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

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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 multi-ton ^{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 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 realtime 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 non-zero ν-mass differences and flavour 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 1$\sim$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 non-zero *effective* mass $< m_\nu >$ [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 $< m_\nu >$ in the sub-eV to eV region. The $0\nu\beta\beta$ process is, in fact, sensitive not only to the ν mass ($< m_\nu >$) but also to a right-handed weak current and other terms beyond the Standard Model(SM) [6] [7] [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 $< m_\nu >$. NEMO III will study $< m_\nu >$ 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 non-realtime and inclusive measurements that do not identify the ν sources in the sun. Realtime 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 $< m_\nu > \sim$0.03 eV and the inverse-β decay induced by solar ν are extremely small, 6$\sim$ 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 $< m_\nu > \sim$0.03 eV, and realtime 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 to be $(g_A/g_V)^2 B(GT)$=0.52$\pm$0.06 by both charge-exchange reaction and electron capture [21] [22]. Capture rates are large even for low energy solar ν's, as shown in Table 1. 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 can absorb ^{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 $10^{-5} \sim 10^{-6}$ [13].

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

$$R_{0\nu} = G^{0\nu}(M^{0\nu})^2| < m_\nu > |^2, \qquad (1)$$

where $G^{0\nu}$ is the phase space factor and $M^{0\nu}$ is the matrix element [6] [7] [8], both relatively large for ^{100}Mo.

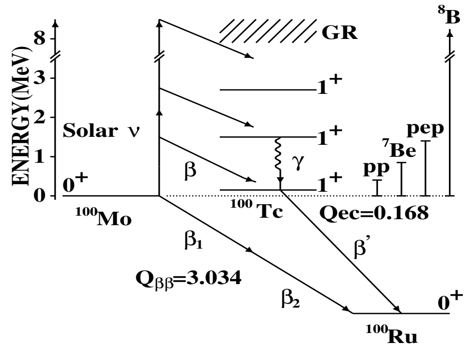

FIG. 1. Level and transition schemes of ^{100}Mo for double beta decays ($\beta_1\beta_2$) and two beta decays ($\beta\beta'$) induced by solar-ν absorption. GR is the Gamow-Teller giant resonance. $Q_{\beta\beta}$ and Q_{ec} are given in units of MeV.

TABLE I. Solar-ν absorption rates R_ν for ^{100}Mo.

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

$E_\nu^{(max)}$, $E_\beta^{(max)}$ are the maximum ν energy and maximum β-ray energy, respectively.
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 $g^\nu_{7/2} - g^\pi_{9/2}$ 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].

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 $R_{0\nu}$=6.6×10^4$| < m > |^2/(\mathrm{eV})^2$ by RQRPA [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 ΔT=30 sec($10^{-6}y$) 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 8 efficiencies implicitly 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 preceeding decays from ^{214}Pb being detected. The efficiency for ^{208}Tl with the effective Q_β ~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.

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

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

10^{-13}(0.1ppt) ^{238}U~ 1.25 $10^{-3}b$(Bq/ton) for ^{214}Bi.
10^{-13}(0.1ppt) ^{232}Th~ 0.45 $10^{-3}b$(Bq/ton) for ^{208}Tl.

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 acidental 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 resolution.

The lower limit (sensitivity) on $< m_\nu >$ 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 $< m_\nu >\sim 0.03$ 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 case of the $0\nu\beta\beta$. It is of the order of ~ 100 SNU for one year measurement by using 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($\Delta T = 10^{-6} y$) 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 [25]. An ensemble of plastic scintillator modules is newly designed on the basis of recent developments [23,24,13]. The supermodule with a fiducial volume of (x, y, z)=(6m,6m,5m) is composed of 1950 modules with (x, y, z) = (6m,6m,0.25cm). Each module may consist of 30 extruded plastic bars of (x,y,z)=(6m,0.2m,0.25cm).

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 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 1.2mm in diameter and 6 m in length. An extrapolation of the results of [23,24] suggests the large fraction of the WLS with respect to the scintillators and the arrangement in both x and y directions may give adequate photo-efficiencies 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 6800 16-anode PMTs (photomultiplier tubes) with a large photo-electron efficiency, each accepting 128 fibers with 8-fold multiplexing. All PMTs are well separated through the clear fibers from the scintillator to avoid BG from PMTs.

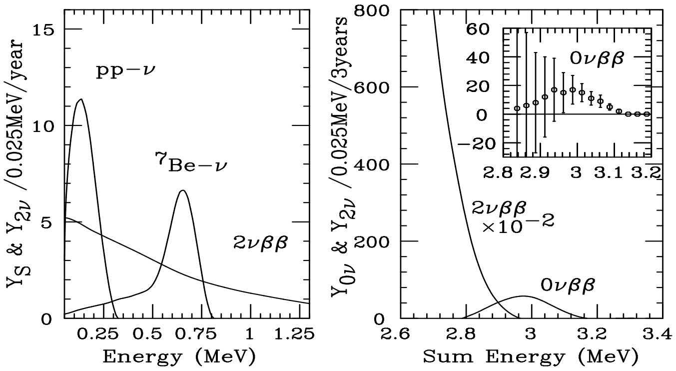

FIG. 2. Schematic energy spectra for a possible detector with 3.3 tons of ^{100}Mo (see text). Right hand side: Sum energy spectra for 3 year measurement of $2\nu\beta\beta$ and $0\nu\beta\beta$ for $< m_\nu >= 0.1$ eV with $M^{0\nu}$ in [8]. The inset shows the $0\nu\beta\beta$ spectrum with $< m_\nu >$=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

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 $\Delta x = \Delta y \sim 0.5$ cm $/\sqrt{E}(MeV)$ with $\pm 2\sigma$. Then the energy resolutions of 7, 15, and 30 %, and the spatial ones of $1/K$=0.11×10^{-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 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 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 [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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