nEXO Photo-detectors: specification guidelines and plans

nEXO photo-detector group, June 2014

nEXO

The purpose of the next generation Enriched Xenon Observatory (nEXO) is to search for the neutrino-less double beta decays of ^{136}Xenon. The mass of liquid Xenon is expected to be about 5 ton. The energy resolution target is 1% or better at 2.5MeV energy deposited, which can only be achieved by measuring both scintillation light and ionization charge simultaneously because the numbers of scintillation photons and ionization electrons fluctuate event by event in an anti-correlated way. nEXO is a time project chamber with the electrons being collected by a single anode shown in purple on top in Figure 1.

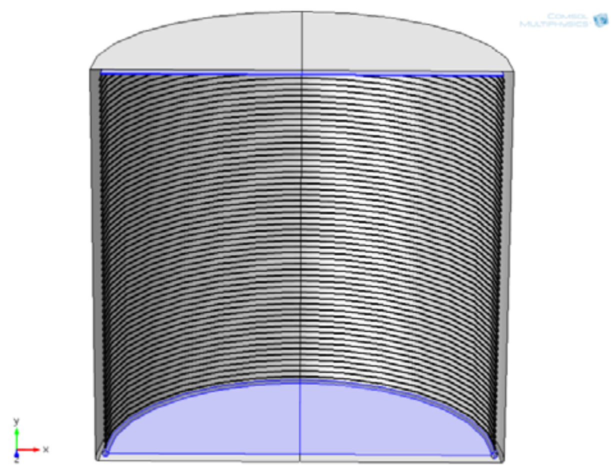

Figure 1

The photo-detectors will most likely be located along the barrel wall. The total surface of the barrel is roughly 5 m^2. Accounting for unavoidable dead space, the photo-detector could cover as much as 4m^2. The lower limit of the active area is 1m^2 if excellent (50% or more) photon detection efficiency can be achieved.

Specifications

Photo-detection efficiency

Xenon scintillates at 175-178nm and it is highly advantageous to detect the light directly without wavelength shifting material. The target overall scintillation photon detection efficiency is 10% which is the product of the probability that a photon is absorbed by the photo-detector times the internal detection efficiency of the photo-detector, i.e. excluding reflections. Reflections on the photo-detector have to be separated from the internal detection efficiency because 1) reflected photons have a non-negligible probability of being absorbed later on and 2) the index of refraction of liquid Xenon is 1.7, which has to be accounted for if the photo-detector external photon detection (PDE) efficiency (i.e. including reflections) is measured in gas or vacuum. For simplicity, our specification is given for the external PDE measured in gas or vacuum at normal incidence. We must however know how to extrapolate to liquid Xenon and the manufacturers should either disclose the types and thicknesses of the layers located on top the silicon or ensure that no interferences occur. The external PDE minimum value is 15%. It was calculated for silicon. At 175-180nm, the index of refraction of LXe and SiO2 (usually covering the Si photo-detectors) are 1.69-1.7, while it is about 0.8+2.2i for Silicon. Then Fresnel reflection probability is about 50%, therefore the internal PDE requirement is 30%. An anti-reflective coating would be highly beneficial, but as far as we know only MgF2 could be used for producing interferences. Indeed, it is the only material that we found that is transparent to VUV light and has an index of refraction of about 1.4 at 175nm.

Radiopurity

The radioactive content of the photo-detectors must be as low as possible. The photo-detector contribution to the overall background should be less than 1%. The nEXO collaboration will be responsible for assessing photo-detector radioactive content.

For reference, the 1% requirement can be translated to limits for each specific radio-element neglecting the other elements. The limits for ^{238}U and ^{232}Th are <9μBq/kg (<0.73pg/g) and <43μBq/kg (<10pg/g) respectively. Limits for ^{40}K and ^{60}Co are being worked out.

The limits are very small considering that one would need to count for 30h on average to measure one count with a 100% efficient detector due to ^{238}U decay with 1kg of material. Counting is hence highly impractical. U and Th contents are to be investigated by neutron activation, which very significantly enhances the sensitivity. The manufacturers are to provide unpackaged (possibly defective) devices for radiopurity assessment. The nEXO collaboration will investigate low radioactive package either independently or in collaboration with the manufacturers.

Dark noise rate

Dark noise pulses start contributing to the energy resolution if their rate exceeds ~200MHz for the total area. Assuming 4m^2, the dark noise rate limit is then 50MHz/m^2 or 50Hz/mm^2. This dark noise rate is to be achieved at -100°C.

Correlated avalanche

For SiPMs, correlated avalanches are the combination of cross-talk and after-pulse. They start contributing to the energy resolution if the number of additional (correlated) avalanches created by one avalanche exceeds 0.2, which is more or less equivalent to having a 20% correlated avalanche probability (though using Poisson statistics is more correct).

Electrical properties

Scintillation light is emitted isotropically, hence the spatial distribution of the light does not need to be sampled finely. In practice, the number of feedthroughs required for reading out the photo-detectors must be minimized. One important requirement for nEXO is to have the ability to identify single photo-electron equivalent avalanches. Hence the noise per channels must be less than 0.1 photo-electron equivalent and the probability that two dark noise pulses overlap must be no more than 10%. Two readout options are being considered, so called fast and slow option. In the fast, option the number of channels is about 100 corresponding to an area per electronics channel of 20×20cm^2. In this case, the electronics must ensure that the pulse widths are less than 100ns. Early conceptual studies show that this solution can only achieve the required electronics noise if the photo-detector capacitance per unit area is no more than 500pF/cm^2 which is an order of magnitude smaller than currently achieved by Hamamatsu MPPCs for example. The slow option involves reading out about 10,000 channels and digitizing them right away for data reduction purposes. This option is not as sensitive to the capacitance per unit area and it requires single photo-detector channels of 2×2cm^2. This option is however more complex to implement and the development of a low capacitance photo-detector solution is hence of interest.

Timing resolution

Good timing resolution is not required for nEXO. Several ns single photon timing resolution is more than enough. Nevertheless, single photon timing resolution might prove useful for enhancing the electron/nuclear recoil separation using pulse shape discrimination and for position reconstruction with light only using time of flight.

Summary table

The parameters are listed in order of priority. nEXO must identify a high efficiency, low radioactivity solution by 2016. The other requirements could be achieved later on or/and should the exact specifications prove difficult to meet, solutions for accommodating them could be developed.

Parameters	**Value**
Photo-detection efficiency at 175-178nm (without AR coating in gas/vacuum)	≥15%
Radiopurity: contribution of photo-detectors to the overall background	≤1%
Dark noise rate at -100°C	≤50Hz/mm^2
Average number of correlated avalanches per parent avalanche at -100°C	≤0.2
Single photo-detector active area	≥1cm^2
Gain fluctuations + electronics noise (see text for details)	*≤0.1 photo-electron*
Pulse width (after possible electronics shaping)	*<100ns*
Single photon timing resolution	*<1ns*

Table 1. The parameters in italic are desirable and not required.

Development time scale

Phase 1: 2014-2016. Identification of suitable photo-detector candidate(s)

To date no photo-detector fulfills all the specifications outlined earlier. The Hamamatsu MPPCs developed for the MEG experiment fulfill the requirements with the exception of the radiopurity. Photo-detector performance and radiopurity should be tested in parallel as much as possible. Test setups in nitrogen gas and vacuum are being put together at Stanford and TRIUMF. They will be operational by June 2014. They will be used to measure efficiency, dark noise rate, correlated avalanche rate and electrical properties using small devices (1mm^2 to 1cm^2) as a function of temperature. Direct feedback will be provided to the manufacturers.

The manufacturers should provide samples with ideally non-zero efficiency at 175-178nm and compatible with operation at -100°C. Samples should be received by the end of 2014 at the latest, but preferably by September 2014. A minimum of 4 devices of each type will be needed (2 at Stanford and 2 at TRIUMF). The manufacturers should provide information about possible coating on top of the photo-detector so that the efficiency measured in gas/vacuum can be extrapolated to liquid Xenon.

The goal of phase 1 is to identify promising candidates by the end of 2015. This phase may continue in 2016 if necessary. Measurements of the efficiency as a function of angle may only be completed in 2016.

Phase 2: 2016-2018. Validation and integration of photo-detector candidate(s)

The purpose of phase 2 is to 1) ensure reliable operation of the photo-detectors in liquid Xenon and measure the energy resolution, 2) investigate electrical and mechanical interface issues, and 3) investigate large area readout. One or more liquid Xenon test setup is expected to be completed by 2016. One of the gas/vacuum test setups is expected to be repurposed to test large area ($\geq 10\times 10cm^2$) readout. The nEXO collaboration is expected to purchase a significant number of photo-detectors for investigating integration issues during this phase.

This phase must be mostly completed before nEXO has to provide a design report for the neutrino-less double beta decay experiment selection process to be setup by the US Department Of Energy. This process is expected to start in 2017.

Phase 3: 2018-2020. Procurement of photo-detectors for nEXO

Procurement of the photo-detector is expected to happen as soon as funds are available, which could be as early as 2018.

Time scale summary table

Task	Who	When	Phase
Completion of gas/vacuum test setups	Stanford & TRIUMF	Jun. 2014	1
Samples for performance and radiopurity studies	Manufacturers	Sep. 2014 or earlier	1
Feedback to manufacturers	nEXO	Nov.-Dec. 2014	1
Second round of samples for performance studies	Manufacturers	Mar. 2015	1
Final (if needed) round of samples	Manufacturers	Sep. 2015	1
Selection of 1-3 photo-detectors for phase 2	nEXO	Dec. 2015	1
Completion of LXe test setup commissioning	nEXO	Early 2016	2
Procurement of photo-detectors for phase 2	nEXO / vendors	Early 2016	2
Validation of 1 or more photo-detectors for nEXO	nEXO	Jun. 2017	2
Write photo-detector section of design report	nEXO	2017	2
DOE down select decision	DOE	2017-2018	2
Photo-detector procurement for nEXO	nEXO / vendors	2018	3