nEXO Photo-detectors R&D

F. Retière, November 2014

Specifications

Geometry

nEXO 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.

Scintillation photon detection efficiency

The target overall efficiency for detecting the scintillation photons produced in liquid Xenon is 10%. Simulations show that this efficiency is achievable if:

1. The cathode and shaping rings (that shadow the photo-detectors in the barrel geometry) reflectivity is larger than 80%. The anode reflectivity needs to be at least 50% to maintain sufficient uniformity.
2. The internal photo-detector (PDE) efficiency is larger than 30% at 175nm. Internal PDE excludes reflection, which are large (~50%) in liquid Xenon if using silicon due to the very large index of refraction mismatch (n=1.7 for LXe and n~0.8+2.2i for Si). It would also be acceptable to use a wavelength shifting material to go from 175nm to a longer wavelength were photo-detectors tend to be more sensitive.

The first step of the photo-detector R&D for nEXO will done using setups operated either in vacuum or in a gas transparent at 175nm such as gaseous nitrogen in order to test a large number of possible photo-detectors. However, The index of refraction issue is a concern for silicon photo-detector that are often covered with SiO2 and other possible anti-reflective coating that may work when operating in gas/vacuum but not in liquid Xenon. Hence, once compelling photo-detectors have been indentified using the vacuum/gas setups, operation in liquid Xenon will be necessary to verify their performances. Furthermore, reflectivity of the various optical elements including the photo-detectors will have to be measured as a function of angle in gas/vacuum and if possible in liquid Xenon.

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.

The radioactivity limit for the field shaping ring needs to be clarified.

Photo-detector nuisance parameters

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.

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).

Photo-detector electrical properties

<u>Not critical.</u> *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. The size of single photo-detector elements should be at least 1x1cm2. Larger areas, up to 20x20cm2 are desirable but they are limited by the electronics noise that scales with the capacitance per channel. Therefore low capacitance per unit area is desirable (e.g. <500pF/cm²).*

Timing resolution

<u>Not critical.</u> *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.*

Integration in liquid Xenon

Very long electron drift time (ms scale) must be achieved in nEXO which require very low level of electron absorbing contaminants. Therefore, the photo-detectors and associated ancillary mechanical and electrical interfaces will have to be tested in liquid Xenon together with the passive optical elements. Furthermore, operation of the complete light detection system must be demonstrated in liquid Xenon.

Summary table

The parameters are listed in order of priority. nEXO must identify a high efficiency, low radioactivity photo-detector solution and develop reflective electrodes by early 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.

Parameter	**Value**
Photo-detection efficiency at 175-178nm (without AR coating in gas/vacuum)	≥15%
Shaping ring and cathode reflectivity	>80%
Radiopurity: contribution of photo-detectors to the overall background	≤1%
Dark noise rate at -100°C	$\leq 50Hz/mm^2$
Average number of correlated avalanches per parent avalanche at -100°C	≤0.2
Single photo-detector active area	$\geq 1cm^2$
Gain fluctuations + electronics noise (see text for details)	*≤0.1 photo-electron*
Capacitance per unit area	*$<50pF/mm^2$*

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

Current status

Parameter	FBK-2010	HPK	KETEK	SensL
Over-voltage	5V	2.5V	2.5V	
PDE at 175nm in liquid Xenon (%)	10^{S}	17^{S} 19^{M}	0	0
Dark noise rate (Hz/mm^2)	1000	0.5^{T}	4	
Cross-talk probability	0.05	0.34^{T}	0.06^{T}	
After-pulsing rates (x100)			$5/1/25^{T}$	
After-pulsing time constants (μs)		6///	$1/10/500^{T}$	
Total correlated av. rate within 10μs		0.38^{T}	0.15^{T}	
Recovery time in ns		25^{T}	900^{T}	
Pulse rise time (Gaussian sigma in ns)		1.6^{T}	0.5^{T}	
Pulse fall times (exponential tau in ns)		30^{T}	$6_{(0.9)}/300_{(0.1)}{}^{T}$	
Capacitance (pF/mm^2)	330	35	100	80 / 3.2
Thorium (^{232}Th) content (μBq/kg)	<13	?	?	< 2 10^6
Uranium (^{238}U) content (μBq/kg)	<250	?	?	< 94 10^6
Potassium (^{40}K) content (μBq/kg)	<140	?	?	< 47$10^6$

Table 2. FBK data are for first generation (2010) device. For HPK, the MEG MPPC was used for the efficiency measurement and a new 2014 3x3mm2 device was used for the nuisance and electrical parameter measurements. The KETEK devices tested was a TR (trench) series from 2013. The PDE was extrapolated from vacuum to liquid Xenon by accounting for reflections using known refractive indices and assuming no interferences. The radioactivity content was measured for silicon wafer only for FBK by Ge counting after nuclear activation and for packaged devices for SensL by Ge counting (without activation).

Time scale

To date no photo-detector fulfills all the specifications outlined earlier. Test setups at Stanford and TRIUMF will be fully operational by the end of 2014 and photo-detectors will be fully characterized in 2015. Radioactivity of promising photo-detectors and mirrors will be assessed in parallel under the U. Alabama group leadership. If possible photo-detectors will be tested independently of their associated package but this may not be possible for some manufacturers and the package may dominate the radioactivity content. Therefore, the development of a low radioactivity package must start in 2015 either in collaboration with a manufacturer or independently. Promising photo-detector and their associated package must be assayed by early 2016.

Solutions for reflecting 175nm light must be developed in 2015. Reflectivity must be measured either in gas/vacuum or liquid Xenon. The reflectivity should be measured as a function of angle and wavelength especially if using a gas/vacuum setup because interferences are a concern. The nEXO collaboration must develop a new setup to characterize material reflectivity in 2015.

While the gas/vaccum setups provide flexibility, they are not sufficient for assessing the photo-detector (and associated readout electronics) and mirror performances in nEXO conditions. In 2016, the nEXO collaboration will operate a test setup for measuring photo-detector and reflector performances in liquid Xenon. The plan is to build a small Time Projection Chamber surrounded by 4 planes of photo-detectors (about 10x10cm^2 each). Design of the liquid Xenon test setup (mini-nEXO) must start in 2015.

Task	Who	When
Completion of gas/vacuum test setups	Stanford & TRIUMF	Dec. 2014
Identify photo-detector(s) with PDE>15%	Stanford & TRIUMF	2015

Design photo-detector package	TRIUMF?	2015
Development and test of mirrors (and PD reflectivity) - Procure material - Design and build test setup or contract out	UMass?, Erlangen?	2015
Small scale test of photo-detectors in liquid Xenon - Cryogenic system and light source - Photo-detector and electronics	At UMass? UMass? TRIUMF?	2015 Early 2015 2015
Radioactivity assay of photo-detectors	Alabama	2015-2016
Design and construct TPC for photo-detector test - Cryogenic system - Time projection chamber - Photo-detector and support - Warm electronics - Cold electronics	At Carleton? Carleton? UMass? TRIUMF? Carleton? BNL, ORNL, UI	Apr 2015-2017 2015 2015 2015-2016 2015 2016-2017
Design and construction of reflective electrodes	UMass? Erlangen?	2016-2017
Radioactive assay of reflective electrode components	Alabama	2016-2017