$ Bq/ton) are larger than the solar ν rate by factors $\sim 10^7$ and $\sim 10^5$, respectively. The fine localization in time ($\Delta T = 10^{-6}$ yr) and in space ($1/K = 10^{-9}$), which is possible with the present two-β spectroscopy, is crucial for reducing BG rates in realistic detectors.

The cosmogenic isotopes to be considered are long-lived ^{93}Mo, and 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 β rays. They are estimated to give negligible contributions to the present energy and time windows. The ^{14}C and other single β BG's become negligible in the present two β detection.

One possible detector is outlined below. It uses a supermodule of 3.3 tons of ^{100}Mo (34 tons of Mo) purified to 10^{-3} Bq/ton for ^{238}U and ^{232}Th or less. This purity level has been achieved for Ni and other materials for the Sudbury Neutrino Observatory [23]. An ensemble of plastic scintillator modules is newly designed on the basis of recent developments [13,24,25]. The supermodule with a fiducial volume of $(x, y, z) = (6\text{ m}, 6\text{ m}, 5\text{ m})$ is composed of 1950 modules with $(x, y, z) = (6\text{ m}, 6\text{ m}, 0.25\text{ cm})$. Each module may consist of 30 extruded plastic bars of $(x, y, z) = (6\text{ m}, 0.2\text{ m}, 0.25\text{ cm})$.

The Mo foils with thickness of 0.05 g/cm^2 are interleaved between the modules. Light outputs from each scintillator module are collected by 222 WLS (wave length shifter) fibers with a 2.7 cm interval for the x direction at the front side of the plane and the same for y at the back side, each with 1.2 mm in diameter and 6 m in length. An extrapolation of the results of [24,25] suggests the large fraction of the WLS with respect to the scintillators and the arrangement in both x and y directions may give adequate photoefficiencies and energy resolutions. The attenuation along the WLS can be corrected for by reading the position. The total 8.66×10^5 WLSs are viewed through clear fibers by 13 600 16-anode PMTs (photomultiplier tubes) with a large photoelectron efficiency, each accepting 128 fibers with eightfold multiplexing. All PMTs are well separated through the clear fibers from the scintillator to avoid BG from PMTs.

Here the surface of the whole detector should be covered by active shields composed by similar scintillators, and the detector modules (~2000) have to be treated carefully to minimize surface contamination.

The scintillator ensemble designed gives a time resolution of $\Delta T/T \sim 1$ ns in FWHM, and adequate energy and spatial resolutions of $\Delta E/E \sim 0.125/\sqrt{E}$(MeV) in FWHM and $\Delta x = \Delta y \sim 0.5\text{ cm}/\sqrt{E}$(MeV) with $\pm 2\sigma$. Then the energy resolutions of 7%, 15%, and 30%, and the spatial (position) ones of $1/K = \Delta x \times \Delta y \times 2.5\text{ mm}/(6 \times 6 \times 5\text{ m}^3) = 0.11 \times 10^{-9}$, 0.55×10^{-9}, and 2.5×10^{-9} are expected for $0\nu\beta\beta$, ^{7}Be-ν, and pp-ν, respectively. Expected energy spectra are shown schematically for $0\nu\beta\beta$ and solar ν, together with the major remaining BG of $2\nu\beta\beta$ in Fig. 2.

The detector can be used also for supernova ν studies and other rare nuclear processes, and for other isotopes. Another option is a liquid scintillator [26] in place of the solid one, keeping similar configurations of the WLS readout. The energy and spatial resolution are nearly the same. Then ^{150}Nd with the large $Q_{\beta\beta}$ may be used either in solid or solution in the liquid scintillator for $0\nu\beta\beta$. Of particular interest is ^{136}Xe because liquid Xe is a scintillator. The energy resolution is extremely important to select the $0\nu\beta\beta$ peak (signal) and to reduce the $2\nu\beta\beta$ tail (BG) coming into the $0\nu\beta\beta$ window. Actually, setting the $0\nu\beta\beta$ window at the higher half of the $0\nu\beta\beta$ peak reduces the $2\nu\beta\beta$ contribution as seen in the inset of Fig. 2. In this context, the bolometric method as used by the Milano group [11] would be interesting for Mo.

The present spectroscopic method for $0\nu\beta\beta$ measures selectively the ν mass term. In view of the dependence of $R_{0\nu}$ on $M^{0\nu}$ calculations, $0\nu\beta\beta$ studies on different nuclei

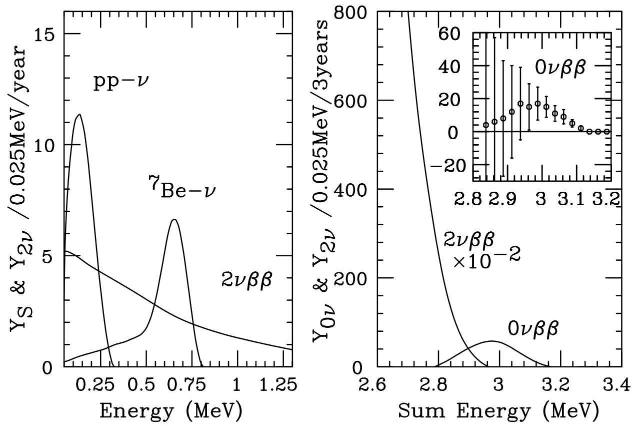

FIG. 2. Schematic energy spectra for a possible detector with 3.3 tons of ^{100}Mo (see text). Right hand side: Sum energy spectra for three year measurement of $2\nu\beta\beta$ and $0\nu\beta\beta$ for $\langle m_\nu \rangle = 0.1$ eV with $M^{0\nu}$ in [8]. The inset shows the $0\nu\beta\beta$ spectrum 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 ν on the basis of SSM [17], and possible $2\nu\beta\beta$ backgrounds. The detector threshold is set at 50 keV.

are important. Thus the present method is complementary to the calorimetric $\beta\beta$ measurements with high energy resolutions for ^{76}Ge [10] and ^{130}Te [11]. The present method for solar ν gives adequate yields for both pp-ν_e and ^{7}Be-ν_e via charged current interaction, and their ratio is independent of the $B(GT)$ value. BOREXINO [19], which requires much higher purity of $b \sim 10^{-6}$ Bq/ton, will give large yields for ^{7}Be-ν_x and higher energy ν_x with $x = e, \mu, \tau$ mainly via the charged current interaction and partly via the neutral current interaction. LENS (low energy neutrino spectroscopy) [20] is sensitive to ^{7}Be-ν and pp-ν charged currents with different technique and relative yields. Thus the present method provides important data for solar ν, which are supplementary to existing geochemical and planned real-time experiments.

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*Electronic address: ejiri@rcnp.osaka-u.ac.jp

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