Calorimeter R&D for the SuperNEMO Double Beta Decay Experiment

Robert Flack - on behalf of the SuperNEMO Collaboration[a]

[a] *Dept. Physics and Astronomy*
University College London
Gower Street
London, UK
WC1E 6BT

Abstract

SuperNEMO is a next-generation double beta decay experiment based on the successful tracking plus calorimetry technology of the NEMO 3 experiment currently running in the Modane Underground Laboratory. The baseline design uses ^{82}Se as the source. A sensitivity to a $0\nu\beta\beta$ half-life greater than 10^{26} years can be reached giving access to Majorana neutrino masses of 50–100 meV. SuperNEMO sensitivity is dependent upon the calorimeter parameters such as energy and time resolution, radio-purity and aging. One of the main challenges of the SuperNEMO project is the development of the calorimeter. This calls for an unprecedented energy resolution for plastic scintillators of 4% FWHM at 3 MeV ($Q_{\beta\beta}$ value of ^{82}Se) and radio-purity. The collaboration is carrying out a broad R&D programme focusing on the development of liquid and solid scintillators and ultralow radioactive highly efficient photo-detectors. Extensive laboratory measurements are complimented by the most up-to-date Monte Carlo optical simulations using GEANT4. In parallel an alternative design for SuperNEMO using 2 m scintillator bars as the calorimeter is being investigated and is also discussed.

Key words:
double beta decay, Majorana neutrino, calorimeter, scintillator bars

1. Introduction

The recent observation of neutrino oscillations and the resulting measurements of the neutrino mass differences has motivated the development of experiments to measure the absolute neutrino mass. Neutrinoless double beta decay ($0\nu\beta\beta$) is the only practical way to understand the nature of neutrino mass and one of the most sensitive probes of its absolute value. Ettore Majorana proposed that neutrinos could be their own anti-particles [1], and this lead to Furry's conclusion [2] that neutrinoless double beta decay is possible via neutrino exchange if the neutrinos are Majorana particles and have non-zero mass.

The effective Majorana neutrino mass $\langle m_{\beta\beta}\rangle$ is proportional to the square root of the $0\nu\beta\beta$ decay half-life $T^{0\nu}_{1/2}$ in equation (1), where $G^{0\nu}$ is the kinematic phase-space factor and $M_{0\nu}$ is the nuclear matrix element. The experimental signature of $0\nu\beta\beta$ is two electrons with the energy sum equaling the $Q_{\beta\beta}$ of the decay. There are other mechanisms to explain neutrinoless double beta decay [4], but the above mechanism is the most favored due to the minimal required modifications to the Standard Model.

$$[T^{0\nu}_{1/2}]^{-1} = G^{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2 \tag{1}$$

The SuperNEMO collaboration comprises over 90 physicists from 12 countries. The baseline design consists of 20 modules ($\sim 4\times5\times2$ m), each holding 5 kg of source isotope. Both sides of the source foil have nine layers of Geiger mode drift cells forming the tracker and is enclosed by the calorimeter walls. Each module will hold ∼600 8″ photo-multiplier tubes (PMT). It is based on the successful tracking plus calorimetry technology of the NEMO 3 experiment [3] currently running in the Modane Underground Laboratory. A three year R&D program which has covered all aspects of the experiment. The four main areas of study has been isotope enrichment, tracking detector, calorimeter and ultra-low background materials production and measurements. This paper focuses on the calorimeter and is divided into three parts: energy and time resolution studies, calibration and PMT radio-purity.

2. Calorimeter R&D

Good energy resolution is a powerful background rejection tool and the only way to separate the $0\nu\beta\beta$ signal peak from the tail of the standard model double beta decay process with two electrons and two neutrinos in the final

*Corresponding author. Tel.: +44 (0)207 679 3425; fax: +44 (0)207 679 7145.
Email address: `robflack@hep.ucl.ac.uk` (Robert Flack - on behalf of the SuperNEMO Collaboration)

state ($2\nu\beta\beta$) as shown in figure 1. SuperNEMO aims to reach an energy resolution of 7-8%$\sqrt{\mathrm{E\,(MeV)}}$ (FWHM). This is a formidable task for low energy electrons in the MeV range because factors such as backscattering and energy losses through multiple scattering play a significant role.

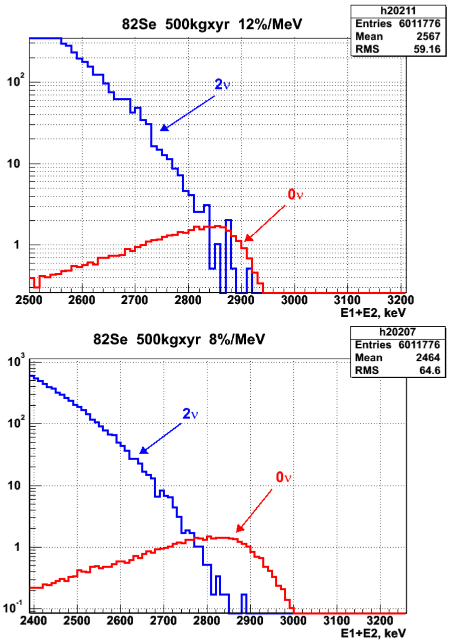

Figure 1: Simulations for 500 kg·yr ^{82}Se. The $0\nu\beta\beta$ half-life (RED) is normalized to 10^{26} years. Expectations for energy resolutions 12% (left) and 8% (right) $\frac{\Delta E}{E}$ FWHM at 1 MeV.

Optimization of the energy resolution is the result of a high number of photo-electrons which reduces the statistical error $1/\sqrt{N_{pe}}$. This can be simplified into three experimental objectives which are described by equation (2).

$$\frac{N_{ph}}{E_e} \cdot \varepsilon_{col}^{light} \cdot \left(QE^{PMT} \cdot \varepsilon_{col}^{PMT}\right) = N_{pe} \tag{2}$$

N_{ph}/E_e is the number of photons per unit energy and is determined by the scintillator light output. The light collection efficiency, $\varepsilon_{col}^{light}$, depends upon the characteristics of the calorimeter components such as the scintillator geometry, transparency, reflector efficiency and the quality of the optical coupling. Intrinsic characteristics of the PMT include the quantum efficiency of the photo-cathode QE^{PMT}, and the cathode to first dynode collection efficiency ε_{col}^{PMT}.

Assuming the energy resolution of the scintillator detector is mainly determined by the photon statistics the resolution can be expressed in terms of the number of collected photo-electrons given in equation 3.

$$\frac{\Delta E}{E} = \frac{FWHM}{E} = \frac{2.35\sigma}{E} = \frac{2.35}{\sqrt{N_{pe}}} \tag{3}$$

The scintillator must be a low Z material to minimize backscattering electrons and has to have a good timing resolution (a coincidence time resolution of $\sigma \leq 400$ ps at 1 MeV is required). It has to be cost effective and radiopure. These requirements essentially rule out many popular non-organic scintillator, such as NaI(Tl), CsI(Tl) and CaF_2(Eu), which would otherwise provide a good energy resolution due to their high light output. The choice of reflective material is also limited to low density reflectors to reduce electron energy loss through the material.

The collaboration has carried out a large number of tests studying the scintillator material, mineral, plastic and liquid, and the shape, size and coating of the calorimeter blocks. Many different scintillator, reflector, and PMT combinations were studied. Solid scintillator candidates included polystyrene (PST) based scintillators from ISM and JINR labs (1.5% PTP, 0.0175% POPOP) and polyvinyltoluene (PVT) based scintillators from the manufacturers Bicron (BC404, BC408) and Eljen (EJ204, EJ200). Liquid scintillators are toluene based and from CENBG, INR, ISM, and JINR labs (0.5% PPO, 0.0025% POPOP). Various specular and diffusive reflectors being tested include: Teflon, Kapton, Aluminized Mylar, and Enhanced Specular Reflector (ESR) from the Vikuiti and ReflechTech manufactures. Exceptional 6.5% resolutions have been obtained for small (5x5cm) blocks of polyvinyltoluene (PVT)[5]. The collaboration has reached an important milestone with the energy resolution: 7.1% with a large (25cm) ELJEN-200 PVT scintillator block coupled to a Photonis 8″ PMT and 7.6% using the same scitillator and a Hamamatsu 8″ PMT. This is the best resolution reached for a plastic scintillator detector of this size. Therefore this is the option chosen for the baseline design and all others have been discarded

There has been a significant breakthrough in the development of new high QE PMTs based on bi-alkali photocathodes by Hamamatsu and Photonis. The SuperNEMO group is working very closely with PMT manufacturers on characterizing these new photo-detectors which now have a QE in the range of 35–43% at the peak wavelength (to be compared with more usual ∼25% QE). As with all PMT based calorimeters, the stability of the gain and the linearity must be both intrinsically good and experimentally well understood to ensure the accurate reconstruction of data. The PMTs are one of the main sources of contamination with emphasis on the purity of the glass which is closest to the active volume of the detector. The Barium salt used to make conventional glass is chemically the same as Radium, and therefore very difficult to purify during production. Photonis has provided preliminary samples of their new ultra-pure glass that has met R&D requirements.

3. Experimental Setup

The energy resolution measurement was carried out by exciting the scintillator under test with a flux of electrons of known energy and then analyzing the resulting distribution. The mono-chromatic source of electrons approximates the delta function and therefore any smearing of the distribution is due to the light collection of the scintillator and PMT under study. The test setup can be broken into three subcategories: the calorimeter block (scintillator + reflector + PMT), the electron source, and the data acquisition (DAQ).

There are two methods used to obtain a mono-chromatic source of electrons. The first method is simplest to implement using the K-shell 976 keV conversion electrons (CE) from a ^{207}Bi source. The drawback to this method is that the fitting function needs to incorporate the convolution of additional x-rays, gammas, L-shell and M-shell conversion electrons. The second method is more involved to set up, but in principle leaves a spectrum that can be easily fit with a Gaussian function. The β emission from a highly active ^{90}Sr source is passed through a magnetic field so that β's of a particular energy can be selected. For the energy resolution measurements, 1 MeV electrons are used.

Data acquisition is accomplished with a gated charge to digital converter (QDC). The PMT signal is split in two, half the signal is used for triggering of the electronics and generating the gate signal for the QDC, the other half of signal goes directly to the QDC after some passive delay to match the timing of the electronics. In the method of the ^{207}Bi source, three different data runs must be taken to obtain a pedestal, an energy spectrum of just the gammas (achieved by shielding out the electrons with 2 mm of Aluminum) and the energy spectrum of the gammas + CEs. The Compton edges from the gamma distribution are sufficiently described by a modified Heaviside step-function. The free parameters of the gamma distribution are determined and then fixed while the gamma + CEs distribution is fit. The CEs are a sum of three Gaussian distributions from the K, L, and M shells Fig:2.

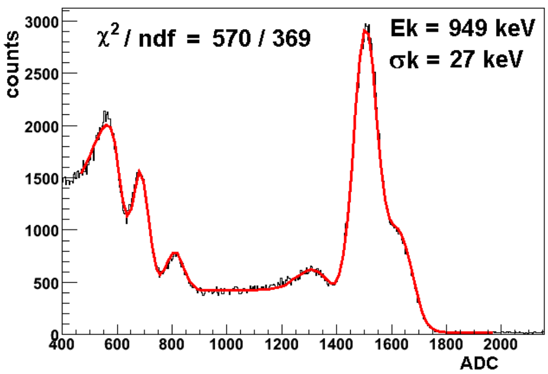

Figure 2: The fit to data (RED line) results in 6.5% FWHM at 1 MeV.

4. Long Bar Scintillator Measurements

An alternative to the baseline design has been proposed and is being investigated. In this configuration two metre long scintillator bars, with a 3″ PMT coupled to each end of the bar, span the volume of the tracker. This arrangement has several advantages; the number of channels is greatly reduced, the PMTs are exterior to the man detector volume and the source foil is thinner, 20mg/cm^2 rather than 40mg/cm^2, as in the baseline design. Less channels makes it cheaper because of the drastically reduced number of PMTs. Moreover, due to a significantly reduced mass of PMT glass and their relatively remote locations from the detector fiducial volume, the bar design should have a much lower background from PMTs which is one of the main background sources in SuperNEMO.

A resolution of 7% at 1 MeV is probably impossible to reach with two metre bars. Thus the crucial question for feasibility of this design is whether a better background rejection and higher detection efficiency compensate for a worse energy resolution. Estimates show that it might be a valid option if a resolution of 10–11% is achievable with the bars especially with the thinner source foil. This resolution has been achieved in a test bench with 2 m long Eljen plastic scintillator bars coupled to two 3″ high QE Hamamatsu PMTs.

5. Conclusion

The calorimeter R&D programme for SuperNEMO has been very successful and the required resolution of 4% at 3 MeV has been achieved. The method adopted for the baseline design is a hexagonal PVT scintillator block optically coupled to a high QE 8 ″ PMT. An alternative design using 2m scintillator bars has been investigated and this work is still ongoing.

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