USING GPUS TO DESIGN A WATER CHERENKOV DETECTOR FOR A NEUTRINOLESS DOUBLE BETA DECAY SEARCH IN nEXO

SUMMARY: This article summarizes how nEXO uses GPUs to simulate and design a next-generation neutrinoless double beta decay experiment.

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WHAT IS nEXO?

nEXO is a proposed next-generation non-collider particle physics experiment. The experiment will search for a hypothesized nuclear decay mode in the isotope Xe-136 known as neutrinoless double beta decay ($0\nu\beta\beta$) [1]. In $0\nu\beta\beta$ decays, two electrons are ejected from the nucleus without the emission of corresponding electron antineutrinos. An observation of this decay mode, which is only possible in a handful of isotopes across the nuclear chart, will be evidence of physics beyond the standard model addressing several open and possibly connected questions: why is there more matter than antimatter in the Universe, and why are the neutrino masses so incredibly small relative to the other particles in the standard model?

An observation of this decay mode would prove that lepton number can be violated in nature. It would also show that neutrinos and antineutrinos are the same particle, i.e. a neutrino would be deemed a Majorana fermion (with spin ½), a property physicists have been investigating since the discovery of neutrino masses. A measurement of the $0\nu\beta\beta$ decay half-life would also inform on the absolute mass of neutrinos, a presently unknown quantity.

nEXO consists of three detector volumes: a liquid xenon time projection chamber (TPC) at its heart, enriched in the isotope Xe-136, a vacuum insulated cryostat filled with a hydrofluoroether cryogenic fluid, and a water-Cherenkov Outer Detector (OD) on the exterior (Fig. 1). The $0\nu\beta\beta$ signals are searched for in the TPC, which is kept at 165K and shielded from environmental radiation by the cryogenic fluid surrounding it, while the OD keeps track of the nearby ambient radiation that may otherwise create $0\nu\beta\beta$-like signals in the TPC.

Energy released in the TPC by ionizing radiation, i.e. particles that lose their energy by ionizing xenon atoms (these include x-ray and gamma-ray photons, alphas, betas, and muons), produces two measurable signals: localized "clouds" of ionization charge and a flash of 175 nm scintillation light. Ionization is drifted under an applied electric field to an instrumented anode where its distribution and total charge are recorded. Scintillation light pulses are detected with a large array of silicon photomultipliers (SiPMs). Together, charge and light readings provide a measurement of total energy, and a 3D reconstruction of the location and topology of the individual energy depositions. This information is used to distinguish the type of particle that interacted in the TPC [2].

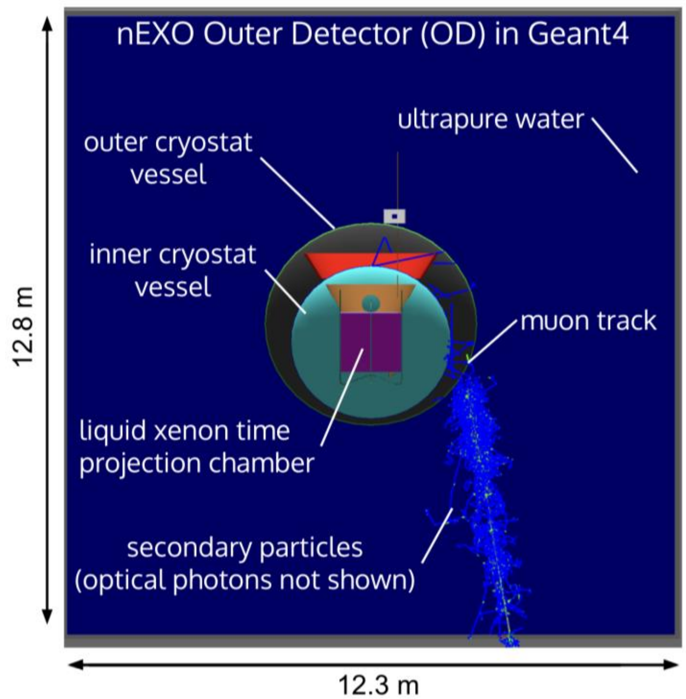

Figure 1. Geant4 rendering of the nEXO experiment. A cosmogenic muon track is displayed going through the Outer Detector and producing secondary particles of concern.

THE OUTER DETECTOR

In the Outer Detector, we use ultrapure water to serve as a passive shield from ambient gamma and neutron radiation from the surrounding rock and concrete. The Outer Detector also plays an active role as a water-Cherenkov detector [3]. The Cherenkov effect occurs whenever high energy charged particles pass through a dielectric medium (such as water) at velocities greater than the local speed of light, i.e. materials with a real index of refraction greater than 1 that are transparent to the ultraviolet-to-optical wavelength range. In the case of nEXO, which aims to be situated 2 km beneath the surface at SNOLAB, the only high energy particles making it so deep underground are cosmogenically produced muons from the Earth's upper atmosphere. These cosmogenic muons have energies extending into the TeV range, well above the Cherenkov threshold of a muon passing through water (160 MeV), and so their passage through the Outer Detector emits a burst of light in a forward-facing cone with a broad wavelength spectrum that peaks in the ultraviolet and extends into the visible. nEXO uses photomultiplier tubes (PMTs) which are installed all over the interior of the OD walls to detect this light, and veto any subsequent backgrounds produced in the TPC that could mimic the $0\nu\beta\beta$ signal.

DESIGNING A NEXT-GENERATION PARTICLE PHYSICS EXPERIMENT

All modern particle physics experiments begin with a detector concept in the minds of scientists. This concept then needs to be validated and fleshed-out by testing it in Monte Carlo simulations. By measuring the proposed detector's response to expected signals and backgrounds, we can make more confident statements on which particular designs perform best after examining an ensemble of many Monte Carlo particle interactions in each said design.

nEXO is no outlier to this design framework. Although nEXO is based on the successes of the EXO-200 experiment [4], many changes were introduced due to the better technology available to us today, compared to two decades ago. In particular, we highlight two of these changes here: the use of SiPMs, the photodetectors inside the TPC [5], and the move to a water-Cherenkov veto system (the OD) due to tighter background constraints. Both photon-detection systems must be studied by propagating and ray-tracing the photons resulting from either the scintillation of the xenon (in the TPC), or the Cherenkov photons resulting from high energy charged particles traversing the water in the OD.

Ray tracing is notoriously a computationally expensive task. Conventional techniques for particle physics experiments employ an industry standard Monte Carlo software called Geant4 [6]. Although extremely powerful and well validated, Geant4 is a CPU-based program that, until recently, did not support multi-threaded photon propagation [7, 8]. It is also notoriously difficult to manipulate and build complex geometries within Geant4, and so the iterative process of trying out new detector geometries is a time consuming task. nEXO gets around this by building the detector using standard CAD files, and opting to use Chroma [9, 10], an open source ray tracing software, for photon propagation studies.

CHROMA: A GPU-BASED RAY-TRACING SOFTWARE

Chroma is a program optimized to run on Graphical Processing Units (GPUs), devices that have recently become infamous due to their unstable prices and usage in cryptocurrency mining. Originally developed to perform graphical calculations for visual renderings, including those for video games, GPUs are now a staple element in any modern computational toolset. GPUs are purpose-built to handle many parallelizable computations on shared memory. I.e. tasks which require performing similar calculations on independent subsets of a large dataset. This ability makes GPUs particularly good at training neural networks, mining cryptocurrencies and, of course, ray tracing many photons in parallel.

nEXO uses Chroma for optical simulations in both of the experiment's major detector components. In the TPC we use Chroma to map-out the photon detection efficiency of the SiPM array for energy deposits anywhere in the liquid xenon [1]. This allows for a better estimate of the scintillation energy that will be measured for a given energy deposit, while bypassing the need to slowly track all photons that are produced in the Geant4 simulation as was done in [3]. The second place that nEXO employs Chroma is to simulate cosmogenic muons' Cherenkov emission in the OD; muons with a mean energy of 350 GeV produce hundreds of thousands of photons as they traverse the OD, which is a lot of particles to track and parse through sequentially for a single event. Chroma is being used here to optimize the muon detection efficiency of the OD by deciding on the placement of the PMTs on Outer Detector surfaces, and examining the effect of different optical properties on the surfaces of OD components (e.g. whether to use a reflective liners or bare stainless steel components).

nEXO collaborators encoded the expected underground muons' angular, and energy spectra in Python scripts which then call Chroma to set the photon starting positions, wavelengths, and angles relative to the muon track before passing all the photons to the GPU for propagation. In this way, many photons are propagated simultaneously for each step of the muon's track all the way to their detection on the photocathode of a PMT. This allows for rapid studies evaluating various PMT configurations, reflectivity variation of components, and a speedup of ~100x compared to equivalent Geant4 simulations. An example Cherenkov cone propagated in Chroma is displayed in Fig. 2.

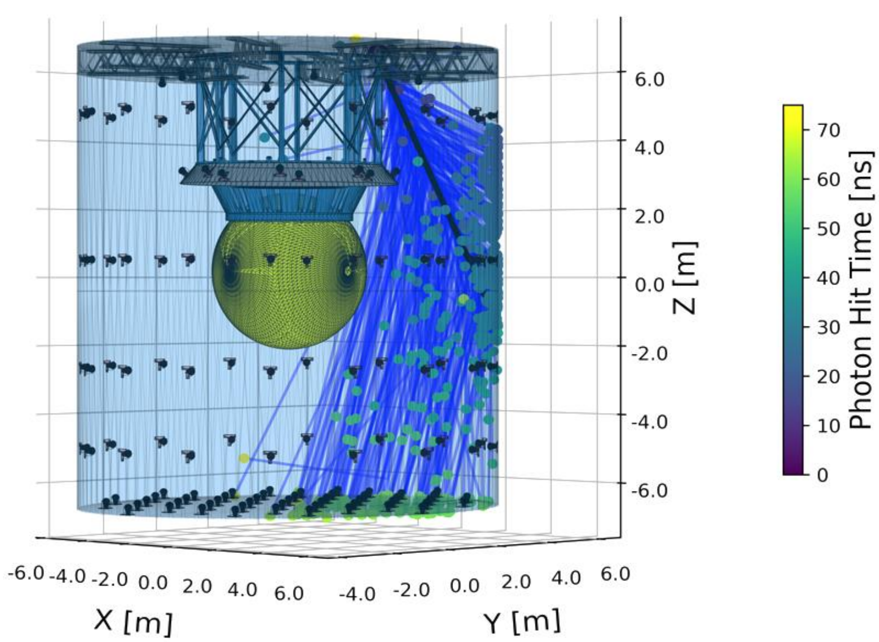

Figure 2. The nEXO Outer Detector simulated in Chroma with an example array of 127 photo-multiplier tubes. A nominal muon track entering from above and exiting the right hand side of the tank emits Cherenkov photons in a characteristic cone shape.

Although this GPU-accelerated analysis of muon tracks is still missing a lot of the microphysics (muons of such high energy produce secondary particles that can cause even more Cherenkov light) one can imagine a future where the amplification of the total light yield from secondary particles is parameterized so well that the default go-to programs used to simulate any high-energy Cherenkov detector would make use of the wonderful technology that is the GPU.

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