New Approach to the Search for Neutrinoless Double Beta Decay

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Sub-eV Majorana neutrino masses $\langle m_\nu \rangle$, can be explored by a new approach to neutrinoless double β decay using ^{136}Xe in a Xe gas-loaded, multiton liquid scintillator installed in a very low background detector such as the Kamiokande facility. With enriched ^{136}Xe, a readily implementable, 10 ton detector experiment can establish an $\langle m_\nu \rangle = 0.45$ eV at 3σ in 1 yr (or exclude an $\langle m_\nu \rangle < 0.23$ eV in 2 yr). A 100 ton detector can extend the limit to $\langle m_\nu \rangle < 0.1$ eV, compared with the present limit of $\langle m_\nu \rangle < 1.3$ eV.

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Neutrinoless double β decay $(0\nu 2\beta)$, represented by the process $A(Z) \rightarrow A(Z+2) + 2\beta^-$, violates lepton conservation and demands two nonstandard neutrino properties: (1) $\nu_e = \bar{\nu}_e$, i.e., a Majorana type neutrino and (2) a nonzero Majorana neutrino mass $\langle m_\nu \rangle$ which introduces an admixture of opposite helicity [1]. Thus, $(0\nu 2\beta)$ decay is one of the few direct pointers of physics beyond the standard model and offers a rare experimental tool for the direct observation of a *small* neutrino mass. For these reasons, $(0\nu 2\beta)$ decay has been intensively searched for in recent years. The best limit achieved on $\langle m_\nu \rangle$ is < 1.3 eV with ~ 7 kg yr of ^{76}Ge in enriched Ge detectors [2]. A breakthrough into the regime of sub-eV masses (suggested indirectly as the likeliest by present limits on neutrino oscillations), requires a large source mass m and very low background b [the sensitivity to $\langle m_\nu \rangle \propto (m/b)^{-1/4}$]. Just these criteria are also basic for recent designs of very low energy (< 1 MeV) solar neutrino detectors which thus offer a possible new framework for high sensitivity $\beta\beta$ studies [3]. As described in this Letter, this idea can indeed be directly realized in practice in the case of ^{136}Xe since large masses of Xe gas can be loaded into a large-scale liquid scintillation detector such as Borexino [4]. Such an experiment is, in fact, less demanding than the detection of < 1 MeV solar neutrinos because of the higher energy of the ^{136}Xe $(0\nu 2\beta)$ line signal at 2.45 MeV, which also opens other facilities such as Kamiokande (K-II) where this approach can be readily implemented by installing a Ze scintillator setup.

A 100 ton scale Xe scintillator can ultimately lead to a limit $\langle m_\nu \rangle < 0.1$ eV with enriched ^{136}Xe and 0.25 eV with natural Xe, thus introducing a new level of sensitivity for the search for $(0\nu 2\beta)$ decay. As a first stage experiment, a small 10 ton scintillator loaded with enriched ^{136}Xe is sufficient to establish a Majorana mass $\langle m_\nu \rangle = 0.45$ eV with 3σ precision in 1 yr (or set a limit $\langle m_\nu \rangle < 0.23$ eV in 2 yr). Sub-eV mass sensitivity in this speedily realizable experiment is particularly attractive at present in view of recent observations of suggestive $(0\nu 2\beta)$ line features consistent with a mass $\langle m_\nu \rangle \sim 1$ eV [5]. The standard lepton-number *conserving* $(2\nu 2\beta)$ decay of ^{136}Xe producing a continuous 2β spectrum with an end point at 2.45 MeV can be $\sim 10^3$ times faster than the $[0\nu 2\beta(\langle m_\nu \rangle = 1$ eV$)]$ decay. In the Xe scintillator approach, these signals will occur at unprecedented rates of hundreds/day at a high signal/noise; note that this rare process was first detected at all (in ^{82}Se) only recently [6] and is yet unobserved in Xe.

The marked advance in sensitivity is made possible by two factors: First, the Xe scintillator approach facilitates, for the first time, observation of a $(0\nu 2\beta)$ source mass of tons (rather than kg). With a solubility as high as 2% of Xe in organic liquid scintillators [7], a Xe source mass of up to 2 ton can be observed in a 100 ton detector, compared to ~ 6 kg (enriched Xe), the maximum employed so far in gaseous Xe detectors [8,9]. In addition, the detection efficiency is $\sim 100\%$, compared to $\sim 20\%$ in gas detectors. Second, the specific background b/m is lowered many orders of magnitude (compared to Ge) because of the high radiopurity of liquid scintillators [10] and the massively shielded environment inherent in a direct-counting facility for low energy solar neutrinos. These two factors more than offset the much poorer energy resolution (compared to Ge) and the relatively low concentration of Xe in the scintillator. A noble gas such as Xe is one of the few types of dopants in a liquid scintillator that guarantees no degradation of chemical/radiopurity and detector response. Indeed, an inert gas is normally loaded into the scintillation liquid to improve and maintain optical performance. Gas loading also offers the key advantage of a source in/source out facility which allows a direct blank measurement without affecting the spectroscopy quality of the detector or the background. A Xe $(0\nu 2\beta)$ experiment thus fits naturally and elegantly with the technique of large-scale liquid scintillation spectroscopy.

Based on theoretical nuclear matrix elements for ^{136}Xe [11], the neutrino mass follows as $\langle m_\nu \rangle \approx [2.7/T_{1/2} \times (0\nu 2\beta)]^{1/2}$ ($T_{1/2}$=half-life in units of 10^{24} yr). Reference [8] has reported the best limit (90% C.L.) of $T_{1/2} \sim 0.25 \times 10^{24}$ yr for the ^{136}Xe $(0\nu 2\beta)$ decay; thus a limit $\langle m_\nu \rangle < 3.3$ eV. Large quantities of high purity, natural Xe as well as isotropically enriched ^{136}Xe are commercially obtainable at reasonable cost [12]. The main contaminant in these samples as observed in $(0\nu 2\beta)$ experiments so far [8,9] is radioactive 10.8 yr ^{85}Kr which β decays with an end point of 670 keV. The activity is not observed above background after rejecting mass numbers

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below 124 (by diffusion or ultracentrifugation) [9]. Large quantities of such mass-rejected samples are available [12]. The only other activities in well-sealed, mass-rejected Xe gas samples are small amounts of sea-level cosmogenic ^{3}H and 36-d ^{127}Xe (which emits only a single 390 keV γ ray) [13].

There are several options for implementing a Xe scintillator double β decay experiment, the most attractive being K-II, used so far as a water Cerenkov detector [14] for solar neutrino studies now nearing completion. It can be readily adapted by placing up to a few hundred tons of liquid scintillator in a transparent vessel in the center of the water tank and using the present photon detection and other systems unchanged. A 4 ton liquid scintillation counting test facility (CTF) [15] will operate in 1994 at Gran Sasso. The Borexino facility itself is a possibility following completion of its solar neutrino objectives (a concurrent $\beta\beta$ study is contingent on more sensitive data on ^{85}Kr content of Xe samples). The intensively studied Borexino design [4] is basic to all the options; we can thus apply it to illustrate practical figures of merit in these options.

Borexino consists of 300 ton of liquid scintillator contained in a transparent vessel of radius $R=4.25$ m, at the center of a 17 m diam$\times$17 m water tank. The scintillation light is observed by 1700 photomultipliers (PM) arranged at $R=6.25$ m. A ^{136}Xe $(0\nu 2\beta)$ event triggers $\sim$500 PM. The total charge in the PM and their relative trigger times yield the energy and spatial location of the events, with $\Delta(\mathrm{FWHM})\sim 250$ keV and $\Delta r/r(1\sigma)\sim 8$ cm at 2.5 MeV. Nuclear events are detected *calorimetrically*; i.e., only the summed energy is observed for prompt cascade nuclear decays, Compton showers, or 2β emission. The good spatial resolution allows a relatively well-defined fiducial volume (FV), thus an (off-line) choice of the $(0\nu 2\beta)$ source mass. The nominal FV is set at $R=3$ m ($\sim$100 ton of scintillator) which leaves a 1.25 m active buffer shield. For the Xe $(0\nu 2\beta)$ studies, a hardware trigger at $\sim$500 keV will reject most of the events due to ^{85}Kr.

An important part of the unshieldable background $B(I)$ is set by radiocontaminants in the scintillator. The energy of the ^{136}Xe $(0\nu 2\beta)$ line, 2.45 MeV, is particularly favorable, freeing interference from lower energy sources such as ^{7}Be, ^{210}Pb, and ^{40}K (of major concern in Borexino). Of the conceivable naturally radioactive contaminants, *only* ^{214}Bi (and, to a small extent, ^{212}Br [16]) are relevant to signals in the 2–3 MeV region. The Bi events are, however, just the type that can be ideally tagged because they are followed at the same spatial location within a few hundred μs by $\sim$8 MeV α's which appear in the scintillator as $\sim$0.8 MeV events. The delayed coincidence tag can remove these events by a factor >500 [17], creating in effect a 2–3 MeV gap in the background spectrum. The efficient taggability of the ^{214}Bi background also minimizes the problem of ubiquitous radon, since the only relevant radon decay product is ^{214}Bi. Long-lived (<10 s) cosmogenic activity via muon capture, spallation, or by reactions due to muon-induced neutrons on C and H in the scintillator, results mostly in 20 min ^{11}C which β^{+} decays with a total energy of $(1.02\gamma\gamma+0.96)=1.98$ MeV, well short of the 2–3 MeV gap. Activities induced in the Xe additive ($\sim$10–20/(ton Xe) yr [13]) produce only a relatively small background in the signal window.

The background profile in a Xe-filled Borexino is illustrated in Fig. 1. The Monte Carlo simulation [18] generates events in the full scintillator volume due to all contaminant decays in the U, Th chains and from ^{40}K (assuming as in Borexino, U/Th at 10^{-16} g/g and K at 10^{-12} g/g), reconstructs the scintillation response, and filters out the spectrum of events occurring within a chosen FV. Figure 1 shows the 2–3 MeV gap [19] due to the coincidence tags. The residual Bi events in the gap are only $\sim$10/MeV yr (100 ton) smaller than electron scattering events of ^{8}B solar neutrinos ($\sim$20/MeV yr) and resolution-smeared spillage from the $(2\nu 2\beta)$ signal continuum ($\sim$20/MeV yr) [20], for a total of $B(I)\sim 50$/MeV yr (100 ton). Clearly, the Borexino-grade purity assumed above can be relaxed significantly. The background from external sources, B(E), depends on the FV radius R and arises from materials closest to the FV, viz., the inner vessel and the adjacent shield water. The latest

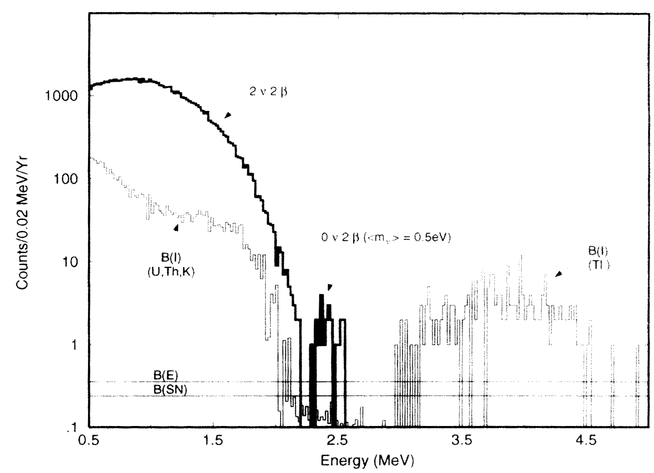

FIG. 1. Monte Carlo simulation of 2β signals and background in the Borexino design option (see line 1 of Table I and text) with 58 ton FV of Xe scintillator (2 wt.% natural Xe) or equally for 90% enriched ^{136}Xe loaded, K-II option of a 6 ton FV scintillator (line 6 of Table I) with 10$\times$ higher impurity concentration. Shown are the spectral profiles of background (thin lines) due to internal sources B(I) and estimated levels from external sources B(E) and solar neutrinos B(SN) and the signals (thick lines) due to the $2\nu 2\beta$ continuum and a possible $0\nu 2\beta$ peak due to a neutrino mass $\langle m_\nu\rangle=0.5$ eV. The only analysis cuts applied in the B(I) profile are tags of the ^{212,214}Bi delayed β-α coincidences.

designs employ a thin (~ 1 mm) membrane type vessel [15] and the possibility of an outer membrane vessel enclosing a 0.5 m thick buffer of high-purity (water or organic) liquid. With these improvements, the limiting background, due mostly to fixtures such as the PM and their supports, is estimated at $B(E,R=3\text{ m})\sim 180$/MeV yr [21]. The total specific background is thus $B(R)\Delta=[B(I)+B(E,R)]\Delta=60$/yr (100 ton) for $R=3$ m. With a more optimal choice of $R=2.5$ m (60 ton) [and with $B(I)\propto R^{-3}$, $B(E,R)\propto \exp(-\delta R/21.5\text{ cm})$], we estimate $B\Delta\sim 12$/yr (60 ton). Figure 1 is based on this choice of design parameters.

In a Xe-K-II experiment, the larger water shield at K-II can accommodate the higher rock radioactivity. The muon flux and thus the cosmogenic ^{11}C are 10× higher, still posing no interference. The smaller PM coverage produces a worse energy resolution, $\Delta\sim 350$ keV. The background from the PM is $x\sim 5$ smaller [22]. Overall, we estimate $B(E,R=3\text{ m})\sim 40$/MeV yr. $B(I)$ may be higher because of added spillage of ($2\nu2\beta$) events due to the poorer resolution, thus $B(I)\sim 70$/MeV yr. Thus, for a 300 ton Xe-K-II scintillator, $B\Delta(R=3\text{ m})\sim 40$/yr (100 ton). For the optimum $R=2.5$ m as above, $B\Delta\sim 16$/yr (60 ton). A smaller total mass (100–200 ton) can be chosen in K-II, reducing the total Xe inventory without serious loss of sensitivity.

The use of enriched Xe (90%) is of great practical interest since $\langle m_\nu\rangle$ sensitivities possible in the above 100 ton devices can be attained with only ~ 10 ton of scintillator contained in vessels $R<1.5$ m. Note that Fig. 1 based on a 60 ton (FV) design applies equally to a 6 ton (FV) scintillator with enriched Xe with a scintillator purity of 10^{-15} g/g (10× worse than assumed in the 60 ton simulation). These purities are readily attained in organic scintillators [10]. Indeed, for purities even worse, Fig. 1 shows that the contaminant background is smaller than those from other sources. Because of the smaller R (and thus the larger water shielding), the value of B(E) is set only by residual background due to the vessel material (and the high-purity buffer) rather than the more external fixtures such as PM and their supports. We estimate $B\Delta\sim 18$/yr for a 6 ton FV in a 10 ton vessel, approaching $B\Delta$ values reached above for an equivalent 60 ton FV but a total mass of 300 ton. The low-mass regime with enriched Xe at Kamiokande clearly offers the highest sensitivity in terms of mass to background ratio.

Another possibility for experiments in the "low-mass" regime is the CTF detector. The CTF follows the basic design of Borexino but is dimensioned smaller, in a 11 m diam×11 m water tank [15]. The scintillator mass, contained in a vessel of $R=1$ m, is 4 ton. The water shield thickness is ~ 1 m smaller and the PM placed closer to the FV than in Borexino. Thus, in the CTF, the background is higher, and it is dominated by B(E) from fixed external sources. The energy resolution is $\Delta\sim 300$ keV. On the basis of simulations of background in the CTF [15] (with a high-purity buffer), $B(R)\sim B(E,R=0.8\text{ m})=270$/MeV yr or $B\Delta\sim 80$/yr (2 ton). The source size is limited to this level since larger masses entail a sharply rising $B(E,R)$.

The double-beta decay signals, ($0\nu2\beta$) as well as 2ν, are also simulated in Fig. 1 for Borexino with a 58 ton FV loaded with ~ 1.2 ton natural Xe or a 6 ton FV at K-II with 90% enriched Xe (and a 10× worse scintillator purity). The 2ν continuum assumes a $T_{1/2}=4\times 10^{21}$ yr [23] while the 0ν peak assumes a $\langle m_\nu\rangle=0.5$ eV. The large 2ν signal and its high signal/background are evident. Two-ν decay to the first excited state (1.31 MeV) of ^{136}Xe (not shown) will also contribute a much weaker continuum extending (by calorimetric summation of the γ ray) from 1.31 MeV to the common end point of 2.45 MeV. The 0ν peak is situated in the middle of the 2–3 MeV gap with residual background B(SN) from solar neutrinos and B(E) from external sources. Clearly, the peak due to a 0.5 eV neutrino can be statistically secured in this 1 yr spectrum.

With the above design options and the likely backgrounds, the attainable neutrino mass sensitivities are summarized in Table I. The design regime of low detector masses 4–14 ton using enriched Xe covers the same sensitivity region as the 100–300 ton detectors with natural Xe. The cost of Xe (last column) is approximately

TABLE I. Majorana neutrino mass sensitivities in Xe scintillator design options.

Option	R' Scint. vessel (m)	M' Scint. mass (ton)	M FV mass (ton)	$B\Delta$ (FV) (/yr)	$\langle m_\nu\rangle$ Limit (90% C.L./2 yr) (eV)	$\langle m_\nu\rangle$ Min. det. (3σ/1 yr) (eV)	Cost of Xe (10^6 \$)
Borexino	4.25	300	58	12	0.21	0.42	3.9 (Nat.)
Xe-K-II	3.5	180	100	74	0.25	0.45	2.3 (Nat.)
Hi-Mass	3	100	58	100	0.36	0.63	1.3 (Nat.)
					0.11	0.2	13 (Enr.)
Xe-K-II	1.5	14	9	24	0.2	0.38	4.5(Enr.)
(Lo-Mass)	1.33	10	6	18	0.23	0.45	3.2(Enr.)
	1	4	2	10	0.35	0.7	1.3(Enr.)
CTF	1	4	2	80	0.58	1.0	1.3(Enr.)

the same for the two regimes but the outlay and technical basis for the larger detectors are significantly larger. Thus, a first phase program with the 4–14 ton designs with enriched Xe at Kamiokande offers the fastest route to a breakthrough into the sub-eV Majorana mass regime, with the potential to set a best limit of $\langle m\nu \rangle < 0.2$ eV and establish an $\langle m_\nu \rangle < 0.4$ eV in 1 yr. A second phase in the 100 ton scale using major quantities of enriched Xe can extend the search to $\langle m_\nu \rangle < \sim 0.1$ eV. To our knowledge, this is the only directly implementable program yet conceived for the measurement of such tiny neutrino masses.

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[2] H. Klapdor-Kleingrothaus (Heidelberg-Moscow Collaboration); the limiting mass sensitivity in this experiment is claimed to be 0.2 eV (private communication).

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[16] Events from ^{212}Bi, with a decay energy of only 2.25 MeV, can occur in the 2–3 MeV interval since some daughter α's appearing at ~0.9 MeV with a mean life of ~440 ns can be summed within the detector time resolution. An estimated fraction (2.5%) untagged is included in the simulation of Fig. 1.

[17] Rejection factors > 500 are attained with a tag time of ~1.6 ms (~10 half-lives) and a tag radius of search $=6\times\Delta r(1\sigma)$; the few Hz trigger rate in the entire detector poses no limitations. Even with a base trigger level at 0.5 MeV, simulations show that 0.8 MeV α's lost below this level will be $< 2\times 10^{-3}$.

[18] The code is a local version of CRONOS, S. Bonnetti *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **239**, 314 (1993).

[19] The spectrum above the gap is due to ^{208}Tl which appears only above 3.2 MeV because of the calorimetric summing of the Tl decay cascades (these events will also be largely removed by a different delayed coincidence tag; see Ref. [4]).

[20] M. Moe, Phys. Rev. C **44**, R993 (1991).

[21] This background is about 5× smaller than that estimated in Ref. [4] for a thick acrylic shell design (à la SNO) and shield water of 10^{-13} g/g purity.

[22] The 50× higher Th in the K-II PM [which determines $B(E,R)$ at 2–3 MeV], the 50% fewer PM, and the ~1 m additional water shield are taken into account in this estimate.

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