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Search for 0νββ Decay with EXO-200 and nEXO

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On behalf of EXO-200 and nEXO collaboration

The search for neutrinoless double beta decay (0νββ) process becomes a quite hot topic after the establishment of non-zero neutrino mass by oscillation experiments, as the observation of 0νββ process would indicate the discovery of the new physics beyond the standard model. The EXO-200 is a running detector based on liquid xenon TPC, which is the first 100 kg-class experiment producing results and well demonstrating the key technologies in 0νββ search. The most recent 0νββ half-life sensitivity of ^{136}Xe from EXO-200 has been improved to 3.7×10^{25} yrs at 90% C.L., by combining the data set collected in phase I and phase II. nEXO experiment is extrapolated from EXO-200, aiming to reach 0νββ half-life sensitivity of 10^{28} yrs by using 5 tonne enriched liquid xenon TPC, which can entirely cover the region of inverted hierarchy. Lots of R&D activities in nEXO are being carried out to enhance the TPC performance. In this proceeding, part of them will be highlighted.

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1. Introduction

The double beta decay is the rarest known nuclear weak process. The products of the ordinary double beta decay (2νββ) consist of two electrons, two electron antineutrinos and one daughter nucleus. In this process, baryon number and lepton number are conserved respectively. Up to now, 2νββ decays of about a dozen isotopes have been observed [1-2], with half-life in the range of 10^{18} to 10^{22} years. 2νββ process is allowed in the framework of the standard model. Another type of the double beta decay is neutrinoless double beta decay (0νββ), which is proposed by Wendell H. Furry in 1939 [3] after the establishment of the Majorana theory of neutrino [4]. The Feynman diagrams of the two different double beta decays are shown in Fig. 1. The Fig 1. indicates that the 0νββ process is a lepton number violation process, since only two electrons are emitted from the decay. The 0νββ decay can only occur when the neutrino is a Majorana particle and the mass of neutrino is not zero. In the past several decades, the non-zero neutrino mass has been established by neutrino oscillation experiments [5-7], which also increased the interest in the search for 0νββ process worldwide, because it would indicate the discovery of new physics beyond the standard model. The observation of 0νββ decay would establish the Majorana nature of the neutrino and demonstrate the lepton number is not conserved. In addition, the rate of 0νββ decay can also provide the information about the absolute neutrino mass.

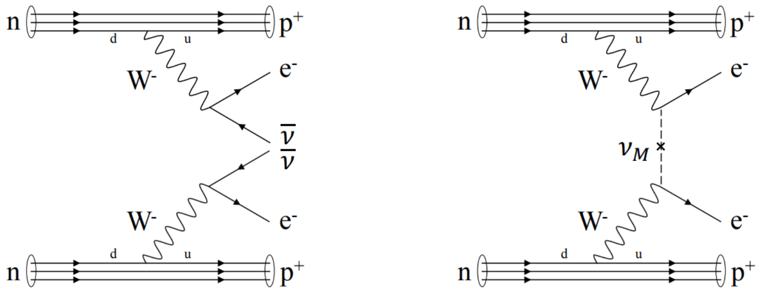

Fig. 1: Feynman diagrams of the ordinary double beta decay (left) and the neutrinoless double beta decay (right).

Since the two electrons from the 0νββ decay carry all energy of the decay which equals to the Q-value, the spectrum of total observed energy should have a narrow peak at this value. In the past, a dozen experiments have been proposed and built to search for 0νββ decays of different isotopes by using various detection techniques. The target masses of these experiments are at the level of hundreds of kilograms or smaller. Most stringent limits on the half-life are set to the order of 10^{25} years so far. Recently, several ton-scale experiments are proposed, aiming to improve the sensitivity by 1-2 orders. For experiments relying solely on the measurement of total event energy, the only way to enhance the sensitivity is to reduce the background and improve the energy resolution. A more powerful detector should provide more power to reject background and simultanously fit the signal and background. The Enriched Xenon Observatory (EXO-200 and nEXO) are two typical detectors which show such feature.

2. EXO-200 and nEXO experiments

EXO-200 is a running detector based on a liquid xenon time projection chamber (LXe TPC), which is also the first 100 kg-class experiment to produce results and has demonstrated key technologies for 0νββ search [8]. nEXO is a proposed 5 tonne detector, and will take full advantage of LXe TPC to reach the sensitivity of half-life of 10^{28} years and entirely cover the parameter space of inverted hierarchy [9]. Since xenon can serve as both the source and detector medium, and ^{136}Xe enrichment is easier and safer, the LXe detector can be easily scaled to tonne-class. The radioactive background originating inside the LXe is negligible, because xenon can be continously purified. The LXe TPC measures the energy by simultaneously collecting the ionization and scintillation signals. Due to energy conservation, the charge and light signals from LXe are anti-correlated. The energy resolution can be improved by combining the two signals, and the energy resolution in EXO-200 can reach sigma of 1.2% at the Q-value (2.458 MeV) of ^{136}Xe decay, as shown in Fig. 2. The designed goal of energy resolution for nEXO is better than 1% at the Q-value. Instead of mutiple segmented detectors, a monolithic detector will be built for nEXO due to its excellent background rejection capabilities. The major background in the region of interest is caused by gamma rays emitted from sources external to the xenon. On one hand, the outer part of LXe in TPC can effectively shield the background and keep the inner part of LXe clean, since the attenuation length of a 2.4 MeV gamma is about 8.7 cm in LXe. This self-shielding is more efficient when the detector becomes larger. On the other hand, the gamma rays can be

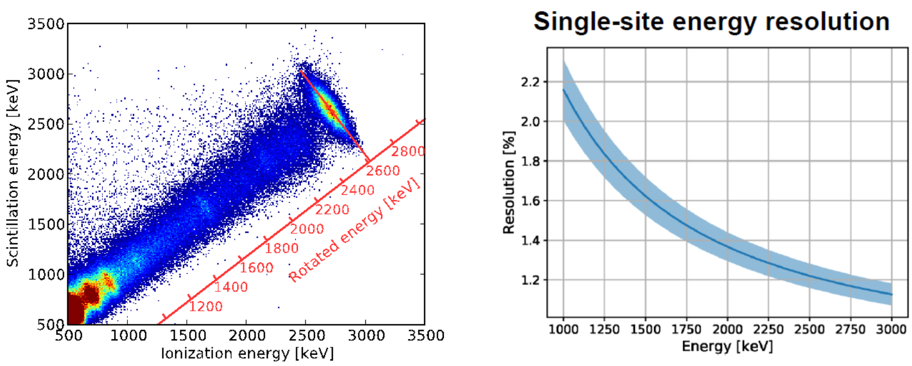

Fig. 2 Left: The anti-correlation between ionization and scintillation signals, the data are taken from ^{228}Th calibration source. Right: The energy resolution versus energy for SS events.

measured and identified by the multiple Compton scattering, which can lead to multiple energy deposits in TPC, called multi-site (MS) in EXO. This feature is quite different with that of electrons, which is dominated by the single-site (SS). As shown in Fig. 3, the SS/MS discrimination is a very powerful tool to reject gamma backgrounds, and this is well demonstrated in EXO-200.

3. Most recent $0\nu\beta\beta$ results from EXO-200

The data taken by EXO-200 detector are collected in two phases. Phase I started in 2011 and stopped in 2014 due to WIPP accidents. After two years, the phase II data taking started with an upgraded detector, in which, the electronics of LA-APDs has been upgraded to reduce the electronics noise, a system has been implemented to suppress the radon background and the operating voltage on cathode has been raised by 50% compared to the phase I. The data taking of phase II is still ongoing and expected to finish in the end of 2018. By combining the full data set from phase I and phase II, the $0\nu\beta\beta$ half-life sensitivity of ^{136}Xe is extracted and found to be 3.7×10^{25} yrs at 90% C.L., and no significant excess is observed. The lower limit on the half-life of 1.8×10^{25} yrs at 90% C.L. is derived from a Maximum Likelihood fit. The fitting results are presented in Fig. 4. More details can be found in a recent published paper by the EXO-200 collaboration [10].

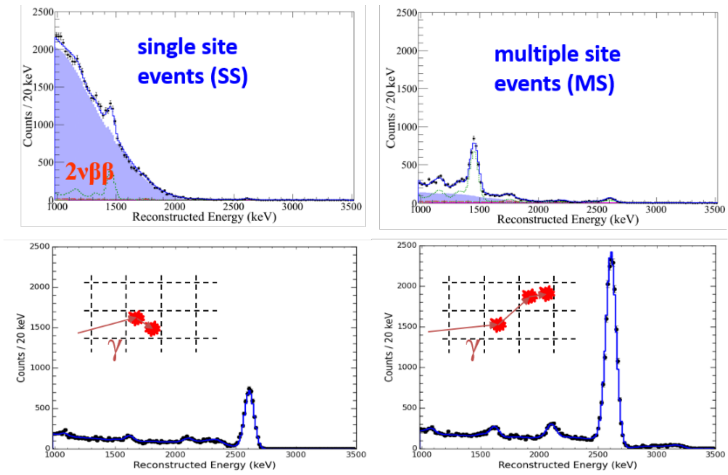

Fig. 3: Demonstration of SS/MS discrimination. The upper two plots are from low background data, the lower two plots are from ^{228}Th calibration data.

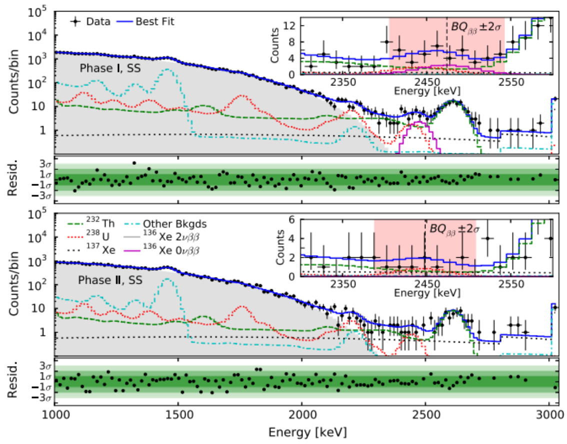

Fig. 4: Best fit to the SS energy spectrum for Phase I (top) and Phase II (bottom).

4. Highlights of R&D activities in nEXO

Even though lots of experiences are gained from the successful running of EXO-200 detector, some optimizations are still required in nEXO, in order to enhance the TPC performance. Fig 5. shows the conceptual design of TPC in nEXO. The cathode and a pad-like charge readout tile are located at the bottom and the top of the TPC, respectively. A photo-detector system based on large area VUV sensitive SiPMs will be installed in the barrel of TPC behind the field shaping rings, used to detect ~175nm scintillation lights from liquid xenon. In nEXO, lots of R&D activities are ongoing, while only part of them are presented in this proceeding.

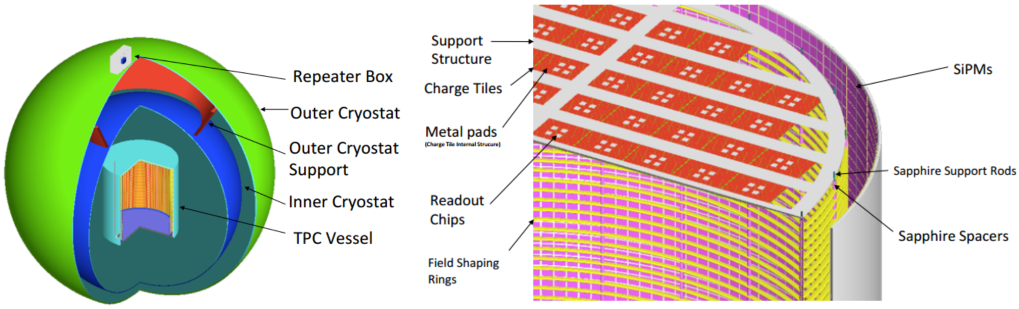

Fig. 5 Left: Conceptual design of nEXO detector. Right: Detailed structure of TPC.

One of the main factors contributing to the energy resolution of nEXO is the overall photon detection efficiency of the photo-detector system. The overall efficiency is determined by photon detection efficiency (PDE) of SiPMs and photon transport efficiency (PTE) in TPC. More than 50% VUV photons (~175nm) can be reflected by SiPMs, due to the mismatch of refractrive index of SiO_2 and Si. In principle, the reflected photons have the chance to be re-detected by the SiPMs in TPC, so the higher reflectivity means the higher PTE. However, the PDE of SiPM will decrease because of the lower transmittance. Given the importance of the photon detection efficiency for the energy resolution, the R&D efforts in nEXO is focused on optimization of the PDE and the reflectivity of SiPMs. The left plot in Fig 6. shows the SiPM PDE measurements performed by nEXO [11]. The red box indicates the region that can meet the requirements of nEXO. The performance of NUV-HD-LF device from FBK is promising and this device is one of candidates that we are interested in. The right plot in Fig. 6 presents the results of specular reflectivity measurements made in vacuum. The oscillation is caused by the thin SiO_2 layer on the top of FBK SiPM. For a comparison, a silicon wafer with 1.5 μm SiO_2 film on top is also measured, which shows the higher reflectivity because of no extra structure on the surface of the wafter. With the current arrangement of SiPMs in TPC, part of them will be exposed to the high external electrical field, up to 20 kV/cm. The performance of SiPM operating in difference electric field strength has been carefully studied, and the results show no influences on SiPM characterizations [12].

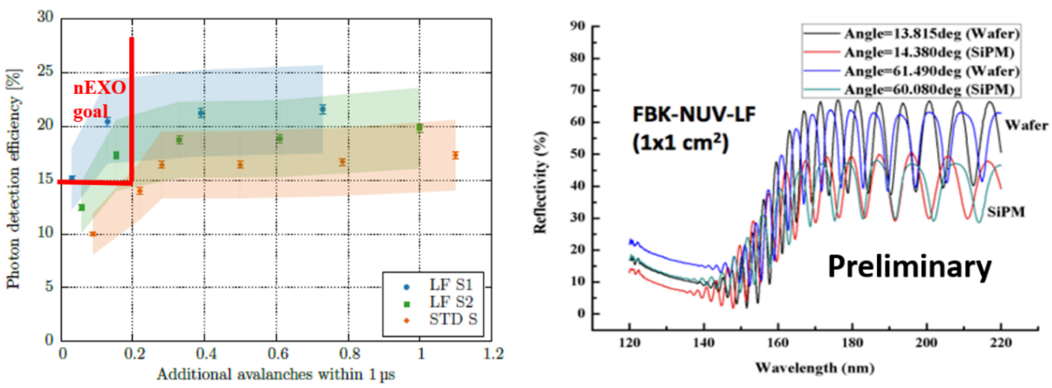

Fig. 6 Left: PDE versus correlated avalanches measured for three different devices from FBK. Right: The specular reflectivity versus wavelength measured in vacuum.

In nEXO, a modular and pad-like charge readout tile is under study. The tile is produced by depositing 60 orthogonal metal charge-collecting strips, 3 mm wide, on a 10 cm × 10 cm fused-silica wafer, shown in the left picture in Fig 7. The prototype has been made by IHEP/IME in

China and tested at Stanford University. The characterization of the tile can be fully understood [13], shown in the right plot in Fig. 7.

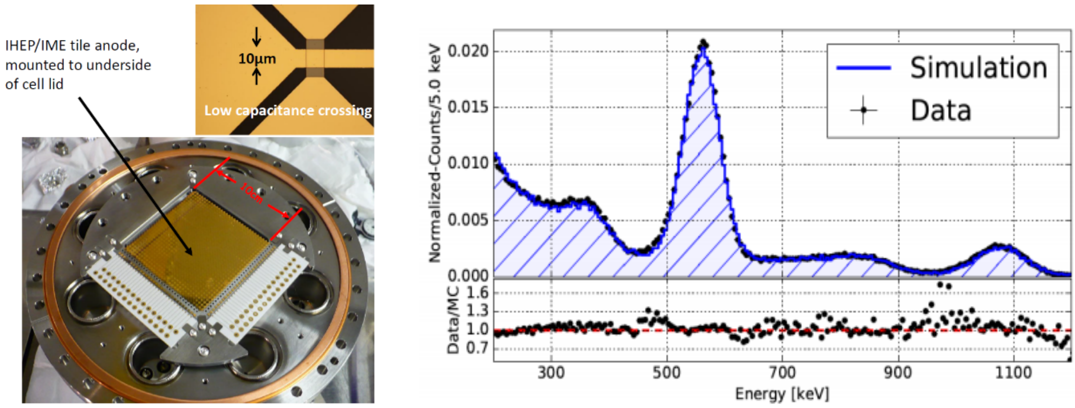

Fig. 7 Left: the picture of the 10 cm x 10 cm prototype of charge tile. Right: The comparison between data and simulation, the data are taken with ^{207}Bi source.

5. nEXO sensitivity

Based on experiences gained from EXO-200, and combined with the better energy resolution and more powerful SS/MS discrimination in nEXO detector, the 0νββ half-life sensitivity has been carefully estimated. A detailed detector simulation software has also been implemented and used to build the background model with the measured radioassay inputs. More details are reported in the Ref [9]. As shown in Fig. 8, with 10 years data taking, a 3σ discovery potential for the ^{136}Xe 0νββ half-life is expected to be 5.7×10^{27} years in nEXO. The exclusion sensitivity at 90% C.L. can reach $9.2{\times}10^{27}$ years. Under the assumption of a light Majorana neutrino exchange, the effective Majorana neutrino mass is computed with various nuclear matrix elements choices, which can cover the whole region of inverted hierarchy.

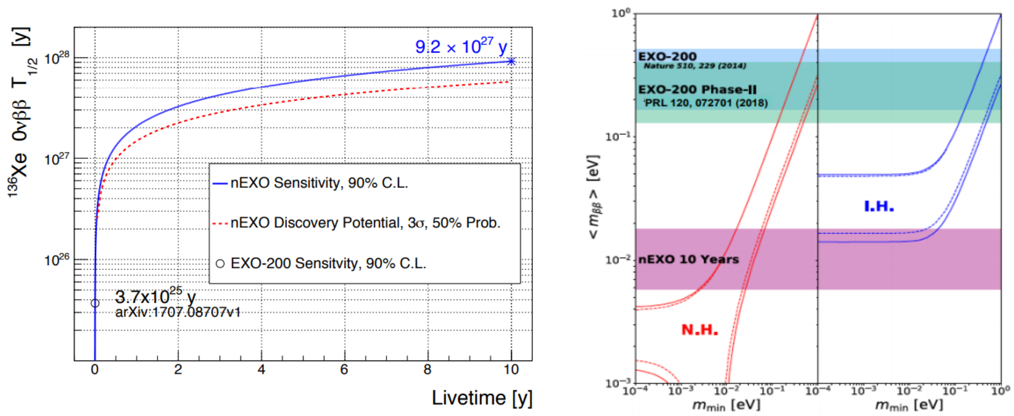

Fig. 8 Left: nEXO median sensitivity at 90% C.L. and 3σ discovery potential as a function of the experiment livetime. Right: Exclusion sensitivity at 90% C.L. reach to the effective Majorana neutrino mass $m_{\beta\beta}$ as a function of the lightest neutrino mass for normal and inverted neutrino mass hierarchy.

6. Summary

It will be a great discovery if 0νββ decay is observed. EXO-200 has demonstrated the key technologies in 0νββ search and achieved 0νββ half-life sensitivity of 3.7×10^{25} yrs at 90% C.L.

for ^{136}Xe by combining the data sets of phase I and phase II. The sensitivity can be further improved to 5×10^{25} after phase II running, which is one of the most competitive experiments in the field. nEXO is a proposed 5 tonne LXe TPC, aiming to reach 0νββ half-life of 10^{28} yrs, which can entirely cover the inverted hierarchy region. Lots of R&D work are ongoing in nEXO, in order to enhance the TPC performance.

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