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SENSITIVITY ESTIMATES FOR A LARGE VOLUME LIQUID XENON DOUBLE BETA DECAY DETECTOR

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ABSTRACT

Assessment of backgrounds arising from the construction and underground operation of an unenriched 200 liter liquid xenon detector indicates a sensitivity of order $10^{27}\sqrt{t}$ yr for the neutrinoless decay of ^{136}Xe. The lower energy background is however too severe for observing the 2ν process without significant isotopic enrichment.

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The current demand to conclusively affirm/deny the existence of neutrinoless (0ν) double beta ($\beta\beta$) decay provides the impetus for new experiments of increased sensitivity. Among the new approaches to this search has been the development of large volume, high pressure gas xenon chambers to search for the decay of ^{136}Xe. The spatial resolution of these devices permits track reconstruction, which significantly improves their ability to identify and reject backgrounds. Three experiments, summarized in Table I, are currently acquiring data [1-3]; as indicated, despite enrichment, all are mass-limited to lifetimes of 10^{24} yr, coinciding with the best limit on the 0ν process already derived from ^{76}Ge experiments [4] and an order of magnitude below the 10^{25} yr sensitivities projected for three second-generation ^{76}Ge efforts now underway using enriched germanium in low background cryostats [4].

To increase the sensitivity of the ^{136}Xe experiments, two groups [5] have proposed the replacement of the xenon gas with liquid in a high resolution tracking device. This results not only in a direct increase in number of decay candidates, but also in the detector efficiency because the small spatial extent of an event in the higher density liquid results in a fiducial volume very close to the total chamber volume.

Liquid xenon (LXe) detectors are still undergoing development [6], and several technical challenges face their large volume application to $\beta\beta$ decay. These problems aside, it however remains unclear that the potential sensitivity (S) can be achieved experimentally since its statistical estimator also depends strongly on the background rejection capability of the detector:

$$S(0\nu) = 4.2\times10^{26}\ [a/A][Mt/B\Gamma]^{1/2}\ \varepsilon, \qquad (1)$$

where M is the detector mass in kg, a is the isotopic abundance, A is the atomic number, B is the background rate in events per keV per year, Γ is the energy resolution at the 0ν energy, t is the measurement time in yrs, and ε is the detector efficiency. While the backgrounds are in nature identical to those of the xenon gas experiments, their reduced track lengths in liquid xenon increases the difficulty of discriminating them from signal events. This change in background identification and rejection efficiency, so far unaddressed in the literature, is a fundamental question in assessing the potential sensitivity of the LXe proposals .

To explore this question, background estimates were made by considering the radiopurity of detector construction materials and their neutron activation, both above and below ground, assuming a hypothetical non-enriched LXe ionization detector operated as a time projection chamber (TPC). The detector model, consisting of a cylindrical vessel 75cm long and 70cm inner diameter with a wall thickness of 2.5cm, would provide a 200 liter active volume comparable with that of the Caltech-Neuchatel-PSI detector. It is assumed that the vessel is constructed entirely of low background OFHC copper. The active volume is defined by a cathode plane and 92 field shaping rings, all made of copper. The thickness of the cathode and rings is 0.15cm, and the radial ring thickness is 1.0 cm. Five teflon columns of 0.5cm diameter support the rings. The shielding grid, separating the drift region from the XY readout region, is assumed made of 25μm thick copper mesh. For the orthogonal multi-wire planes of the readout, we assumed Cu-Be wires as a worst possible case. Other components, such as the resistors of the HV divider chain and the vacuum feedthroughs, were however not included in the analysis.

The event trigger for the TPC is provided by the primary scintillation light signal [7]. This is detected by eight UV-sensitive photomultipliers symmetrically positioned on the chamber walls, the backgrounds of which are included in the analysis [8]. The detector is assumed to be operated deep underground, and to be shielded with ultraclean lead and copper comparable with current experiments.

Low background construction materials were chosen on the basis of published experimental studies [8,9] of materials for ^{76}Ge experiments. For components more unique to TPC construction, backgrounds are less well documented and some approximations were made. In general however, all primordial backgrounds originate from ^{40}K and from the complex ^{238}U/^{232}Th decay chains, in amounts depending upon the specific material and supplier. Additional man-made contaminants in the materials include ^{137}Cs and ^{60}Co.

For the operation of a LXe chamber, the total concentration of electronegative impurities must be below 1 ppb. Since a detailed chemical analysis of the remaining impurities in the purified liquid is generally unavailable, we have conservatively

assumed an overall concentration of 10 ppb, which accounts mostly for krypton which passses all normally-used purifier systems. Manmade ^{85}Kr is also included in its 1952 concentration, although its specific contribution will depend upon the xenon supplier and its above-ground storage time [10].

Neutron-activation of the copper, the most abundant material in the detector, yields the additional contaminants ^{54}Mn, ^{59}Fe, ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, ^{64}Cu, and ^{66}Cu [11] in quantities dependent upon the material history, especially its above-ground exposure time. Most of these cosmogenics have less than 1 yr halflives [12] so that their contribution may at least be reduced by simple underground aging of the detector. The same is true for products of above-ground (n,γ) reactions in the liquid itself, most of which have halflives of less than 40 d [12]. The daughters ^{125}I and ^{137}Cs are however sufficiently long-lived, and their decays sufficiently energetic, to cause concern. Subterranean neutron activation yields were estimated using the Gran Sasso thermal neutron flux measurement of 2.1×10^{-6} $cm^{-2}s^{-1}$ [13] and full neutron absorption. For the xenon impurities, this flux generally yields insignificant quantities of radiocontaminants, as is also the case for the containment vessel and shielding. Epithermal and fast neutron activations were not considered.

The detector performance was studied in two windows of total deposited energy. The first window, 2.396-2.544 MeV, represents a 3% energy resolution centered on the total decay energy of 2.470 MeV and corresponds to the best experimental value so far obtained in LXe [14]. Since the 2ν decay is also of interest, a second window between 0.75-1.0 MeV was selected on the low energy side of the 2ν distribution maximum, whose turnover is critical to its identification. About 25% of all 2ν events are contained in this window.

Background estimates in each of the two windows (ΔE) were obtained via

$$B(\Delta E) = \sum \sum \int_{\Delta E} B^m{}_k(E)\, A^m{}_k(E',E)\, dE' dE d\Omega, \qquad (2)$$

where the $B^m{}_k$ are distributions obtained by energy-analyzing the possible radiations ($k = \alpha, \beta, \gamma$) from the decay of each contaminant into bins of 250 keV spanning the

interval 0.5-3.5 MeV, and then scaling the resulting spectra for the mass of each of the m detector components using the specific activity measurements of Refs. 8,9, and 12. These were minimally-corrected for self-absorption and geometry (basically a 2π cut only). In cases where numerous β branchings exist, only those with branching ratios greater than 0.2% were included; where a range of activity is reported for a material, such as ^{214}Bi, the lower limit was adopted. The $A^m{}_k$ are absorption probabilities for initial energy E and average path length s. For the α and β fields, these were estimated using range formula and dE/dx curves [15]; for the γ field,

$$A^m{}_\gamma(E',E) = 1 - e^{-\mu_n(E)s} \tag{3}$$

where $\{\mu_n\}$ are appropriate attenuation coefficients for pair, photoelectric, and Compton processes [16] .

With the exception of neutron-activated liquid contaminants, virtually all contributions of the β field from the detector vessel and photomultipliers could be ignored, since the 5cm dead layer of LXe enclosing the active volume is sufficient to stop electrons of energy up to 20 MeV. The Compton contributions were obtained by subtraction of the direct (pair+photoelectric) absorption events from the respective window content, and uniformly distributing the result over the energy interval between zero and the corresponding Compton edge. This interval generally includes those events which scatter one or more times and then exit the active volume. For a 200 liter detector, most of the radiation is contained and would appear in the photopeak, so that this background source is grossly overestimated.

The results of the background estimate are shown in Table 2. The total signal rates per year of detector operation, 1.2 $X10^5$ for 2ν events and 5.8 $X10^1$ for 0ν, were estimated in the absence of background using the approximate expression

$$R_j \approx \ln 2 \, [\, N_{136_{Xe}} \,] \, [\, T_{1/2}{}^j \,]^{-1} \, \varepsilon \tag{4}$$

where $j = \{2\nu, 0\nu\}$, $N_{136_{Xe}}$ is the number of candidate decay nuclei, and the detector efficiency (ε) was assumed unity. Halflife estimates ($T_{1/2}$) for the 2ν and 0ν decay modes are 3.8 $x10^{20}$ and 3.0 $x10^{24}$ yr, respectively [17]. The neutrinoless mode corresponds to a 1 eV neutrino mass, which is at the current horizon of experiment. As seen, primary backgrounds in each of the two energy windows are of sufficient quantity

to render a purely calorimetric experiment unfeasible, and further contributions were therefore not considered.

The spatial signature of a $\beta\beta$ event in a LXe detector is a charge blob of less than 4mm extent, uncorrelated with any other ionizing activity within the chamber. While the assumed 2mm position resolution cannot resolve the two electron tracks, it can be used to discriminate those backgrounds characterized by spatially-distant multiple ionization events. In the case of a pair production event within the active volume, for example, detection of the Compton electrons and their correlation with the pair event origin would distinguish the event from a true signal. With the addition of position resolution, the A^m_k were modified to further include the contributions of secondary processes, in particular those in which the photon first scatters and is then absorbed within 2mm of the scattering point. The scattering probability in these events was weighted by the probabilities for absorption via photoelectric and pair production, which generally range between $5X10^{-3}$ and $1X10^{-4}$ over the energy range [15], so that the total probability is of order 10^{-5}. Also included were double Compton scattering, internal conversion (IC) processes, IC+γ summing, and both single and double annihilation photon escape.

The background estimates using both energy- and position-resolution cuts are also shown in Table 2. The apparent discrepancy of the Compton entries with the energy-only result arises from the inclusion of secondary processes. It is clear that events associated with the decay of ^{214}Bi dominate both windows. These contributions have generally been vetoed in gas experiments by track identification of the α of the subsequent ^{214}Po decay, which follows that of ^{214}Bi by 164μs [18]. In liquid xenon, this form of veto is impossible because of the reduced track lengths. The detection of a second event at the same location after 164μs can however be used effectively to discriminate against this background. Additional pulse-shape discrimination of the scintillation signal can also be used to identify the α particle [7].

For our detector model, the background estimates then yield $S(0\nu) = 3X10^{27}\sqrt{t}$ yr assuming a complete ^{214}Bi event veto. Clearly, assuming $\varepsilon < 1$ and even a factor of ten uncertainty in these estimates, a large volume unenriched LXe detector with good

energy- and position-resolution seems capable of significantly extending the sensitivity of searches for $0\nu\ \beta\beta$ decay beyond the $10^{25}\sqrt{t}$ yr limit of the new germanium experiments, and should be pursued. Of the associated backgrounds, Compton-scattering is the most serious potential problem and detailed Monte Carlo studies are required to further evaluate its contribution. Further studies of low background detector construction materials are also required.

In contrast, a sensitive search for the 2ν process appears less promising with such a detector without the use of enriched xenon, primarily due to background from the decay of ^{40}K. The photomultipliers used for detection of the scintillation light account for only half of this background, so that their replacement by other techniques will not solve the problem. A simultaneous search for the $\beta\beta$ decay of ^{134}Xe, as a byproduct of the detector operation, is similarly precluded by its endpoint energy of 0.8 MeV. With the increase in decay candidates in a liquid detector, a simultaneous search for the analogous neutrinoless β^+/EC decay of ^{124}Xe seems feasible [19], and is presently under consideration.

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TABLE 1: Comparison of Operating Gas and Proposed Liquid ^{136}Xe ββ Decay Experiments.

Experiment	Milano [a]	C/N/PSI [b]	ITEP/INR [c]	LXe
detector type	multielement	TPC	ionization	TPC
location	GranSasso	St. Gottnard	Baksan	GranSasso
depth (mwe)	3500	3000	850	3500
pressure (atm):	10	5	25	liquid
volume(liter):				
total	140	355	--	269
active	79	208	3.14	198
fiducial	46	80	--	198
enrichment (%)	64	60	93	-
E resolution (%): FWHM@ 2.5 MeV	3.7	5	3.8	3
^{136}Xe nuclei	$1.2X10^{25}$	$2.5X10^{24}$	$2.4\ X10^{24}$	$2.5X10^{26}$
0ν sensitivity ($\sqrt{t}$ yr)	$4.2X10^{22}$	$8X10^{22}$	10^{22}	$>10^{27}$

[a] Ref. 1 [b] Ref. 2 [c] Ref. 3

TABLE 2: Signal/Background Estimates in a 200 liter LXe ^{136}Xe Decay Search.

Measurement	Background Source	Signal-to-Background Ratio 2ν window	0ν window
energy only	electrons	0.83	0.02
	pair production	$>10^3$	0.001
	Compton	0.035 [a]	0.003
energy and position	electrons	$>10^3$	$>10^2$
	pair production	$>10^3$	$>10^2$
	Compton [b]	0.015	0.8
	Compton [c]	0.017	$>10^2$

[a] does not include secondary processes
[b] assuming no veto of ^{214}Bi events.
[c] assuming complete veto of ^{214}Bi events.