Barium tagging for a nEXO upgrade and future ^{136}Xe 0νββ detectors

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Abstract

The "tagging" of the ^{136}Ba daughter of ^{136}Xe double beta decay is attractive for its potential to increase the sensitivity of ^{136}Xe 0νββ decay experiments and as an additional confirmation signal if a positive 0νββ signal is found. Current efforts within the nEXO Collaboration aim to demonstrate the basic principles of Ba tagging in a research apparatus. One of the next phases of research will be on Ba^+ ion extraction methods from a LXe TPC. In order to demonstrate Ba tagging in situ and determine the efficiency, it is desirable to use a radioactive beta decay that produces a Ba daughter within LXe. This could occur through radioactive Cs atoms implanted at an accelerator facility through a thin foil into LXe or created by an energetic proton beam by (p,n) reactions in ^{136}Xe. The focus of this LOI is a road map of necessary R&D toward a nEXO upgrade or a next generation 0nbb detector that utilizes Ba tagging.

The current generation of 0νββ experiments have not yet found evidence of 0νββ decay in several different isotopes with half-life limits in the 10^{25}-10^{26} year range. Next generation experiments at the tonne scale are in the stage of advanced planning and will reach sensitivities sufficient to probe the inverted mass hierarchy and start accessing the normal hierarchy with lifetimes up to about $1x10^{28}$ years. At this level, isotope procurement is one of the dominant experiment costs. To go a step beyond this next level without substantially greater isotope costs, it is desirable to reduce background events as much as possible and to use the isotope as efficiently as possible. For example, the proposed nEXO detector is expected to have a very low background due to the intrinsic capability of an homogeneous detector with event topology identification, and a careful program of materials testing. However, a small number of indistinguishable background events in the 0nbb decay energy region of interest in 10 years of operation limit the projected half-life sensitivity to about $1x10^{28}$ years. A similar projection with only 2nbb decay background gives about a factor of 4 times larger sensitivity.[1]

In 1991 M. Moe introduced the idea that spectroscopic detection of the ^{136}Ba daughter of ^{136}Xe double beta decay in addition to the emitted electrons could "tag" real ^{136}Xe decay events and discriminate against all other backgrounds.[2] This possibility is unique of ^{136}Xe-based experiments and merges together the two traditional techniques of the identification of the final state atom and of real-time ionization detectors. In the nearly three decades since this proposal, much progress on "Ba tagging" has been made, and a few schemes are beginning to show real potential. This LOI builds on current research within the nEXO Collaboration on two leading Ba tagging methods and provides a roadmap for the future R&D needed for possible implementation of Ba tagging in a future nEXO upgrade.

Among a number of Ba tagging technologies explored in the EXO-200 and nEXO Collaborations over the past two decades, two front-running schemes have emerged. In part, this is because during the transport to a Ba identification region, both methods keep the daughter ion or atom away from all surfaces that might contain a few other Ba atoms from natural contamination. In one scheme being developed in the U.S., the ^{136}Ba daughter ion or atom is captured in a solid xenon (SXe) layer on a sapphire substrate mounted on a cryogenic probe and is then removed from liquid xenon (LXe) to xenon gas (GXe) above the liquid. After closing a valve, the probe temperature and Xe gas pressure is reduced toward the 10-30 K and near vacuum regime where more optimum imaging and counting of individual Ba^+ ions or Ba atoms can be done.[3] Current research has shown that individual Ba atoms can be imaged with high signal-to-noise ratio in two of the four SXe matrix sites in which they reside, from single- to seven-vacancy. Work is in progress toward similar imaging of Ba in the other two matrix sites and Ba^+ in the one single-vacancy site expected. Studies of implanting Ba^+ ions in SXe on a cryogenic substrate, both in LXe and GXe, are in progress. A second scheme, initially developed in the US[4] and now further pursued by a trans-Canadian collaboration of nEXO institutions, is based on extraction of the daughter Ba^+ ion in a capillary tube from LXe to GXe, passing to vacuum in differential pumping regions while being guided by an RF ion carpet, Ba^+ capture and single-ion spectroscopic identification in a linear Paul trap, and finally $^{136}Ba^+$ mass identification in a multi-reflection time-of-flight mass spectrometer. Many of these processes have been verified separately with various ions, including Ba^+ ion counting in the trap. Construction and assembly of the whole system is planned to be completed by the end of 2020 or thereabouts. Ba tagging R&D in this system with Ba^+ ions from a ^{252}Cf fission source and a laser ablation source is expected to demonstrate transport and detection of single Ba^+ ions from GXe. Research on extraction of Ba^+ ions from LXe to GXe in a capillary and then implementation on this system is a second R&D phase of the work.

To be prepared for a possible Ba tagging upgrade of nEXO in a 10+ year time frame, a further phase of R&D is envisioned in which Ba tagging of daughters of individual beta decays of Cs isotopes is demonstrated. This would occur first in small LXe cells at an accelerator facility with 1-dimensional probe extraction from a localized decay region and later in 3-dimensional probe extraction from the full volume of a mid-sized TPC with ~100 kg of LXe.

Several possibilities for accelerator-driven radioisotope tagging tests are being considered. Following early work performed at Argonne National Laboratory (ANL) on SXe, a 250 MeV ^{139}Cs beam could be introduced through a thin Havar window into a LXe cell. The resulting ^{139}Ba decay daughters would be themselves radioactive and their subsequent decays could provide an additional signal for studying the extraction process. Beams of several different Cs or La isotopes at similar energies could be produced at TRIUMF, which would provide a range of possible decay topologies and Ba daughter half-lives. An alternative approach would be to use ~MeV protons to produce ^{136}Cs *in situ* via the (p,n) reaction. This approach would be well suited to Van de Graaff facilities where beamtime is readily available. A pilot irradiation has been carried out at the Triangle Universities Nuclear Laboratory (TUNL) demonstrating production in a gas cell, and a follow up measurement at the University of Kentucky Accelerator Laboratory (UKAL) is being considered.

A 100 kg natural xenon TPC is being developed at Carleton University for studies of probe insertion and daughter extraction methods. Initial studies will be done with daughters of radon decay. R&D on 3-D daughter extraction with a probe will be an important component of the next phase of preparation for engineering design of an upgrade TPC that incorporates Ba tagging.

References

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