Snowmass2021 - Letter of Interest

A 3rd generation liquid xenon TPC dark matter experiment sensitivity to neutrino properties: magnetic moment and $0\nu\beta\beta$ decay of ^{136}Xe

Thematic Area: NF05: Neutrino properties

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Abstract: (maximum 200 words)

In this letter we present the case of how a 3rd generation (G3) two-phase liquid xenon TPC could not only explore new regions of parameters space of dark matter, but also competitively search for some neutrino processes of interest, such as neutrinoless double beta decay and the neutrino magnetic moment. We consider a detector with 75 tonnes of active mass, and our sensitivity projections are based on already demonstrated low-levels of radioactivity in detector components and energy resolution capabilities. This represents a straightforward improvement over G2 experiments: a G3 detector with a 68% reduction in materials backgrounds, and a factor 2.2 larger in linear dimensions compared to the LUX-ZEPLIN (LZ) experiment. Overall, a half-life sensitivity of 8×10^{27} years of the $0\nu\beta\beta$ of ^{136}Xe and a sensitivity of 1.3×10^{-12} μ_B for the neutrino magnetic moment are projected.

Introduction: Active research is underway to scale up existing two-phase liquid xenon (LXe) TPCs to a detector of a target mass between 40 and 100 tonnes, the so-called 3rd generation experiments. This is in accordance with one of the recommendations from the 2014 P5 report [1]. A detector with these characteristics will have sensitivity to dark matter-nucleon cross-sections down to the "neutrino floor" [2] for WIMP masses above $\sim$4 GeV [3], as well as a variety of other dark matter models. Furthermore, this technology has been shown to be competitive for the search of neutrinoless double beta decay ($0\nu\beta\beta$) [4–6] and has the potential to improve on the current best limit on the half-life for $0\nu\beta\beta$ of ^{136}Xe, set by KamLAND-Zen at 1.07×10^{26} years [7], by almost two orders of magnitude.

In this work, we present the projected ^{136}Xe $0\nu\beta\beta$ half-life sensitivity for a G3 experiment with a cylindrical TPC of 320 cm in both diameter and height, containing 75 tonnes of xenon. We also note that such detector would have a world-leading sensitivity to the neutrino magnetic moment (NMM), a complementary approach to answering the question of whether the neutrino is a Majorana or Dirac particle.

Backgrounds: Contaminants mixed in the xenon, such as ^{222}Rn and ^{85}Kr, are uniform across the detector, as are the irreducible ^{136}Xe $2\nu\beta\beta$ decay and solar neutrino backgrounds. For this study, a ^{222}Rn contamination of 0.2 μBq per kg of xenon is considered, while 0.03 ppt g/g are assumed for $^{\mathrm{nat}}$Kr. A detector of this size greatly benefits from xenon self-shielding, resulting in an extremely low rate of external γ background, in particular at low energies. Under these assumptions, a sensitivity of 1.3×10^{-12} μ_B is achievable for the neutrino magnetic moment, calculated using the profile likelihood ratio (PLR) technique. This is shown in Figure 1 along with current experimental limits.

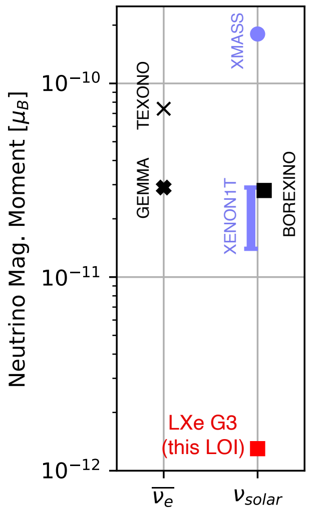

FIG. 1: Projected neutrino magnetic moment sensitivity along with current limits from reactor-based experiments (left markers) and experiments that are exposed to a solar flavor mixture (right markers). All the upper limits are reported at 90% CL, except the XENON1T result, which shows the 10–90% confidence interval [8–10].

Figure 2 shows the expected rates from the dominant background sources to $0\nu\beta\beta$ in ^{136}Xe considered in this study as a function of fiducial mass. An energy resolution of 0.8% at the $Q_{\beta\beta}$ value of 2,457 keV is assumed, as previously measured in ref. [11]. In the ^{136}Xe $0\nu\beta\beta$ decay energy region of interest (ROI), interactions from high energy γs from ^{238}U and ^{232}Th present in detector materials quickly become dominant with increasing fiducial mass. Rather than relying on detailed MC simulations, for this preliminary study a semi-analytical toy model of γ-ray attenuation in a cylindrical detector was developed [12], focusing on the ^{214}Bi 2447 keV line which is largely dominant in the ^{136}Xe $0\nu\beta\beta$ signal region. This model has been shown to be able to reproduce the LZ [4] and DARWIN [13] γ background dependency with fiducial volume. Moreover, it is assumed that the overall detector design and construction materials used will be similar to those of LZ, and therefore the background estimates from ^{214}Bi γs in the inner fiducial volume of LZ were used as the basis for the model in this study (see Table I in ref. [4]).

A significant reduction of these backgrounds can realistically be achieved through a combination of careful selection of materials (e.g. in-house developed field shaping resistors can render this source negligible [14]; significantly cleaner capacitors used in the PMT bases can found in the literature [11]; PMT cables can be assembled from cleaner copper batches; use of cleaner PMTs in the skin region, such as the 1" LZ PMTs [15]) and engineering solutions (e.g. SS tank supports and water displacement foam can be removed and replaced by clean acrylic volumes). For the other subsystems, it was assumed that all parts can be made from the cleanest Ti, PTFE, SS, Cu, Kovar and Kapton identified during the LZ assay campaign [15]. No re-

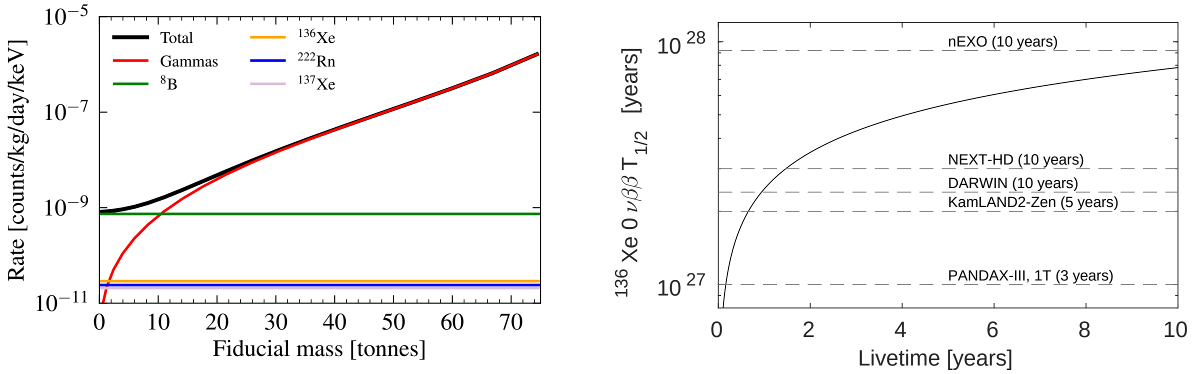

FIG. 2: *Left:* Rates of the various background sources considered in this study in the $0\nu\beta\beta$ $\pm 1\sigma$ ROI with increasing fiducial mass. *Right:* Time evolution of $T^{0\nu}_{1/2}$ upper limit sensitivity (solid line) as well as the projections from other experiments (dashed lines).

duction is assumed for the PMTs used in the TPC. Overall, a reduction of 68.4% in component radioactivity is achievable in comparison to the LZ γ background, based entirely on data from the LZ assay campaign and the published literature.

Moreover, ^{137}Xe, produced by neutron capture in ^{136}Xe, is an important background for $0\nu\beta\beta$ searches in xenon. While it is possible to efficiently shield the xenon from ambient neutrons, a rate of 2.1×10^{-11} counts/kg/day/keV in the ROI is expected from muon induced neutrons at SURF [16], considering that 90% of the muon events leading to the production of ^{137}Xe can be vetoed. ^{222}Rn dispersed in the xenon will lead to a rate of 2.4×10^{-11} counts/kg/day/keV assuming that 99.99% of ^{214}Bi decays to the ground state of ^{214}Po can be excluded by "BiPo coincidences" [4]. The irreducible backgrounds from ^{8}B and ^{136}Xe $2\nu\beta\beta$ decay contribute with 7.4×10^{-10} and 2.9×10^{-11} counts/kg/day/keV in the ROI, respectively.

Sensitivity Projections: The 90% CL sensitivity to the half-life of the $0\nu\beta\beta$ decay in ^{136}Xe is calculated with the figure-of-merit estimator developed in ref. [17]. To account for the spatial dependence of the background sources, the detector volume was divided in N sections, and the corresponding half-life sensitivity was calculated as a weighted sum over each of the sections. This results in a 19% sensitivity improvement compared to a single optimized fiducial volume. The right panel of Figure 2 shows the improvement in $T^{0\nu}_{1/2}$ sensitivity with increased exposure time, along with the projected sensitivities from other experiments. Here we show the best-case scenario, for an energy resolution of 0.8%, reaching 8×10^{27} years after 10 life-years of operation.

Conclusions: A ^{136}Xe half-life sensitivity of 8×10^{27} years is projected for a two-phase xenon experiment with 75 tonnes of active LXe mass, operated for a livetime of 10 years. This projected sensitivity is approximately 2 orders of magnitude larger than the current best limit from KamLAND-Zen [7]. This LXe G3 sensitivity is based entirely on past measurements of detector component radioactivity and demonstrated energy resolution of two-phase xenon detectors. If radioactivity values can be decreased further then this would improve the sensitivity. The solar neutrino magnetic moment sensitivity is projected to be 1.3×10^{-12} μ_B, a factor of 20 lower than the current best limit from Borexino [9].

Non-standard neutrino properties may also be investigated through searches for ^{134}Xe neutrinoless double beta decay and neutrinoless ^{124}Xe decays (both double-electron capture and positron emitting modes). Detailed studies of the LXe G3 experimental sensitivity to these processes will be a topic for future work.

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