Simulations of the nEDM@SNS light collection system efficiency

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ABSTRACT: A system for collecting the scintillation light produced by the capture of ultra-cold neutrons (UCN) on polarized $^3$He is discussed and results from simulations of its performance are presented. This system will be implemented in nEDM@SNS, the experiment searching for the neutron electric dipole moment (nEDM) at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. Simulation results show that the light collection system detects on average 17 photoelectrons per UCN-$^3$He capture event (sufficient to generate a robust signal), reconstructs the event location in the beam direction to approximately 3 cm accuracy, detects capture events with a high and spatially uniform efficiency (0.95 with 1% variation), and rejects greater than 50% of beta decay background events.

KEYWORDS: Photon detectors for UV, visible and IR photons (vacuum) (photomultipliers, HPDs, others); Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators); Simulation methods and programs

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1 Introduction

The presence of a nonzero permanent neutron electric dipole moment (nEDM), a measure of the charge distribution within the neutron, would violate both parity (P) and time reversal invariance (T) and be a clear signature of physics beyond the standard model. The nEDM@SNS experiment [1] will utilize the technique introduced by Golub and Lamoreaux [2] to measure the nEDM with a two order of magnitude improvement in sensitivity over recent nEDM measurements [3]. Neutrons with de Broglie wavelength \( \lambda = 8.9 \text{ Å} \) (kinetic energy = 1 meV) from the Fundamental Neutron Physics Beamline [4] at the ORNL Spallation Neutron Source are directed into two measurement cells filled with superfluid \(^4\text{He}\) and a dilute concentration of polarized \(^3\text{He}\). The superfluid \(^4\text{He}\) downscatters a fraction of the incoming neutrons to energies low enough that they can be trapped within the measurement cells. These “ultracold neutrons” (UCN) can be stored in the measurement cells for long periods (hundreds of seconds [5]), maximizing observation time and increasing sensitivity. Both neutrons and \(^3\text{He}\) have a magnetic dipole moment and will precess in a magnetic field. The neutron-\(^3\text{He}\) capture process

\[
\text{n} + ^3\text{He} \rightarrow p + ^3\text{H} + 764 \text{ keV}
\]  

(1.1)

deeposes 764 keV of kinetic energy into the superfluid \(^4\text{He}\), which in turn produces a burst of extreme ultraviolet (EUV) scintillation light (\(\lambda = 80 \text{ nm}\)) [6–9]. The capture process is strongly spin-dependent. As a result, the scintillation rate will vary as 

\[ 1 - P_3 P_n (\hat{n} \cdot \hat{3}) \]

where \(P_3, P_n\) and \(\hat{n}, \hat{3}\) are the polarization and spin direction of the two species. The nEDM can be extracted with two
different measurement techniques ("free-precession" and "spin dressing"), both of which use the scintillation signal resulting from neutron/$^3$He capture events to monitor the angle between neutron and $^3$He spin vectors.

To measure the scintillation signal, a light collection system, composed of a wavelength-shifting (WLS) coating and thin dielectric reflector embedded in the measurement cell walls, WLS optical fibers, and an array of silicon photomultipliers (SiPM’s), has been designed in accordance with the experiment requirements. A more thorough description of the system is offered in section 2. Many design choices were made prior to this study. For instance, due to the need for flexibility of the system in the face of thermal contraction and overall routing complexity, it was chosen to be fiber-based. Given the emission spectrum of the WLS coating, Kuraray Y-11 fibers were selected. Electrostatic requirements constrain the fiber placement to be adjacent to the ground electrode of the high voltage system. SiPM’s were chosen due to their high photon detection efficiency (PDE) and sufficient dark rate suppression is obtained by cooling them.

The simulation study described in this report was undertaken to address remaining design parameters whose impact can be evaluated with a Monte Carlo approach. These parameters include dielectric reflector surface roughness, fiber dye density, diameter, and length, and the choice of embedding the fibers in the measurement cell walls. With these parameters addressed, we then carried out simulations to quantify the light collection system’s capture event detection and beta decay background rejection efficiencies, as well as event position reconstruction capabilities.

In section 2 we discuss the light collection apparatus in more detail, and the simulation framework used in this study. In section 3, we discuss simulation results, in particular showing the efficiency of signal detection and beta decay background rejection. Finally, in section 4 we present a summary of the findings.

2 Apparatus and procedure

2.1 Light collection apparatus

The light collection system begins in the measurement cells in the experiment’s central volume (figure 1). EUV photons have short absorption lengths in nearly all materials other than helium,

Figure 1. (a) Components inside the nEDM@SNS Central Volume [1]. (b) Beam’s-eye view highlighting components of the light collection system.
so they must be converted into optical wavelengths by a WLS coating on the measurement cell walls. A coating made by dissolving deuterated tetraphenyl butadiene (dTPB) [10] and deuterated polystyrene (dPS) [11] in deuterated toluene has been shown to retain the $^3$He polarization [12] and neutron density [5] for times that are long relative to the neutron beta decay lifetime. The photons re-emitted by the dTPB+dPS layer are wavelength-shifted to a spectrum centered around 450 nm. Measurements of the fluorescence efficiency of TPB in a polystyrene matrix at wavelengths near 80 nm [13] were found to be near the 35% efficiency measured in sodium salicylate [14]. We assign a 17% one-sided (negative) relative systematic uncertainty to the photon yield. These blue photons are then collected by Kuraray Y-11 WLS fibers [15] pressed against the measurement cell wall near the ground electrode. To prevent a substantial number of photons from escaping the measurement cell before reaching the optical fibers, the dielectric reflector Vikuiti™ ESR (Enhanced Specular Reflector) film by 3M [16] will be glued to the other cell walls.

Once in the fibers, the photons are converted to green wavelengths (figure 2, open blue circles) and transported to the surface of the central volume. There they are mated to clear fibers which lead to an array of silicon photomultipliers (SiPMs) that are placed outside the cryovessel due to the strict non-magnetic requirements near the central volume. Hamamatsu 13360-75 SiPMs [17] were selected for their high PDE, their small area well-matched to individual fibers (dark rate is proportional to area), and because they are well characterized at the low temperatures needed ($< -40$°C) to further suppress dark rate [18]. The large pixel size (75 × 75 $\mu$m$^2$) is beneficial for low light conditions, where it is worthwhile to maximize the fill factor and sacrifice some dynamic range for higher efficiency.

![Figure 2](image-url)  
**Figure 2.** Photon detection efficiency vs wavelength (PDE($\lambda$)) of a Hamamatsu 13360-75 SiPM at $V_{BR} + 8 \text{ V}$ and the emission spectrum for Kuraray Y-11 optical fibers at 1.5 m.

A photon counting technique [1], in which any SiPM detection is assumed to correspond to a single photon, is implemented by discriminating each analog SiPM readout at ~0.5 photoelectrons to create a digital signal. With this technique, we record the arrival time of each photon, enabling offline pulse-shape discrimination. Additionally, this technique eliminates optical cross talk, allowing the SiPMs to be operated at a relatively high overvoltage (8 V above the breakdown voltage $V_{BR}$ where signals begin). At this operating voltage, the PDE (figure 2, filled red circles) is maximized.
(~1.3 times greater than standard operating voltage) and its dependence on voltage, temperature, and sensor variation is minimized [18]. Finally, this technique prevents gain dependence on voltage, temperature, and sensor variability from impacting the signal amplitude. This technique is especially appropriate in the low-light conditions of the nEDM@SNS experiment. The probability that an individual sensor will see any photons in an event is small, so the PDE loss suffered when multiple photons from the same event hit the same SiPM is only a few percent.

2.2 Simulation overview

The simulation procedure can be conceptually split into four steps. First, EUV scintillation light is produced from UCN-3He capture or the beta decay background and converted to blue light by the dTPB+dPS layer in the measurement cell wall. Second, the blue light is propagated until it is wavelength-shifted to green light within the fibers or otherwise absorbed. Third, a fraction of the green light is trapped within the fibers and transported through the fibers to the SiPMs. Finally, the photons that reach the SiPMs are detected with some probability. GEANT4, which contains a thorough treatment of optical physics and material properties [19], is used for the first two steps.

2.2.1 GEANT geometry

The GEANT4 detector geometry consists of an acrylic box (7×10×40 cm) containing liquid helium with density 0.145 g/cc. The cell wall surfaces are given the wavelength-shifting property of the dTPB+dPS layer, with a conversion efficiency of 35%. This layer can be defined in the GEANT4 geometry either on the inside or outside of the acrylic, which is used to examine the impact of wavelength-shifted light getting trapped within the acrylic.

A Vikuiti dielectric mirror surface is defined on the non-fiber cell wall surfaces by using a native GEANT4 “rough” optical surface. Measurements of the reflectivity vary from 89–98% [16, 20]; taking the weighted average with 89% treated as an outlier gives 96 ± 1%. The reflectivity has been shown to be consistent with this value at low temperature [21]. Photons incident on the optical surface undergo specular lobe reflection with a spread parameterized by $\sigma_\alpha$, the width of a Gaussian distribution of surface micro-facet normals. $\sigma_\alpha$ can be varied within our simulation to evaluate the importance of optical surface roughness.

The wavelength-shifting fibers are placed against one of the 40 cm walls, running in the vertical direction. The GEANT4 geometry can be configured to simulate fibers of either 1/2 or 1 mm diameter, both of which are available from Kuraray. The wavelength-shifting absorption length of the fibers is given by

$$\lambda_d = \frac{1}{A_r(\lambda)\rho_d \ln 10},$$  \hspace{1cm} (2.1)

where $A_r(\lambda)$ is the absorbance [15] and $\rho_d$ is the dye density, a tunable parameter within the simulation framework.

2.2.2 Fiber transport efficiency and initial number of EUV photons

For UCN-3He capture events the number of EUV photons at an electric field of 40 kV/cm is taken to be 5050 [22]. Photons are emitted at the capture location since the pathlengths of the resulting proton and triton are negligible.
Beta decay events deposit energy into the liquid helium along a finite path length, so photons are no longer emitted from a single event location. Instead, betas are generated from the neutron beta decay spectrum as primary particles and a scintillation process in the $^4$He is defined in GEANT4 to produce EUV photons distributed along the beta trajectory. The scintillation yield of liquid $^4$He is taken to be 15,000 EUV photons per MeV of deposited energy [23, 24] with an electric field quenching factor of 0.58 [25] at 40 kV/cm applied to this number.

Table 1. Assumed fiber transport photon efficiency probabilities.

| Efficiencies in Fiber Transport          |                  |
|------------------------------------------|------------------|
| Fiber trapping                           | 11% [15]         |
| Fiber bends                              | 95% [15]         |
| WLS Fiber transmission                   | 53% [26, 27]     |
| Clear Fiber transmission                 | 74% [28]         |
| WLS/clear fiber interface                | 90% [29]         |
| Fiber/SiPM interface                     | 90% [29]         |
| Total                                    | 3.32%            |

Fiber transport efficiency (step 3) is not simulated within GEANT. Instead, the estimated efficiency (based on measured quantities, see table 1) is pre-applied to the number of initial EUV photons. The probability of a photon to reach a SiPM once it has been successfully wavelength-shifted in a fiber is determined by the product of the Y-11 fiber trapping efficiency assuming a double-clad fiber with readout from both sides [15], transmission efficiencies in the Y-11 fibers (length of $4 \times 1.5 \text{ m} = 6 \text{ m}$) [26, 27] and clear fibers (length of $7 \text{ m}$) [28], and losses from fiber transitions [29] and bends. Taking the product of the efficiencies in table 1, 3.32% of green photons produced in the WLS fibers will be transmitted to the SiPM readout. So, for example, the number of EUV photons for a UCN-$^3$He capture event is sampled from a Poisson with $\mu = 5050 \times 0.0332 = 168 \pm 12.9$).

2.2.3 SiPM detection

Photons captured in the fibers are assigned a wavelength according to the spectrum of green photons exiting Kuraray-11 fibers after 1.5 m (figure 2, open blue circles), and detected with the PDE for Hamamatsu 13360-75 SiPMs at $V = V_{BR} + 8V$ (figure 2, filled red circles). The photon counting algorithm is implemented by restricting an individual SiPM to a single photon detection per event.

3 Results and discussion

3.1 Parametric studies

The first simulation task was to explore the impact of unresolved design parameters related to the optical fibers, dTPB, and Vikuiti dielectric film on the light collection efficiency. These parameters all impact the transport of the blue photons in the measurement cell to the optical fibers and their subsequent wavelength-shift to green. Hence, in this task, design geometries with different parameter choices are simulated in GEANT4 by emitting monoenergetic blue light uniformly throughout the measurement cell, and transporting it to the fibers where it is converted to green.
light with a native GEANT4 wavelength-shifting process. We use $\epsilon_{BG}$, the fraction of blue photons that are successfully converted to green, as the metric for these effects.

The surface roughness of the Vikuii reflector, $\sigma_\alpha$, was investigated first. It was found that $\epsilon_{BG}$ does not depend strongly on $\sigma_\alpha$ (figure 3). Due to the relative independence of $\epsilon_{BG}$ with $\sigma_\alpha$, it is taken to be $3^\circ$, the median value between a perfect specular reflector and maximum efficiency, with 5% uncertainty. Measured angular distribution profiles of Vikuii are consistent with $\sigma_\alpha \sim 3^\circ$ [20]. Simulations at 95% and 96% Vikuii reflectivity find an additional 6% systematic contribution to $\epsilon_{BG}$ due to the uncertainty on the reflectivity.

![Figure 3. Blue to green photon conversion efficiency vs. Vikuii surface roughness.](image)

The next parameter studied is the dye density in the wavelength-shifting fibers. One method for increasing $\epsilon_{BG}$ is to use higher concentration of the WLS dye. By concentrating the dye, the probability of a photon shifting wavelength while traversing a fiber increases. This is tested in our simulation framework by scaling the dye density and, hence, the wavelength-dependent absorption length (equation (2.1)). The resulting simulations indicate that $\epsilon_{BG}$ is only weakly dependent on the dye density in this light collection system, (figure 4) suggesting the fibers can be used at their nominal concentration of 200 ppm.

The impact of fiber diameter on $\epsilon_{BG}$ was also investigated by simulating fibers with $\frac{1}{2}$ mm and 1 mm diameters. Due to mechanical tolerances, the SiPMs should be somewhat larger than the clear fibers, which should in turn be somewhat larger than the WLS fibers. Larger differences ease mechanical tolerance requirements, but since the dark rate is proportional to sensor area the sensors cannot be made arbitrarily large. The chosen SiPMs are 1.3 mm on a side. The next-largest sensor is 3 mm on a side; five times the area and five times the dark rate. There is only $\sim$5% performance difference for the different fiber diameters (figure 4) so $\frac{1}{2}$ mm diameter was chosen to relax mechanical tolerances.

Another idea for increasing $\epsilon_{BG}$ is to embed the fibers in the acrylic of the cell walls. Embedding the fibers reduces the change in the index of refraction at the fiber/cell wall interface by eliminating the helium gap. This should decrease the number of photons that are prevented from reaching the fibers because of total internal reflection off this boundary.
Fiber embedding was tested in four scenarios: with dTPB light produced within the acrylic on the measurement cell wall boundary or outside of the acrylic (on the $^4$He side of the boundary) and with fibers embedded or unembedded. As seen in figure 5, there is little dependence of $\epsilon_{BG}$ on these parameters. Due to the mechanical challenges of embedding the fibers, we adopt the unembedded geometry moving forward. It is unknown experimentally whether the dTPB light is produced within or outside the acrylic since the absorption length is on the order of 10 nm $^{[30]}$. We conservatively choose production within the acrylic for the remainder of the simulations and assign a 12% one-sided (positive) relative systematic uncertainty to the photon yield.

3.2 UCN-$^3$He capture events

Our optimized geometry consists of 192 $\frac{1}{2}$ mm diameter unembedded fibers with 200 ppm dye density. Each fiber is looped into four adjacent segments along the cell wall with both fiber ends read out by individual SiPMs, leading to 384 total SiPMs. $\sigma_{\alpha}$ for the Vikuiti reflector film was set to $3^\circ$. 
Following the framework outlined in section 2.2, UCN\(^{3}\)He capture events are simulated by generating primary EUV photons from a capture event position into \(4\pi\) whose multiplicity is sampled from a Poisson distribution with \(\mu = 167 \pm 12.9\). A simulation of 100,000 capture events emitted uniformly throughout the cell found the mean number of detected photoelectrons (NPE) to be 17.15 per event (figure 6) with systematic uncertainties given in table 2. The other quantities present in the simulation, most notably the fiber transport efficiencies, the EUV photon multiplicity, and the SiPM detection efficiency, have either negligibly small errors or no quoted errors.

![Figure 6](image)

**Figure 6.** Number of photoelectrons detected in SiPMs from UCN\(^{3}\)He capture events distributed uniformly throughout the measurement cell volume.

**Table 2.** Systematic uncertainties on the number of detected photoelectrons from UCN\(^{3}\)He capture events.

| Systematic                      | Relative Uncertainty |
|---------------------------------|----------------------|
| dTPB+dPS conversion efficiency  | -17%                 |
| dTPB light production/trapping  | +12%                 |
| Vikuiti reflectivity            | ±1%                  |
| Vikuiti \(\sigma_\alpha\)       | ±6%                  |

### 3.3 Event location reconstruction

Each readout channel (a group of 16 SiPMs) collects photons from fibers distributed over a strip of the cell wall limited to a 3.2 cm range in the beam direction. Thus, the distribution of hits binned by readout channel provides information on the event position in the beam direction. This information can be utilized to identify systematic effects and, as seen in section 3.4, improve signal cuts that suppress experimental backgrounds.

Event z-position is reconstructed by calculating the mean position of struck readout channels weighted by the NPE detected in each channel (figure 7). At event positions near the cell windows (\(|z| \geq 15\) cm), the reconstructed position is skewed by the asymmetric tail of the SiPM readout distribution towards the center of the cell. This effect is reduced by implementing a truncation method, in which readout channels with 1 photoelectron are removed before the weighted mean is calculated.
Figure 7. Reconstructed vs. true position along the beam axis ($z_{\text{rec}}$ vs. $z_{\text{true}}$) of UCN-$^3$He (blue) and beta decay (red) events using a truncated weighted mean of hit readout channel positions.

3.4 Background suppression cuts

The primary source of background events is beta decay of the stored UCN, which produces an optical signal comparable to that of the UCN-$^3$He capture events. Beta decay events are simulated as described in section 2.2.2. The distribution of NPEs detected per event from neutron beta decays is then normalized by the ratio of the beta decay rate to the capture rate at nominal wall loss, polarization loss, and $^3$He density, $k_{\beta}/k_3 = 0.55$ [31] to produce figure 8. Background contributions from neutron activation, UCN wall loss, and cosmic rays are smaller and not studied here.

Figure 8. Photoelectron distribution of UCN-$^3$He capture (signal) and beta decay (background) events. The details of the beta decay simulation, including the relative number of beta/capture events, are described in the text.

In order to maximize signal sensitivity, the beta decay background (and other background sources with broad energy deposition distributions) can be suppressed via cuts on the NPE distribution relative to the expected yield from monoenergetic UCN-$^3$He capture events. The design goal of the nEDM@SNS experiment is to reduce the beta decay background by a factor of two ($\xi_\beta = \frac{1}{r_\beta} > 2$) while maintaining a high capture event detection efficiency ($\epsilon_3 \geq 0.93$). This can
be accomplished with relatively narrow NPE cuts about the capture peak, with an especially tight cut placed on the lower side of the capture peak where the beta signal is concentrated. The tight and asymmetric nature of the cuts about the capture peak, while maximizing rejection of the beta background, introduce position-dependent event detection efficiencies since the signal amplitude is modestly position-dependent along both the beam (z) direction and the x-direction (figure 9).

![Figure 9](image)

**Figure 9.** (NPE) detected from UCN-$^3$He events (a) in the beam (z) direction, and (b) in the direction perpendicular to the beam and the fiber plane (x; fibers at x = +3.5 cm). Insets are the same data without the suppression of 0 on the y-axis.

![Figure 10](image)

**Figure 10.** Effect of NPE cut values on (a) UCN-$^3$He capture signal detection efficiency (b) beta decay background rejection factor. The region within the red contour in (a) satisfies $\epsilon_3 \geq 0.93$ and in (b) satisfies $\zeta_\beta > 2$. The region within the dashed black contour satisfies both conditions.

The capture signal efficiency variation along the beam axis can be reduced to less than 1% by using the reconstructed beam axis position (section 3.3) to define z-dependent NPE cuts. Figure 10 shows $\epsilon_3$ (left) and $\zeta_\beta$ (right) as a function of the NPE cut lower bound ($C_L$) and upper bound ($C_H$) defined relative to the average number of photons for the event z-position ($\langle\text{NPE}(z)\rangle$). The regions outlined in red show the cut combinations that satisfy at least one of the conditions $\epsilon_3 \geq 0.93$ or
There is no x-position information available, so the analogous efficiency variation in that coordinate cannot be addressed with position-dependent cuts. Instead, simulations were used to select optimal cuts from the 20 cut combinations that satisfy the $\varepsilon_3 \geq 0.93$ and $\zeta_\beta > 2$ requirements. We simulated each cut combination independently, calculating the variation in signal detection efficiency ($\delta\varepsilon_3$) and background rejection ($\delta\zeta_\beta$) as the normalized root mean square deviation across the measurement cell. Additionally, we calculated the fluctuation in the detected capture signal ($\langle\sigma_S/S_{tot}\rangle = k\sqrt{1/S_{tot}}$) where

$$k = \sqrt{\frac{1}{\varepsilon_3}} \sqrt{1 + \frac{2\varepsilon_3 B_{tot}}{\varepsilon_3 S_{tot}}},$$

quantifies the degradation of the signal count uncertainty relative to the background-free case for different background suppression cuts. $S_{tot}$ and $B_{tot}$ are the total signal and background NPE counts, respectively. Figure 11 shows the results for the specified 20 cut combinations.

**Figure 11.** NPE cut placement optimization parameters in region where $\varepsilon_3 \geq 0.93$, $\zeta_\beta > 2$. The color scale is (a) k (see eq. (3.1)) (b) the signal detection efficiency variation across the measurement cell ($\delta\varepsilon_3$) (c) the beta decay background rejection variation across the measurement cell ($\delta\zeta_\beta$).
and \( C_H = \langle \text{NPE}(z) \rangle + 9 \) are selected as the best trade-off between minimizing \( k \), \( \delta \epsilon_3 \), and \( \delta \zeta_\beta \). Figure 12 shows \( \epsilon_3 \) (left) and \( \zeta_\beta \) (right) vs. cell position with these cuts. Over the entire volume of the cell, \( \epsilon_3 \) and \( \zeta_\beta \) meet their design goals with variations \( \delta \epsilon_3 < 1\% \), and \( \delta \zeta_\beta < 10\% \).

The \( \zeta_\beta \) x-dependence is the combined effect of the photoelectron detection efficiency x-dependence (figure 9(b)), the asymmetry of the NPE distribution for beta events (figure 8) and the relatively long pathlength (\( \mathcal{O}(2 \text{ cm}) \)) of beta particles in liquid \(^4\text{He} \). The result of this last effect is that betas produced near the cell walls may only deposit a fraction of their energy in the \(^4\text{He} \), reducing their scintillation signal in a way that can depend on the direction of the electric field. This could conceivably result in different signal to background ratios for different electric field directions, which could indirectly lead to small shifts in the extracted frequency parameter for different electric field directions, and thus, a false EDM. This effect was investigated by repeating the previous simulations after reversing the electric field. Figure 13 shows a small \( \lesssim 1\% \) E-field direction dependence of \( \zeta_\beta \) integrated over the cell’s volume. With no mitigating effects this would lead to a false nEDM of \( \sim 1 \times 10^{-28} \text{ e cm} \) [31]. This is already acceptable, but any frequency shift can be easily suppressed by allowing the signal-to-background ratio to vary in the frequency extraction fit rather than assuming a fixed value. Further cancellation is provided by the nEDM@SNS two-cell design: a true EDM will result in opposite sign frequency shifts for the two cells since they have opposite values of \( \vec{E} \cdot \vec{B} \). In contrast, any frequency shift resulting from a field-dependent signal-to-background ratio depends on \( \vec{E} \cdot \hat{f} \) (\( \hat{f} \) is the normal vector of the fiber plane relative to the cell interior) which is the same for both cells.

This small false nEDM, together with the simulated detection efficiencies, sufficient \( \langle \text{NPE}(z) \rangle \) and negligible dependencies on the parameters addressed in this study, suggest that the current design of the light collection system will meet the requirements of the experiment. Additionally, an increase in the PDE, and thus the \( \langle \text{NPE} \rangle \), could be foreseen with improvements in SiPM devices in the forthcoming years. Although their contribution to the total background is less significant than beta decay, a worthwhile extension to this study would properly model the effect of neutron
activation and UCN wall loss on the signal detection efficiency and background rejection capability of the system.

4 Summary

The light collection system responsible for reading out the signal from UCN-$^3$He capture scintillation in the nEDM@SNS experiment has been simulated. This system consists of a WLS dTPB coating, a thin film dielectric reflector, WLS optical fibers, and silicon photomultipliers.

Simulations indicate that previously untested parameters, such as fiber diameter, fiber dye density, fiber embedding, and thin film reflector surface roughness, have only minor effects on the final results. A mean of $\sim$17 photoelectrons are detected per UCN-$^3$He capture event and the position of the event along the beam direction can be reconstructed to within several cm. Position-dependent cuts on the number of detected photoelectrons reduce the beta decay background to sufficiently low levels. Additionally, the event position information can be used to identify further backgrounds/systematic effects. With optimized cuts, the efficiency of capture event detection is uniform to <1% across the measurement cell and the efficiency of beta decay background rejection is uniform to <10%. These results hold promise for the successful implementation of the light collection system in the upcoming nEDM@SNS experiment.

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