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Status of the EXO double beta decay search

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We review the current status of the EXO-200 double beta decay experiment, and the EXO collaboration's plans for future ton-scale experiments utilizing barium tagging technology.

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1. Introduction

The EXO collaboration is dedicated to addressing the question of neutrino mass and lepton number conservation by searching for the neutrinoless double beta decay $^{136}\text{Xe} \rightarrow {}^{136}\text{Ba}\ e^{-}e^{-}$. Double beta decay ($\beta\beta0\nu$), if it exists, violates the conservation of lepton number by two units, and is mediated by the exchange of a virtual, massive Majorana neutrino. It is our most sensitive tool for discerning the charge properties of the neutrino, and its decay rate can also be used to constrain the absolute mass scale of the neutrinos and their mass hierarchy. Xenon is a compelling $\beta\beta0\nu$ candidate isotope, because it can be highly purified of radioactive contaminants, and because it is a good particle detection medium. In addition, the daughter nucleus produced by the decay of xenon is barium, and modern atomic physics techniques allow single barium ions to be observed and counted. This raises the possibility of identifying the barium ion in each $\beta\beta0\nu$ candidate event, which would reject all conventional radioactive backgrounds and result in an ideal experiment.

2. EXO-200

The first EXO experiment, known as EXO-200, is currently being commissioned at the WIPP facility in Carlsbad, New Mexico. The goals of EXO-200 are 1) to be among the most sensitive double beta decay experiments in the world, 2) to test detector technologies and radiopurity requirements for the next generation of experiments, and 3) to detect for the first time the very rare two-neutrino double beta decay process ($\beta\beta2\nu$) in ^{136}Xe.

The centerpiece of the experiment is 200 kg of xenon enriched to 80% in ^{136}Xe. The xenon is held in a liquid state inside a thin copper vessel, and the vessel is surrounded by 50 cm of HFE-7000, a cryofluid produced by 3M. The HFE acts as a thermal mass and heat transfer fluid, and also shields the experiment from external radioactive backgrounds. The HFE is stored in a vacuum-insulated copper cryostat which is constructed from low-activity NOSV copper produced by Norddeutsche Affinerie. The inner vessel of the cryostat, the HFE, and the xenon vessel are held at liquid xenon temperature ($\sim$169 K) by closed-circuit freon-based refrigerators via three heat exchangers which are integrated into the cryostat. The total cold mass is about four metric tons. The cryostat is surrounded on all sides by 25 cm of low-activity lead from the Doe Run mine in Missouri. The entire assembly is surrounded by a radon-free tent and housed in a class 100 clean room, the exterior of which is instrumented on five sides with plastic scintillator panels for vetoing cosmic rays with 98% efficiency. The laboratory is located 2150 feet underground for an overburden of 1585 meters water equivalent.

The design and construction of the copper liquid xenon vessel was one of the primary technical challenges of the experiment. ICPMS measurements of the copper material determined that it contains less than 3 ppt of ^{238}U and ^{232}Th, but even these strong limits place significant constraints on the total mass of the vessel which is allowed[1]. Therefore the vessel was carefully engineered to minimize its mass while insuring its structural integrity. In addition, a sophisticated and redundant feed-and-bleed system continually monitors and automatically adjusts the xenon pressure in the interior of the vessel to match the pressure of the HFE on its exterior. Xenon gas is supplied from storage cylinders through two parallel regulators and recovered via two xenon gas compressors. In the event of a power outage to the experimental facility, the refrigerators, compressors, and control

Case	Mass	Eff.	Run time	$\sigma(E)/E$	b.g.	$T^{0\nu}_{1/2}$	ν mass (meV)	
	(ton)	(%)	(year)	(%)	(events)	(yr, 90% CL)	QRPA[4]	NSM[5]
EXO-200	0.2	70	2	1.6	40	6.4×10^{25}	109	135
full EXO	1	70	5	1.6	1	2.0×10^{27}	19	24
	10	70	10	1	1	4.1×10^{28}	4.3	5.3

Table 1: Neutrino mass sensitivity of several EXO scenarios. EXO-200 is currently being commissioned at the WIPP facility in Carlsbad, New Mexico. Two possibilities for a ton-scale EXO utilizing barium tagging technology are also shown.

systems will continue to operate on battery backup power, and, if necessary, the xenon will be automatically recovered to the storage cylinders without human intervention..

The copper vessel hosts a time projection chamber (TPC) for observing scintillation and ionization from charged particle interactions in the liquid xenon. A high voltage cathode in the middle of the vessel divides the detector into two equal halves 20.44 cm in length (see Figure 1). Ionization charge drifts towards the two ends of the cylinder where it is detected and collected by a pair of crossed wire planes which measure its magnitude and x-y coordinates. In addition, each end of the cylinder is monitored by a planar array of avalanche photodiodes (APDs) which observe the 178 nm scintillation light produced by the primary interaction[2]. The interior of the TPC field cage is lined with teflon sheets which reflect the scintillation light and increase its total acceptance. This provides a second, complementary energy measurement for the event, and a start time for measuring the charge drift time. The drift time is converted to a z coordinate using the known drift velocity of charge in the liquid xenon. Since the event location is determined in all three dimensions, a fiducial cut can be made to reduce the number of events near the edges of the detector where radioactive backgrounds are expected to be most prominent. The simultaneous measurement of both the charge and scintillation of the event allows the energy resolution of the detector to be 1.5% at the ($\beta\beta0\nu$) Q value of 2.458 MeV[3].

The EXO-200 TPC was installed in its cryostat in January 2010 and subsequently cooled to liquid xenon temperature for the first time in the summer of 2010. A initial commissioning run of at least two months using natural (unenriched) xenon is planned for the fall of 2010. The commissioning run will be used to measure noise levels, liquid xenon purity, and to exercise the DAQ, data handling, and offline software. Ultimately the detector will be filled with the enriched xenon, and a physics data taking period of two years is planned. The expected sensitivity of EXO-200 is shown in Table 1.

3. Barium tagging and the future of EXO

In parallel with EXO-200, the collaboration is planning for very large xenon-based double beta decay experiments which would utilize barium tagging to eliminate radioactive backgrounds. Currently both liquid and gas TPC technology are being considered to detect the double beta emission from the primary event. To identify the daughter barium ion, several methods are under development, including single-ion fluorescence, resonant ionization spectroscopy (RIS), and mass spectroscopy.

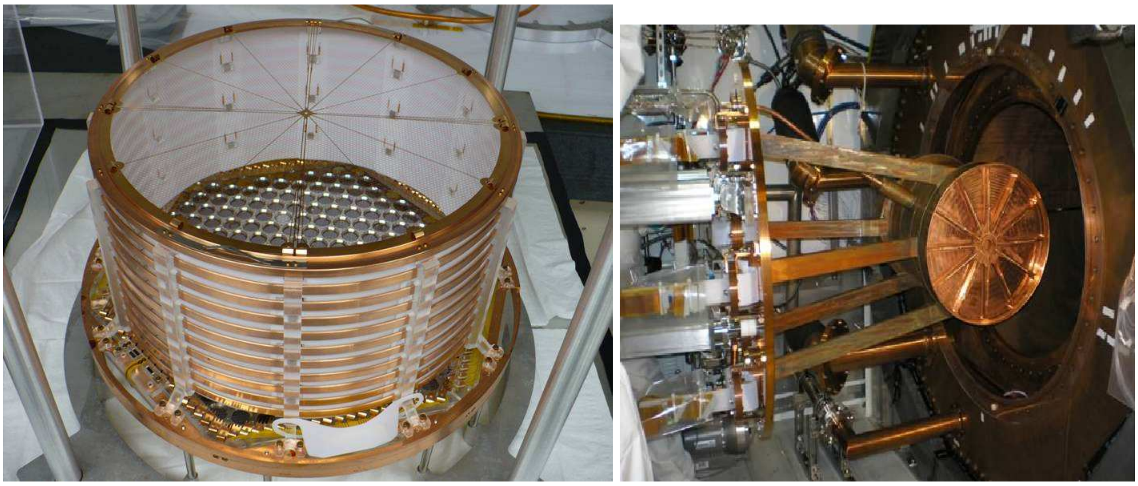

Figure 1: Left: One half of the EXO-200 TPC. Right: The fully instrumented liquid xenon vessel being inserted into the cryostat in January 2010.

Single ion fluorescence is a highly sensitive and highly selective method to observe a barium ion while held under vacuum in an RF trap. In this technique, the Ba^+ is rapidly cycled from its $^2S_{1/2}$ ground state to its $^2P_{1/2}$ and $^4D_{3/2}$ excited states by illuminating it with lasers of the appropriate wavelength (493 nm and 650 nm). As the electronic state changes, the laser photons are scattered in all directions, and the scattered light can be easily detected by a photo-multiplier tube. EXO has achieved good single barium ion identification with this technique, even in the presence of low pressure xenon and helium gas mixtures[6]. However, this technique also requires that the barium ion be retrieved from the TPC volume, transported to the RF trap, released, and trapped, while not altering its chemical or ionization state. RIS, on the other hand, is a technique which allows single barium ions to be observed without requiring a vacuum ion trap. In RIS, barium ions are desorbed from the surface of a transport probe, and subsequently resonantly ionized under illumination by 554 nm and 390 nm lasers. The ionized barium can then be observed with a channeltron. Initial tests with the RIS technique have successfully identified barium being desorbed from the probe tip, so this technique is promising. Other avenues of research include barium identification within xenon ice, and barium extraction from a high pressure gas TPC using gas nozzles. In summary, the expected neutrino mass sensitivity of two future EXO scenarios are listed in Table 1. In this table, the backgrounds are assumed to be one event or less due to the background rejection provided by the barium identification procedure.

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