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Investigation of Double Beta Decay in NEMO-3/SuperNEMO Experiment

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Abstract. The NEMO-3 experiment is searching for neutrinoless double beta decay. The experiment has been taking data since 2003 with seven isotopes decaying via double beta decay. Data up to the end of 2008 show no evidence for neutrinoless double beta decay which permits setting at the 90% CL, limits on the transition half-live times: $T_{1/2}^{0\nu} > 5.8\times10^{23}$ y for ^{100}Mo and $T_{1/2}^{0\nu} > 2.1\times10^{23}$ y for ^{82}Se. NEMO-3 also measures two-neutrino double beta decays for other isotopes and has reached the highest precision measurements to date. The SuperNEMO project aims to extend the NEMO technique to a 100 – 200 kg isotope experiment with the target half-life sensitivity of $1 - 2 \times 10^{26}$ y. The current status of the SuperNEMO R&D programme is described, focusing mainly on the calorimeter R&D.

Introduction

Experimental search for the neutrinoless double beta decay (0νββ) is of major importance in particle physics because if observed it will reveal the Majorana nature of the neutrino and may allow an access to the absolute neutrino mass scale. The 0νββ decay violates the lepton number and is therefore a direct probe for the physics beyond the standard model. The existence of this process may be related to right-handed currents in electroweak interactions, supersymmetric particles with R-parity nonconservation, and massless Goldstone bosons, such as majorons.

The spontaneous two-neutrino double beta decay (2νββ) is a rare second-order weak interaction process. It is the testing ground for nuclear models and provides a valuable input for the theoretical calculations of the 0νββ decay nuclear matrix elements (NME).

The currently running NEMO-3 experiment is devoted to the search for 0νββ decay and to the accurate measurement of two neutrino double beta decay (2νββ decay) by means of the direct detection of the two electrons. This tracking experiment, in contrast to experiments with ^{76}Ge, detects not only the total energy deposition, but also the other parameters of the process. These include the energy of the individual electrons, angle between them, and the coordinates of the event in the source plane. Since June of 2002, the NEMO-3 detector has operated in the Fréjus Underground Laboratory

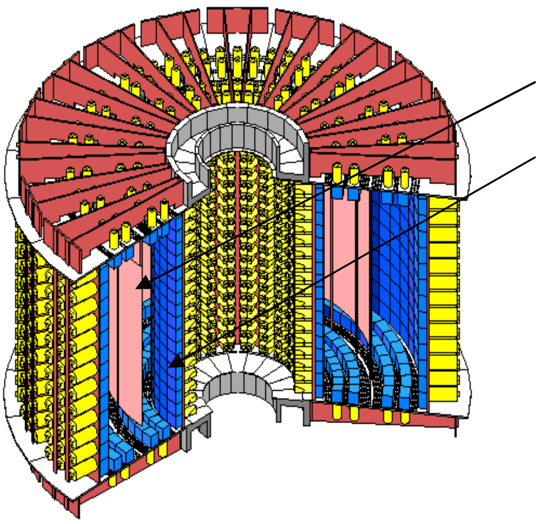

Figure 1a. NEMO-3 detector

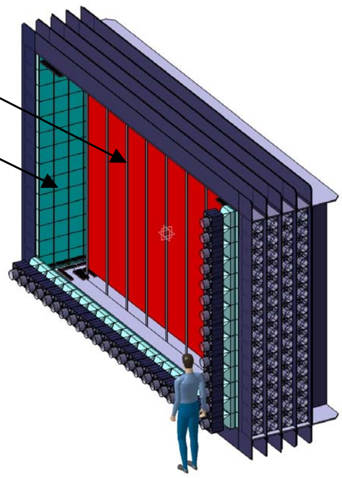

Figure 1b. SuperNEMO module.

(France) located at a depth of 4800 m of water equivalent. Since February 2003, after the final tuning of the experimental set-up, NEMO-3 has been taking data devoted to double beta decay studies. The first obtained results with ^{100}Mo, ^{82}Se, ^{150}Nd and ^{96}Zr were published in [1–6]. The SuperNEMO collaboration has started a Research & Development phase in February 2006 to design a NEMO-3 successor. The goal is to improve the sensitivity on $T_{1/2}^{0\nu}$ by two orders of magnitude, probing the region of ~ 50 meV effective neutrino mass.

Table 1. ββ isotopes installed in NEMO-3 and results for 2νββ decay half-life measurement.

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	$T_{1/2}^{2\nu}$ (y)	S/B
^{100}Mo	6914	3034	[7.11±0.02(stat) ±0.54(syst)]×10^{18}	40
^{82}Se	932	2995	[9.6±0.3(stat) ±1.0(syst)]×10^{19}	4.0
^{150}Nd	37.0	3367	[$9.11^{+0.25}_{-0.22}$ (stat) ±0.63(syst)]×10^{18}	2.8
^{130}Te	454	2529	[7.6±1.5(stat) ±0.8(syst)]×10^{20}	0.25
^{116}Cd	405	2805	[2.8±0.1(stat) ±0.3(syst)]×10^{19}	7.5
^{96}Zr	9.4	3350	[2.3±0.2(stat) ±0.3(syst)]×10^{19}	1.0
^{48}Ca	7.0	4272	[$4.4^{+0.5}_{-0.4}$ (stat) ±0.4(syst)]×10^{19}	6.8

NEMO-3 detector

The NEMO 3 detector is located in the Modane underground laboratory (LSM) in the Fréjus tunnel in France at the depth of 4800 m w.e. The set-up is cylindrical in design; it is divided into twenty equal sectors and combines two detection techniques – particle identification provided by a wire tracking chamber and energy and time measurements of particles with a calorimeter (Figure 1a). Thus, NEMO-3 is able to identify e^-, e^+, photons, and α-particles which allow the recognition of different ββ decay modes, measurement of internal and external backgrounds, as well as good discrimination between signal and background.

The tracking detector is made of 6180 open octagonal drift cells operated in Geiger mode and provides a three-dimensional measurement of the charged particle tracks by recording the drift time and the two plasma propagation times. The calorimeter, which surrounds the wire chamber, consists of 1940 plastic scintillators coupled to very low-radioactivity PMTs and gives an energy resolution of (14−17)%/√E FWHM at 1 MeV and the time resolution of 250 ps. Seventeen sectors of NEMO-3 accommodate almost 10 kg of enriched ββ isotopes (see Table 1) in the form of thin foils. Three sectors are also used for external background measurement and are equipped with purified Cu and natural Te, so they are effectively void of internal backgrounds. These isotopes permit one to study the background near 3 MeV. The detector is surrounded by a solenoidal coil generating magnetic field of 25 Gauss for the e^-/e^+ recognition, and is covered by shielding against external γ-rays and neutrons. More information about NEMO-3 detector design can be found in [1].

Event selection and background

A candidate for a ββ decay is a two-electron event which is selected by requiring two reconstructed tracks with a curvature corresponding to the negative charge and coming from the same vertex in the source foils. Each track has to be associated with a fired scintillator, energy of each electron measured in the calorimeter should be higher than 200 keV and the time-of-flight has to correspond to the case of two electrons emitted at the same time from the common vertex in the foils.

0νββ signal is obtained after subtracting background events from the measured data. For that purpose complete study of background in the 0νββ channel has been performed. The level of each background component has been directly measured from data using different analysis channels. The background can be classified in three groups: 1) internal radioactive contamination of the source, 2) external background from incoming γ-rays and 3) radon inside the tracking volume. The dominant background during the first running period from February 2003 to September 2004 (Phase I) was due to radon diffusion into the wire chamber through tiny air leaks. The radon level inside NEMO-3 during the second running period after installation of the radon trapping facility in November 2004

(Phase II) has been reduced by a factor of ten. Remaining low radon activity inside NEMO-3 is due to detector component degassing [1].

Table 2. NEMO-3 results: 0νββ decay half life limits at 90% C.L.

Isotope	0νββ mode	$T_{1/2}^{0\nu}$, $\langle m_\nu \rangle$
^{100}Mo	(V – A)	> 5.8 × 10^{23} y, $\langle m_\nu \rangle$ < 0.8 – 1.3 eV
	(V + A)	> 3.2 × 10^{23} y
^{82}Se	(V – A)	> 2.1 × 10^{23} y, $\langle m_\nu \rangle$ < 1.4 – 2.2 eV
	(V + A)	> 3.2 × 10^{23} y
^{150}Nd	(V – A)	> 1.80 × 10^{22} y, $\langle m_\nu \rangle$ < 3.7 – 5.1 eV
	(V + A)	> 1.07 × 10^{22} y
^{96}Zr	(V – A)	> 8.6 × 10^{22} y, $\langle m_\nu \rangle$ < 7.4 – 20.1 eV
^{48}Ca	(V – A)	> 1.3 × 10^{22} y, $\langle m_\nu \rangle$ < 29.6 eV

NEMO-3 results

Measurements of the 2νββ decay half-lives have been performed for all the seven ββ isotopes in NEMO-3. The obtained half-lives are given in Table 1. No evidence was found for the 0νββ decay of ^{100}Mo, ^{82}Se, ^{150}Nd, ^{96}Zr, and ^{48}Ca. The 0νββ decay half-life limits and limits on the effective Majorana neutrino mass $\langle m_\nu \rangle$ have been derived and are summarised in Table 2 [9].

SuperNEMO detector design

SuperNEMO aims to extend and improve the experimental techniques used by the current NEMO-3 experiment in order to search for 0νββ decay with a target half-life sensitivity of 1− 2 × 10^{26} year, which corresponds to the effective neutrino mass sensitivity $\langle m_\nu \rangle$ of 40 − 100 meV, depending on nuclear matrix elements (NME) used. The SuperNEMO project is a ~ 100 − 200 kg source experiment and is currently in a three year design study and R&D phase.

Like NEMO-3, SuperNEMO will combine calorimetry and tracking. This technological choice allows the measurement of individual electron tracks, event vertices, energies and time-of-flight, and thus provides the full reconstruction of kinematics and topology of an event. SuperNEMO will consist of about twenty identical modules (Figure 1b), each housing around 5 – 7 kg of isotope in the form of thin foil (~ 40 mg/cm^2). The tracking volume contains more than 2000 wire drift cells operated in Geiger mode (Geiger cells), which are arranged in nine layers parallel to the foil. The calorimeter is divided into ~ 1000 blocks, which cover most of the detector outer area and are read out by low background PMTs [10].

SuperNEMO R&D

The R&D programme focuses on four main areas of study: (i) isotope enrichment, (ii) tracking detector, (iii) ultra-low background materials and measurements, and (iv) calorimeter.

The main candidate ββ isotopes for SuperNEMO are ^{82}Se and ^{150}Nd. A sample of 4 kg of ^{82}Se has been enriched and is currently undergoing purification. The SuperNEMO collaboration is investigating the possibility of enriching large amounts of ^{150}Nd via the atomic vapour laser isotope separation (AVLIS) method [11].

The tracking detector design study has for its goal the optimisation of the wire chamber parameters to obtain high efficiency and resolution in measuring the trajectories of electrons from ββ decay, as well as of γ-particles for the background rejection. The first 9-cell prototype was successfully operated demonstrating propagation efficiency close to 100% over a wide range of voltages [10]. Recently, a 90-cell prototype has been set in operation.

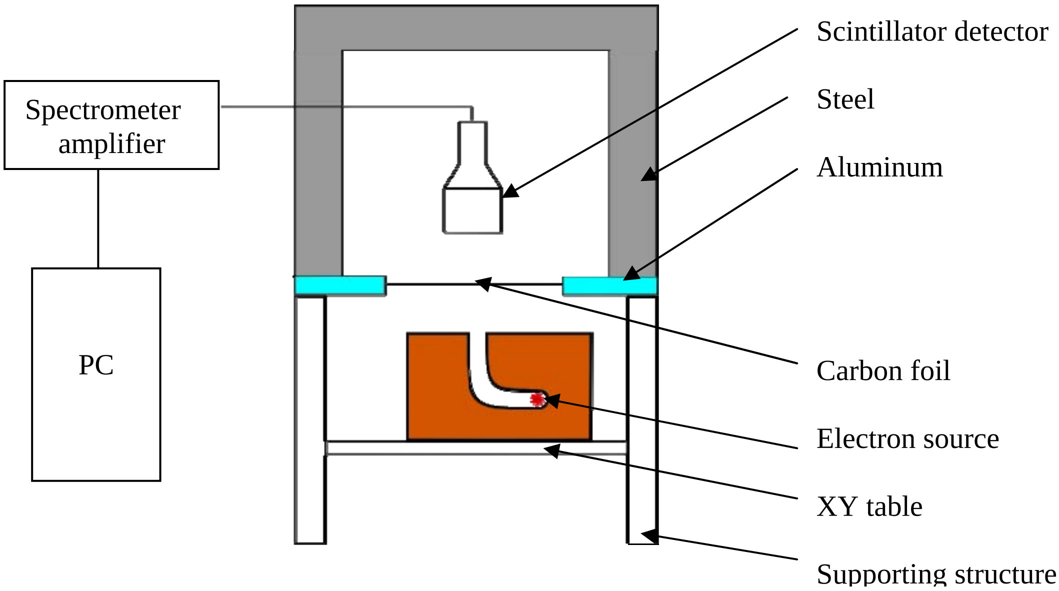

Figure 3. Schematic view of the setup for routine scintillator tests

In order to reach the required sensitivity, SuperNEMO has to maintain ultra-low levels of background (one order of magnitude lower than for NEMO-3), which implies, that the contamination of sources has to be less than 2 μBq/kg for ^{208}Tl and less than 10 μBq/kg for ^{214}Bi. In order to evaluate these activities, a dedicated BiPo detector is being developed. Its first version, BiPo1, reached the background level of < 7.5 μBq/kg for ^{208}Tl (90% C.L.) [7]. Current version (BiPo3) is being developed.

SuperNEMO aims to improve the calorimeter energy resolution to 7%/√E FWHM at 1 MeV. To reach this goal, several studies were performed to investigate the choice of calorimeter parameters such as scintillator material (plastic or liquid), the shape, size and coating of calorimeter blocks [8]. These are combined with dedicated development of PMTs with very low radioactivity and high quantum efficiency.

Setup for routine tests of scintillators

For the SuperNEMO detectors, a large amount of scintillators will have to be tested before installing. The setup for such tests was developed and built in Prague, based on the experience of the collaborators in Bordeaux, France. The setup consists of (i) the steel lightproof black box, with dimensions 100 × 130 × 130 cm^3, (ii) movable XY table with the range 40 × 40 mm^2 and step 25 μm, able to carry up to 100 kg weight, (iii) spectrometer amplifier, (iv) ADC PC card and (v) supporting structure, carrying the black box, XY table and a possible source of monochromatic energy electrons (^{90}Sr), where the electrons with the particular energy may be chosen by applying a magnetic field with variable strength. The setup is designed so that the source is situated below the black box (Figure 3). For this reason the bottom of the black box is made from aluminium with the 40 × 40 cm^2 window, which is covered with thin (12 μm) carbon foil.

In order to ensure the correct functioning of all the constituents of the setup, two functionality tests have been performed with plastic scintillator 50×50×20 mm^3 with Teflon side wrapping and aluminium mylar on the entrance face, Photonis XP5312 3″ photomultiplier, 160kBq ^{207}Bi electron and gamma source placed on the XY table and 80×80×45 mm^3 lead collimator with 5 mm radius hole and movable aluminium filter, which absorbs electrons and leaves gammas (Figure 4).

Position of the detector

The first functionality test was the position scan of the scintillator detector. The scan was performed in X and Y directions with the step of 2 mm, irradiating each point for one minute. In the

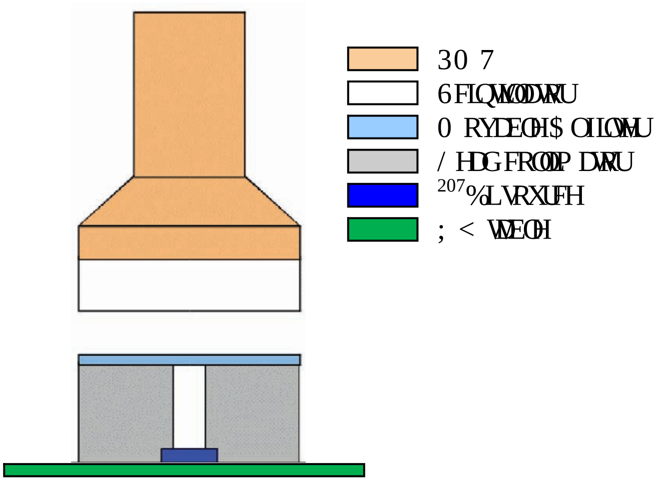

Figure 4. $ UUDQJHP HQW RI WKH IXQFWLRQDOLW\ WHVW

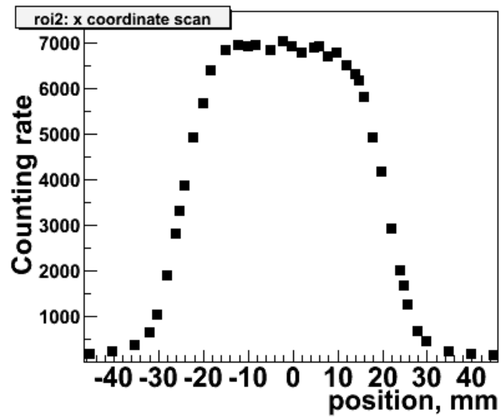

Figure 5. ; SRVLWLRQ VFDQ RI WKH GHWHFWRU

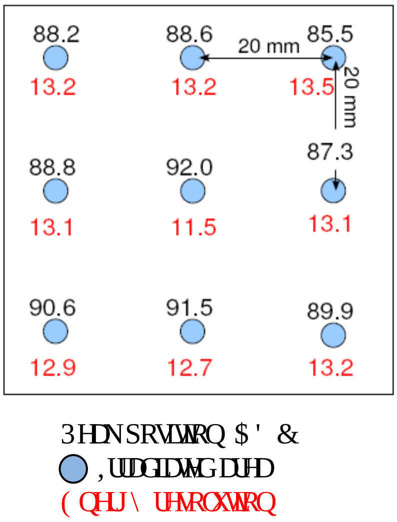

Figure 6. (QHUJ\ UHVROXWLRQ VFDQ

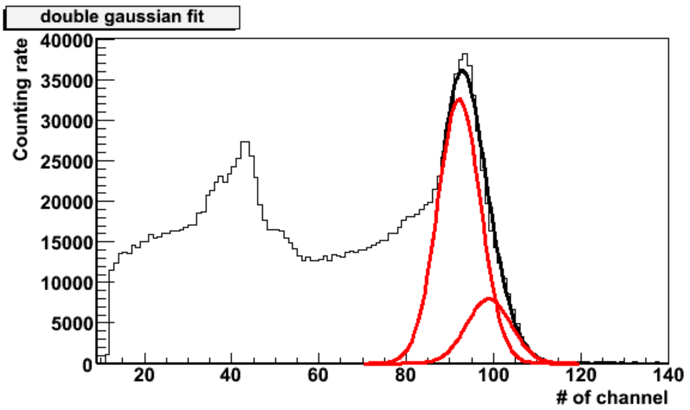

Figure 7. ' RXEOH * DXVVLDQ ILW RI WKH VHFRQG SHDN LQ 207%L HQHUJ\ VSHFWUXP

P HDVXUHG HQHUJ\ VSHFWUXP RQH UHJLRQ ZDV FKRVHQ WKH VHFRQG JURXS RI SHDNV RI WKH FRQYHUVLRQ HOHFWURQV) LJXUH DQG WKH QXP EHU RI FRXQWV LQ WKLV UHJLRQ ZDV UHFRUGHG IRU HDFK SRLQW) LJXUH VKRZ V WKH ; SRVLWLRQ VFDQ : H P D\ VHH WKDW WKH SRVLWLRQ RI WKH GHWHFWRU FDQ EH HDVLO\ GHWHUP LQHG IURP WKLV VFDQ

Energy resolution

7 KH VHFRQG WHVW ZDV GHYRWHG IRU WKH HQHUJ\ UHVROXWLRQ RI WKH GHWHFWRU : LWK WKH KHOS RI WKH OHDG FROOLP DWRU QLQH DUHDV ZLWK WKH ≈ P P GLDP HWHU DQG P P IURP HDFK RWKHU¶V FHQWUH ZHUH LUUDGLDWHG IRU ILYH P LQXWHV HDFK DV LW LV GHSLFWHG LQ WKH) LJXUH) RU HDFK LUUDGLDWHG DUHD HQHUJ\ VSHFWUXP ZDV P HDVXUHG DQG WKH GRXEOH * DXVVLDQ ILW ZDV SHUIRUP HG LQ RUGHU WR GHWHUP LQH WKH HQHUJ\ UHVROXWLRQ) LJXUH 7 KH SHDN SRVLWLRQ ZDV GHWHUP LQHG LQ $' & XQLWV DV ZHOO 7 KH EHVW YDOXH RI WKH HQHUJ\ UHVROXWLRQ ZDV REWDLQHG LQ WKH FHQWUH RI WKH GHWHFWRU DV LW ZDV H[SHFWHG EHIRUHKDQG

Conclusion

7 KH 1 (0 2 GHWHFWRU KDV EHHQ URXWLQHO\ WDNLQJ GDWD VLQFH 7 KH νββ GHFD\ KDOI OLYHV RI VHYHQ LVRWRSHV KDYH EHHQ P HDVXUHG ZLWK KLJK VWDWLVWLFV DQG ZLWK D JRRG SUHFLVLRQ $T^{2\nu}$ (100 0 R > " VWDW " V\VW@ 18 \ $T^{2\nu}$ (82 6H > " VWDW " V\VW@ \ YDOXHV IRU RWKHU

isotopes can be found in Table 1). For the 0νββ decay, limits for the $T_{1/2}$ and $\langle m_\nu \rangle$ have been set: $T_{1/2}^{0\nu}$ (^{100}Mo) > 5.8 × 10^{23} y, $\langle m_\nu \rangle$ < 0.8 – 1.3 eV and $T_{1/2}^{0\nu}$ (^{82}Se) > 2.1 × 10^{23} y, $\langle m_\nu \rangle$ < 1.4 – 2.2 eV (values for other isotopes can be found in Table 2). The next generation experiment SuperNEMO, which is currently in R&D stage, will extrapolate the NEMO technique of calorimetry plus tracking to 100 – 200 kg of ββ isotope scale experiment. Preparations for the calorimeter are being done and the setup for routine tests of the scintillators was designed and built. The detector position scan shows that we can reliably determine the position of the detector from the detector's response to the ^{207}Bi radiation. The best value of energy resolution obtained with the test scintillator is in the center of it and is 11.5%. Approaching the edge the energy resolution grows worse (12.7% – 13.5%). The functionality tests show that the setup is working reliably and is ready for the routine tests.

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