Kilotonne-scale Xe TPCs for $0\nu\beta\beta$ searches at 10^{30} yr half-life sensitivity

M. Heffner[1] and D.C. Moore[2]

[1] *Lawrence Livermore National Laboratory, Livermore, CA, USA*

[2] *Wright Laboratory, Department of Physics, Yale University, New Haven, CT, USA*

We briefly summarize the motivation for searches for $0\nu\beta\beta$ with half-life sensitivities reaching 10^{30} years. Such searches require minimum exposures exceeding 1 ktonne-yr for the isotope of interest. Isotope procurement is thus the key challenge to realizing such ambitious experiments. A possible development path to procuring ^{136}Xe in the required quantities is briefly described, along with extensions to gas or liquid phase Xe time projection chambers (TPCs) that would be expected to meet the requirements for such an experiment. If neutrinos are Majorana particles, the realization of kilotonne-scale Xe TPCs would enable detection of $0\nu\beta\beta$ in the vast majority of parameter space that remains beyond the reach of tonne-scale experiments.

NF Topical Groups:

■ (NF3) Beyond the Standard Model

■ (NF5) Neutrino properties

■ (NF10) Neutrino detectors

IF Topical Groups:

■ (IF8) Noble elements

Contact Information:

Mike Heffner (LLNL) [mheffner@llnl.gov]

David Moore (Yale) [david.c.moore@yale.edu]

Currently operating $0\nu\beta\beta$ experiments have reached half-life sensitivities of $10^{25} - 10^{26}$ yr in a variety of isotopes, including ^{76}Ge, ^{130}Te, and ^{136}Xe [1–5]. Well-developed concepts for extensions to these experiments to exposures of several tonne-yr (corresponding to half-life sensitivities of $T_{1/2} \approx 10^{28}$ yrs) are expected to begin construction in the next few years. Such experiments have substantial discovery potential—the vast majority of the remaining allowed parameter space for the effective Majorana mass lies in the range 1 meV $\lesssim \langle m_{\beta\beta} \rangle \lesssim$ 100 meV (corresponding roughly to 10^{26} yr $\lesssim T_{1/2} \lesssim 10^{30}$ yr) [6, 7]. The upcoming tonne-scale experiments will probe two orders of magnitude further in half-life sensitivity than the best existing searches. However, if $0\nu\beta\beta$ is not discovered at the tonne-scale, experiments reaching half-lives as long as 10^{30} yr may be required to observe $0\nu\beta\beta$ or rule it out over the majority of the allowed parameter space. Xe time projection chambers (TPCs) are expected to provide a scalable path to 10^{30} yr sensitivities, provided ^{136}Xe could be procured in the quantities needed for a $\gtrsim$ktonne-yr exposure.

Isotope procurement: The existing commercial Xe supply chains (reliant on distillation and capture of Xe as a parasitic process in air liquefaction for the steel industry) produce $\sim$ 100 tonne/yr of natural Xe, of which ^{136}Xe constitutes 8.9% (i.e., roughly $\sim$9 tonnes). While this supply chain is sufficient for the upcoming tonne-scale experiments employing ^{136}Xe [8], it does not provide a viable path to 0.1–1 ktonne scale detectors. New methods for Xe procurement are thus required.

The supply chain above and overall current demand for Xe leads to a market price of $\sim$\$2k/kg. However, a simple calculation of the minimum thermodynamic energy to separate Xe from air (where it is present at $\sim$ 90 ppb concentration) gives 42 kJ/mol. At prevailing energy costs, the minimum energy required would cost only $\sim$ \$0.01/kg, roughly a factor of 10^5 lower than the prevailing cost. If the price to procure Xe could be reduced by even one order-of-magnitude out of the remaining factor of 10^5 above the minimum thermodynamic cost, then 0.1–1 ktonne target masses could be realized at potentially viable cost. In addition, alternatives to air extraction through capture of ^{136}Xe from reprocessed nuclear fuel may be viable at substantially lower cost, but are likely only sufficient for a detector in the 50–100 tonne range and we do not consider these further here.

Adsorptive methods may provide a path to air extraction of Xe in the required quantities and cost. Direct xenon capture from air is nothing new and is carried out daily around the world on a very small scale to track radioxenon in the atmosphere using zeolites or cryogenic activated charcoal with a pressure or vacuum swing adsorption cycle [9]. In order to produce the required quantities and cost, a process similar to that used for direct CO_2 capture could be developed. A small research effort does exist to develop such a process, but it is rate limited primarily by funding. It could be accelerated significantly because the advanced absorbents can be industrially developed and produced, and energy efficient cycles have been developed by the direct CO_2 capture companies.

A significant benefit of developing a purpose built xenon extraction for $0\nu\beta\beta$ is that it decouples the large demand from the xenon market, which is known to be very volatile even if the industry would ramp up production levels. The earth's atmosphere contains over 200 MTonnes of xenon, so these ideas could in principle be scaled to very large yearly production. While here we focus on applications to $0\nu\beta\beta$, the development of direct xenon capture could enable a broad, multi-purpose science program in the coming decades, including dark matter searches and other searches for rare processes where Xe may be advantageous to LAr TPCs. This resource may also enable medical advances in lung imaging and anesthesia that are currently not practical due to the cost and availability of xenon.

Detector technologies: A detector with exposure of 3 ktonne-yr (e.g., 0.3 ktonne fiducial mass operated for 10 yrs) would observe $\sim$10 events from $0\nu\beta\beta$ at a half-life of 10^{30} years. This low event rate places extremely stringent constraints on the background levels required to observe such a decay. Scaling existing crystal-based detectors to such size would be extremely challenging both due to cost, and since backgrounds arising at the surfaces of each small scale element must be continually reduced. The key advantage of homogeneous liquid or gas phase detectors is the self-shielding of backgrounds originating from external sources (i.e., for Xe TPCs those outside the Xe itself). For tonne-scale detectors, the higher density of LXe leads to a substantially higher fraction of the active mass shielded from external backgrounds relative to gas TPCs. However, ktonne scale detectors would be sufficiently large that external backgrounds are well-shielded in both gas or liquid phase TPCs. External γ backgrounds are thus not expected to be significant in such large detectors, despite the fact that they play a dominant role in tonne-scale TPCs [8]. A second advantage of Xe TPCs (relative to other proposals employing liquid scintillator-based detectors [10–12]) is that the detector mass is solely comprised of the isotope of interest, rather than included as a small fraction loaded into a much larger detector. This substantially reduces expected backgrounds from solar neutrinos, leading to a sub-dominant expected contribution in the $0\nu\beta\beta$ region of interest even at half-lives as long as 10^{30} yr.

Internal backgrounds distributed within the Xe provide the primary challenge in reaching the required background levels. Backgrounds arising from the tail of the $2\nu\beta\beta$ spectrum near the $0\nu\beta\beta$ Q-value are reducible only through separation in energy. For a 3 ktonne-yr exposure, limiting the leakage to $\lesssim 1$ event from $2\nu\beta\beta$ into the $\pm 2\sigma$ region around the Q-value requires an energy resolution $\sigma \lesssim 0.5\%$ [13]. The third advantage of Xe TPCs relative to liquid scintillator detectors is the ability to reach this resolution. Since the rate of leakage of $2\nu\beta\beta$ events increases as σ^6 [14], the $\gtrsim 2\%$ resolutions achievable in liquid scintillator detectors lead to several orders-of-magnitude higher $2\nu\beta\beta$ backgrounds.

Although $2\nu\beta\beta$ presents the primary irreducible background internal to the Xe, impurities in the Xe must also be removed at levels exceeding those demonstrated to date. ^{222}Rn within the Xe is expected to be the most challenging internal background to remove, and R&D on Rn removal will be required to demonstrate the requisite impurity levels can be reached.

Either gas phase or liquid phase Xe TPCs could allow the required resolution of $\sigma = 0.5\%$ if similar detector parameters could be achieved as in existing $\lesssim$tonne scale experiments. GXe TPCs have the substantial advantage that such resolutions have already been demonstrated with only the need to readout ionization signals [15, 16]. In contrast, LXe TPCs would require detection of both ionization and 175 nm scintillation light with collection efficiencies $\gtrsim$10% to avoid reduction in resolution from electron-ion recombination fluctuations [17].

While scaling such TPCs to the kilotonne scale would present challenges, LAr detectors of this size already exist and much larger LAr detectors are planned. Natural LXe detectors as large as 50 tonnes (as above, limited by the current Xe supply chain) are also envisioned for dark matter searches [18]. In contrast to other technologies such as Te loaded LS detectors or gas TPCs employing SeF_6 [19], the key challenge for LXe is primarily in the isotope procurement rather than requiring substantial improvements in the underlying detector technology. If the technologies for direct air capture described above can substantially change the economics of Xe procurement, a new path towards sensitivities at 10^{30} yr will be opened.

---

[1] M. Agostini *et al.* (GERDA), Science **365**, 1445 (2019), arXiv:1909.02726 [hep-ex].
[2] S. I. Alvis *et al.* (Majorana Collaboration), Phys. Rev. C **100**, 025501 (2019).
[3] D. Q. Adams *et al.* (CUORE Collaboration), Phys. Rev. Lett. **124**, 122501 (2020).
[4] A. Gando *et al.* (KamLAND-Zen), Phys. Rev. Lett. **117**, 082503 (2016), [Addendum: Phys.Rev.Lett. 117, 109903 (2016)], arXiv:1605.02889 [hep-ex].
[5] G. Anton *et al.* (EXO-200), Phys. Rev. Lett. **123**, 161802 (2019), arXiv:1906.02723 [hep-ex].

[6] M. Agostini, G. Benato, and J. Detwiler, Phys. Rev. D **96**, 053001 (2017), arXiv:1705.02996 [hep-ex].
[7] A. Caldwell, A. Merle, O. Schulz, and M. Totzauer, Phys. Rev. D **96**, 073001 (2017), arXiv:1705.01945 [hep-ph].
[8] S. A. Kharusi *et al.* (nEXO), (2018), arXiv:1805.11142 [physics.ins-det].
[9] T. W. Bowyer, Pure and Applied Geophysics (2020), 10.1007/s00024-020-02440-0.
[10] J. Cao, G.-Y. Huang, Y.-F. Li, Y. Wang, L.-J. Wen, Z.-Z. Xing, Z.-H. Zhao, and S. Zhou, Chin. Phys. C **44**, 031001 (2020), arXiv:1908.08355 [hep-ph].
[11] M. Askins *et al.* (Theia), Eur. Phys. J. C **80**, 416 (2020), arXiv:1911.03501 [physics.ins-det].
[12] S. D. Biller, Phys. Rev. D **87**, 071301 (2013).
[13] J. B. Albert *et al.* (nEXO Collaboration), Phys. Rev. C **97**, 065503 (2018).
[14] S. R. Elliott and P. Vogel, Annual Review of Nuclear and Particle Science **52**, 115 (2002), https://doi.org/10.1146/annurev.nucl.52.050102.090641.
[15] C. Adams *et al.* (NEXT), (2020), arXiv:2005.06467 [physics.ins-det].
[16] J. Renner *et al.* (NEXT), JINST **13**, P10020 (2018), arXiv:1808.01804 [physics.ins-det].
[17] G. Anton *et al.* (EXO-200 Collaboration), Phys. Rev. C **101**, 065501 (2020).
[18] J. Aalbers *et al.* (DARWIN), JCAP **11**, 017 (2016), arXiv:1606.07001 [astro-ph.IM].
[19] D. Nygren, B. Jones, N. López-March, Y. Mei, F. Psihas, and J. Renner, Journal of Instrumentation **13**, P03015 (2018).