Calorimeter R&D for the SuperNEMO Double Beta Decay Experiment

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Abstract.
SuperNEMO is a next generation double beta decay experiment, which will employ the successful tracker-calorimeter technique used in the currently running NEMO3 [1] experiment (located in the Laboratoire Souterrain de Modane (LSM)). SuperNEMO will study 100kg of the $^{82}$Se isotope, reaching a sensitivity of a half-life greater than $10^{26}$ years for neutrinoless double beta decay ($0^{\nu}\beta\beta$). This corresponds to a Majorana neutrino mass of $50 – 100$meV. One of the main goals and challenges of SuperNEMO R&D is to reach an unprecedented energy resolution of 4% FWHM at 3 MeV ($Q_{\beta\beta}$ value of $^{82}$Se) for the calorimeter, which has been achieved by the collaboration.

1. Introduction

Neutrinoless double beta decay ($0^{\nu}\beta\beta$), $2n \rightarrow 2p + 2e^-$, is a lepton number violating process forbidden in the Standard Model which occurs via the exchange of a virtual neutrino. It is allowed only if the neutrino has a non-zero mass (as established by neutrino oscillation experiments) and if the neutrino is a Majorana particle (the neutrino and anti-neutrino are the same, as proposed by Ettore Majorana [2]) and can therefore provide further insight into the neutrino, such as its absolute mass and nature.

The experimental signature of $0^{\nu}\beta\beta$ is two electrons coming from a common vertex with an energy sum equal to the $Q_{\beta\beta}$ value of the measured isotope. The half-life $T_{1/2}^{0^{\nu}}$ measured from $0^{\nu}\beta\beta$ experiments can be directly related to the electron neutrino mass $\langle m_{\nu_e} \rangle$, as shown in Equation 1, where $G^{0^{\nu}}$ is the kinematic phase space ($G^{0^{\nu}} \propto Q_{\beta\beta}^{5}$) and $M_{0^{\nu}}$ is the nuclear matrix element. Equation 1 shows $0^{\nu}\beta\beta$ via light neutrino exchange (the mass mechanism mode) as this mode requires minimal modifications to the Standard Model, however other modes also exist.

$$[T_{1/2}^{0^{\nu}}]^{-1} = G^{0^{\nu}} |M_{0^{\nu}}|^2 \langle m_{\nu_e} \rangle^2$$ (1)

2. SuperNEMO Detector

SuperNEMO is based on the technology of the currently running NEMO3 experiment, using a tracker-calorimeter detection technique for particle identification. The detector will hold $\sim$ 100kg of double beta decay source isotope ($^{82}$Se is the ‘baseline’ design isotope, with $^{150}$Nd and $^{48}$Ca being considered depending on enrichment possibilities) to reach a projected sensitivity
of $10^{26}$ years (50 - 100 meV effective Majorana neutrino mass). The baseline design consists of 20 modules (~ 4m (height) x 6m (length) x 2m (width)), each containing 5kg of isotope source foil, surrounded by ~ 2000 Geiger mode drift cells and enclosed by the calorimeter walls (containing ~ 550 8" PMTs), as seen in Figure 1.

SuperNEMO is currently nearing the end of a three year R&D study, with four main areas of focus: source foil production, tracker development, calorimeter development and ultra-low background materials production and measurements. The goals of the R&D are summarised in Table 1.

![SuperNEMO module's components](image)

Figure 1: View of a SuperNEMO module’s components: (from left to right) calorimeter wall, tracker, source foil, tracker and calorimeter wall.

| Parameters                        | Goals          |
|-----------------------------------|----------------|
| Isotope                           | $^{82}$Se      |
| Mass                              | 100kg          |
| $0\nu\beta\beta$ Detection Efficiency | 30%            |
| Energy Resolution FWHM at 3 MeV   | 4%             |
| $^{214}$Bi Purity                  | < 10µBq/kg     |
| $^{208}$Tl Purity                  | < 2µBq/kg      |
| Operation Time                    | 5 years        |
| $T_{1/2}^{0\nu\beta\beta}$ Sensitivity | $10^{26}$ years |
| Effective Majorana Mass ($m_{\nu_e}$) | 50 – 100meV    |

The energy resolution of the calorimeter is of the utmost importance to SuperNEMO, as can be illustrated by the half-life sensitivity formula [4] (Equation 2), where the energy resolution $\Delta E$ is as significant as the isotope mass $M$, the run time $t$ and the number of background events $N_{bkg}$. Factors $N_A$ and $A$ are Avogadro’s number and the atomic mass of the isotope respectively, $\epsilon$ is the detector efficiency and $\kappa_{CL}$ is the number of excluded $0\nu\beta\beta$ events at the chosen confidence level of the half-life sensitivity $T_{1/2}^{0\nu\beta\beta}$. One of the dominant backgrounds to
0νββ is the irreducible 2νββ tail, making the energy resolution the determining factor of the detector's sensitivity to 0νββ. This can be seen in Figure 2, where simulations carried out for 82Se with a calorimeter energy resolution of 12% and 7% FWHM at 1MeV respectively and normalised to a 1026 year 0νββ half-life are shown. It can be seen that a much clearer separation between the 2νββ tail and the 0νββ peak is achieved with a 7% energy resolution.

Figure 2: Calorimeter energy resolution simulations for 82Se for 500kg·yr, with the 0νββ half-life (red) normalised to 1026 years. 12% (left) and 7% (right) FWHM at 1 MeV energy resolutions are shown, illustrating the overlap of the 2νββ (black) tail.

3. SuperNEMO Calorimeter Requirements

SuperNEMO has a need for a robust calorimeter (using reliable and time withstanding technology) with ease of manufacturing and assembly, providing unprecedented energy resolution results at a sensible cost. The calorimeter R&D for SuperNEMO consists of three main areas of study: energy and time resolution (see Section 3.1), calibration and photomultiplier tube (PMT) radio-purity.

During five years of data taking the gain and stability of ~ 11,000 PMTs must be monitored at a 1% level. The detector response must be linear, and any non-linear effects must be monitored at a 1% level up to 3 – 4MeV (the region of interest for 0νββ). The absolute calibration system will use 207Bi sources (providing conversion electrons with single energies of 482keV and 976keV) inserted into the detector on a monthly basis. A UV-LED based light injection system is being developed for gain and linearity monitoring. Using low activity alpha sources embedded into the scintillator to monitor the gain is an additional possibility being studied. 60Co (providing two coincident γs of 1.1 and 1.3 MeV) will occasionally be used for absolute time calibration.

Specific to low background counting experiments ultra-pure materials must be used throughout the detector. One of the main sources of contamination comes from the PMTs, specifically from the cathode glass, which is closest to the active volume of the detector. The requirements for SuperNEMO have prompted development of low-background glass on a new scale and the collaboration is currently working closely with Hamamatsu to develop a radio-pure Barium salt free glass to reach the radio-purity requirements of the detector. Currently, the radioactivity limits reached with glass containing Barium salt are 40K < 0.6Bq/kg, 214Bi < 0.8Bq/kg and 208Tl < 0.06Bq/kg.

3.1. Energy Resolution

In order to achieve a sensitivity of 1026 years SuperNEMO's calorimeter requires an energy resolution of 7%√E(MeV) (or 4% FWHM at 3MeV (the Qββ of 82Se)). A high number of photoelectrons reduces the statistical error 1/√Npe and leads to optimisation of the energy resolution, which can be simplified into three experimental objectives as seen in Equation 3.
\[
\frac{N_{\text{ph}}}{E_e} \cdot \epsilon_{\text{col}}^{\text{light}} \cdot (Q\epsilon_{\text{PMT}}^{\text{PMT}} \cdot \epsilon_{\text{col}}^{\text{PMT}}) = N_{pe}
\]  

\(N_{\text{ph}}/E_e\) is the number of photons per unit energy and is determined by the scintillator light output. \(\epsilon_{\text{col}}^{\text{light}}\) is the light collection efficiency and depends on the material, surface treatment and geometry of the scintillator, the reflector material and its efficiency and the optical coupling quality (gels, light guides etc). The scintillator must be a low Z material to minimise back scattering of low energy electrons and has to have a coincidence time resolution of \(\sigma = 250\)ps at 1MeV, as well as be radio-pure and cost effective. These requirements have led to a choice of plastic scintillator.

Intrinsic characteristics of the PMT include the quantum efficiency (QE) of the photo-cathode \(Q\epsilon_{\text{PMT}}^{\text{PMT}}\), the collection efficiency \(\epsilon_{\text{col}}^{\text{PMT}}\) and, to a lesser extent, the gain of the first dynode.

Significant breakthroughs have been made with new bi-alkali photo-cathodes developed by Hamamatsu and Photonis with a QE in the range of \(35-43\%\) at the peak wavelength (compared to a previous QE of \(\sim 25\%\)) \[5][6]\.

4. Calorimeter Design, R\&D Setup and Measurements

Two possible designs for the calorimeter have been considered by the collaboration - the ‘baseline’ design, consisting of hexagonal 28cm diameter and 10cm minimum thickness polyvinyl-toluene (PVT) blocks and 8” PMTs (similar to that of NEMO3), and the ‘bar’ design, consisting of vertically placed 2m x 10cm x 2.5cm PVT bars and 3” PMTs at each end. The advantages of the block design are that a 7% FWHM at 1MeV energy resolution can be reached, good time resolution (250ps \(\sigma\) at 1MeV is anticipated) and the use of well understood technology from NEMO3 experience. 11,000 block + PMT units would be required for the full detector, which increases the cost and the number of channels (and hence potentially the radioactivity). The advantages of the bar design are more efficient \(\gamma\) tagging (enabled by the layered design of the detector) and the reduction in the number of bar + PMT units to 5,000 – 7,000, reducing the cost and the radioactivity. However, the 10% energy resolution and 400ps \(\sigma\) at 1 MeV time resolution achieved for the bar design do not meet the requirements of the SuperNEMO calorimeter. For this reason and due to the added difficulty of extrapolating the performance of the bar design to the full detector, the collaboration has chosen to focus on the baseline design.

4.1. Baseline Design R\&D Setup and Measurements

The energy resolution measurement is carried out by exciting the scintillator with a flux of electrons of known energy and then analysing the resulting distribution. The monochromatic source of electrons approximates the delta function and therefore any smearing of the distribution that is seen is due to the light collection properties of the scintillator and PMT.

Many different scintillator, reflector and PMT combinations have been studied. The scintillators studied were liquid (toluene based) from CENBG, INR, ISM and JINR labs (consisting of 0.5% PPO and 0.0025% POPOP), liquid and solid hybrids, solid polystyrene (PST) from ISM and JINR labs (consisting of 1.5% PTP and 0.0175% POPOP) and solid PVT from Bicron (BC404 and BC408) and Eljen (EJ204 and EJ200). The specular and diffusive reflectors under study included Teflon, kapton, aluminised Mylar and Enhanced Specular Reflector (ESR) from Vikulti and ReflecTech manufacturers. The three PMT competitors under study were Hamamatsu, Photonis and Electron Tubes Ltd. (ETL). Light-guide and optical gel studies to achieve the best optical contact between the scintillator and the PMT were also carried out.

Two different electron sources are used to measure the energy resolution. The first is a \(^{207}\)Bi source, which is easy to implement in an experimental set up as the 976keV K-shell conversion electron (CE) is used. However, as the fitting function for \(^{207}\)Bi needs to incorporate
a convolution of X-rays, $\gamma$s, L-shell and M-shell CEs the extraction of the energy resolution is complex. The second electron source is a $^{90}\text{Sr}$ $\beta$ beam passed through a magnetic field to select monochromatic $\beta$s of known energy. The spectrum obtained from the beam can easily be fitted with a Gaussian function, however is more difficult to set up. Both methods have been used to cross check the energy resolution measurements acquired and have been found to be consistent (as shown in Figure 3).

Figure 3: Two different fitting procedures for energy resolution acquisition using $^{207}\text{Bi}$ (left) and $^{90}\text{Sr}$ (right). The two methods are consistent with each other.

The target energy resolution of $\frac{7\%}{\sqrt{E(\text{MeV})}}$ has been achieved with a solid PVT scintillator (EJ200) of a hexagonal shape, with the PMT looking directly at the hemispherical entry face of the block (the removal of the light-guide from the set up brought the breakthrough in achieving the target energy resolution) with a combination of aluminised Mylar wrapping on the entrance face and Teflon wrapping on the sides of the scintillator. An unprecedented energy resolution of $\frac{6.7\%}{\sqrt{E(\text{MeV})}}$ has been achieved with an 8” high QE Photonis PMT, compared to that of $\frac{7.2\%}{\sqrt{E(\text{MeV})}}$ with an 8” high QE Hamamatsu PMT. However, Photonis announced a full stop to all R&D and production in 2009 and since then the collaboration has been working closely with Hamamatsu to improve the collection efficiency of the 8” high QE PMT to improve the energy resolution further.

5. Light Collection Simulations with GEANT4
Full calorimeter simulations have been carried out with the GENBB event generator in GEANT4. The model used accounts for wavelength dependence of optical properties (most of which have been experimentally measured) of scintillators (self absorption and re-emission), reflective wrappings, photomultipliers (QE), optical coupling materials and refractive indexes of optical materials. The simulations were verified using data from the currently running NEMO3 detector and were shown to be accurate [7].

A SuperNEMO calorimeter unit of a hexagonal PVT (e.g. EJ200) block of 22.5cm radius wrapped in aluminised Mylar (92% reflectivity coefficient) around the sides and entrance face of the scintillator and Teflon on the top face of the scintillator coupled to a super-bi-alkali 8” hemispherical PMT (e.g. Hamamatsu R5912-MOD) with a QE of 33% was simulated. Using the symmetry of the block, each sextant of the hexagonal face was divided into 16 regions to check the uniformity of the energy resolution across the face of the block. The minimum energy resolution extracted was $2.14\pm0.5\% \sqrt{E(\text{MeV})}$, the maximum: $7.24\pm0.5\% \sqrt{E(\text{MeV})}$ and the mean: $7.19\pm0.5\% \sqrt{E(\text{MeV})}$, showing uniformity of the block and agreement between simulations and test bench measurements.
6. Block Shape Study
Details of the block design are still to be finalised, such as the exact shape of the block to be used. The effect of block geometry on the energy resolution has been studied with a PST block, which was machined to a new geometry after each measurement. Although PVT scintillator has given the best result a PST block was chosen for this study due to ease of availability and manufacturing. A study with a PVT block is currently under way.

All of the measurements were carried out under the same conditions with aluminised Mylar wrapping on the entrance face and Teflon wrapping on the sides of the block, an 8" Photonis standard QE (25%) PMT run at the same high voltage and alcohol to couple the block to the PMT. The source of electrons used was a 1MeV $^{90}$Sr spectrometer beam injected at the centre of the entrance face. The block shapes studied can be seen in Figure 4 and the summary of the results in Table 2. The shape that will be chosen will be 4 or 5, depending on ease of manufacturing and cost.

![Figure 4: Block shapes studied.](image)

| Shape | FWHM (Measured) | FWHM (Simulated) |
|-------|-----------------|------------------|
| #1    | 10.0%           | 10.1 ± 0.1%      |
| #2    | 9.6%            | 9.9 ± 0.1%       |
| #3    | 9.5%            | 9.5 ± 0.1%       |
| #4    | 9.3%            | 9.3 ± 0.1%       |
| #5    | 8.9%            | 8.8 ± 0.1%       |
| #6    | 8.8%            | 8.6 ± 0.1%       |

7. Conclusions and Future Plans
After three years of fruitful R&D an unprecedented energy resolution has been reached for low energy electrons in large volume low Z scintillators. The design energy resolution for the baseline (block) design has been reached at $\frac{7\%}{\sqrt{E(\text{MeV})}}$, as well as the design resolution for the bar design at $\frac{10\%}{\sqrt{E(\text{MeV})}}$. This is an increase of a factor of 2 in size from a NEMO3 block and an energy resolution improvement of a factor of 2. The baseline design has been chosen by the collaboration and the final details (such as the block shape) are close to being completed.

The first SuperNEMO module, known as the ‘demonstrator’, will begin construction in 2010−2011 and will be running with 7kg of $^{82}$Se in 2013. The demonstrator sensitivity will reach a Majorana neutrino mass of $200-500\text{meV}$. Full detector construction will begin in 2014 with physics running from 2014−2019 and a target sensitivity of $50-100\text{meV}$.

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