The NEMO-3 results after completion of data taking

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Abstract. The double beta decay experiment NEMO-3 has compleated data taking in January 2011. The aim of the experiment is to search for the neutrinoless double beta decay and investigate the two-neutrino double beta decay in seven different isotopes (^{100}Mo, ^{82}Se, ^{116}Cd, ^{150}Nd, ^{96}Zr,^{48}Ca and ^{130}Te). After analysis of the most part of available data corresponding to 4.5 yr no evidence for $0\nu\beta\beta$ decay in ^{100}Mo and ^{82}Se is found. The half-life limits at 90% C.L. are 1.0×10^{24} yr and 3.2×10^{23} yr respectively. The two-neutrino decay half live values were precisely measured for all investigated isotopes.

1. Introduction

Experimental search for the neutrinoless double beta decay ($0\nu\beta\beta$)

$$(A, Z) \rightarrow (A, Z-2) + 2e^- \qquad (1)$$

is the only feasible way to establish the charge-conjugation property of neutrino. This process supposes the violation of the total lepton number by two and is possible only if neutrino is Majorana particle ($\nu \equiv \bar{\nu}$). Its decay rate can be written as

$$[T^{0\nu}_{1/2}(A,Z)]^{-1} = \langle m_\nu \rangle^2 \cdot |M^{0\nu}(A,Z)|^2 \cdot G^{0\nu}(Q_{\beta\beta}, Z), \qquad (2)$$

where $\langle m_\nu \rangle$ is the effective neutrino mass, $M^{0\nu}$ is the nuclear matrix element (NME) and $G^{0\nu}$ is the kinematical factor proportional to the transition energy to the fifth power, $Q^5_{\beta\beta}$. So an observation of $0\nu\beta\beta$ decay would also allow to measure the absolute neutrino mass value.

The two-neutrino double beta decay ($2\nu\beta\beta$) is a rare second-order weak interaction process. The measurement of $2\nu\beta\beta$ is important since it constitutes the ultimate background in the search for $0\nu\beta\beta$ decay signal and provifes a valuable input for the theoretical calculations of the NME.

2. The NEMO-3 experiment

The objective of the NEMO 3 experiment is the search for the $0\nu\beta\beta$ decay and investigation of the $2\nu\beta\beta$ decay. Its method is based on the detection of electrons in the tracking device and the energy measurement in calorimeter. The NEMO-3 detector (see Fig. 1) has a cylindrical shape and is composed of twenty equal sectors. It contains almost 9 kg of 7 different $\beta\beta$ isotopes in the form of thin ($\sim$50 mg/cm^2) source foils located vertically in the middle of tracking volume surrounded by a calorimeter. The tracking chamber is made of 6180 open octagonal drift cells

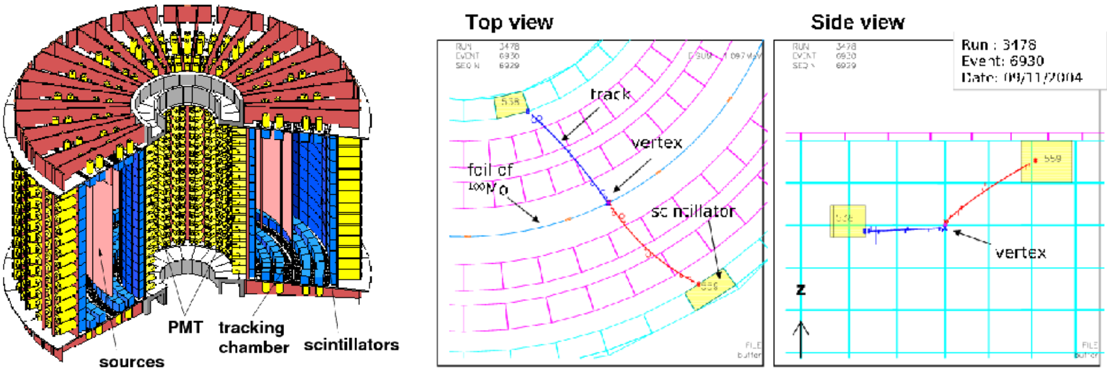

Figure 1. On the left side: schematical view of the NEMO-3 detector without shielding. On the right side: example of an event candidate from two-neutrino double beta decay of ^{100}Mo.

operating in Geiger mode. The position resolution for tracking is 0.6 mm in the horizontal plane and 0.8 cm in the vertical direction. The calorimeter comprises 1940 plastic scintillator blocks coupled to low radioac- tivity photomultipliers (PMT). For 1 MeV electrons the timing resolution is 250 ps and the energy resolution (full width at half maximum) is about 15%. A 25 Gauss magnetic field is used for electron-positron discrimination by the track curvature. The detector is shielded from external gamma rays by 18cm of low activity iron and against neutrons by 30cm of borated water. A full descriprion of the detector and its characteristics can be found in [2].

The detector is capable of identifying e^-, e^+, γ and α particles and allows a good discrimination between signal and background events. The full event kinematics reconstruction available with the NEMO 3 track-calorimetric approach is useful for the study of the underlying $\beta\beta$ decay mechanism.

The detector was operating in the Modane undeground laboratory located in the Frejus tunnel at depth of 4800 m w.e. The data taking started in February 2003 is compleated in January 2011. In total 1.15×10^9 events have been triggered in 6391 runs dedicated to $\beta\beta$ decay study during 6.1 yr of effective data taking.

A typical double beta decay candidate is shown in Fig. 1. Events are selected requiring two reconstructed electron tracks originating from the common vertex in the source foil. The cut on the minimal energy deposited by each electron in calorimeter of 200 keV is used.

The background can be classified in three groups: internal, from radioactive contamination of the source external, from incoming γ-rays and from the tracking volume principally due to the radon. All three were measured with the NEMO-3 data [3]. Initially the radon activity in the volume of tracking chamber of ~1 Bq was observed. It has been successfully reduced by a factor of ~6 after installation of a radon trapping facility in October 2004. Consequently the data is subdivided in two parts: Phase-1 and Phase-2, before and after October 2004.

3. Measurement of $2\nu\beta\beta$ half-lives

The $2\nu\beta\beta$ decay half-lives have been measured in NEMO-3 for 7 available $\beta\beta$ isotopes. The results of measurements are summarized in Table 1.

For all isotopes the energy sum spectrum, the single-electron energy spectrum and angular distribution were measured. These distributions of two-electron events for ^{100}Mo obtained in

Table 1. NEMO 3 results of $2\nu\beta\beta$ half-life measurement.

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	Signal/Bkg	$T_{1/2}^{2\nu}$ (10^{19} years)	
^{100}Mo	6914	3034	76	0.716 ± 0.001 (stat) $\pm$ 0.054 (syst)	
$^{100}Mo(0_1^+)$			3	57^{+13}_{-9} (stat) $\pm$ 8 (syst)	[4]
^{82}Se	932	2995	3	9.6 ± 0.1 (stat) $\pm$ 1.0 (syst)	
^{116}Cd	405	2805	10.3	2.88 ± 0.04 (stat) $\pm$ 0.16 (syst)	
^{150}Nd	37.0	3367	2.8	$0.911^{+0.025}_{-0.022}$(stat) $\pm$ 0.063 (syst)	[5]
^{96}Zr	9.4	3350	1.	2.35 ± 0.14 (stat) $\pm$ 0.16 (syst)	[6]
^{48}Ca	7.0	4772	6.8	$4.4^{+0.5}_{-0.4}$(stat) $\pm$ 0.4 (syst)	
^{130}Te	454	2529	0.5	70 ± 9 (stat) $\pm$ 11 (syst)	[7]

1468 effective days of data taking during Phase-2 are shown in Fig 2 and contain 700000 events.

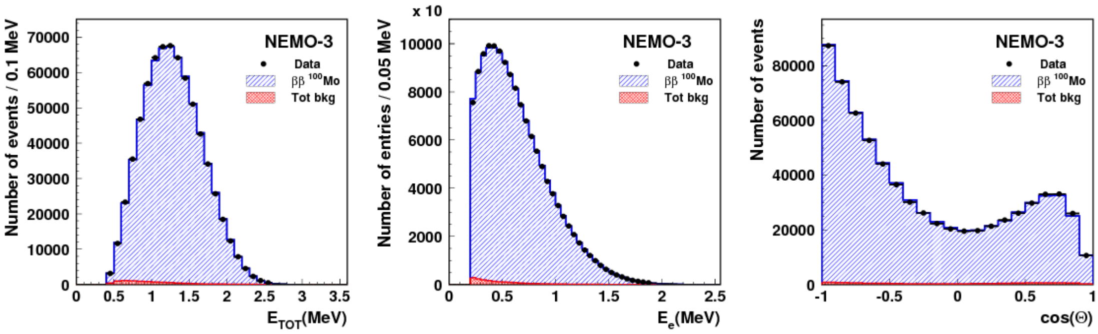

Figure 2. Total energy, individual electron energy and angular distribution of two-electron events from ^{100}Mo for 4 years of Phase-2 data.

4. Search for $0\nu\beta\beta$ decay

The data taken from February 2003 to the end of 2009 has been used for the search of the neutrinoless double beta decay. It corresponds to 1647 effective days of data collections including 372 days of Phase-1 and 1275 days of Phase-2. The $0\nu\beta\beta$-decay search in NEMO-3 is most promising with ^{100}Mo and ^{82}Se because of the larger available sample mass and high enough $Q_{\beta\beta} \sim 3$ MeV. The energy sum spectra are demonstrated in Fig. 3 where the shape of expected $0\nu\beta\beta$-decay signal is shown as a magenta line. The peak is shifted downwards from the endpoint $Q_{\beta\beta}$ value and is smeared due to the energy loss and energy resolution of the detector. No evidence for a neutrinoless double beta decay has been observed. For ^{100}Mo there are 18 events detected in the energy sum interval from 2.8 to 3.2 MeV in a good agreement with 16.4 ± 1.3 expected events. In the case of ^{82}Se the number of observed events between 2.6 and 3.2 MeV is 14 for 11.3 ± 1.3 expected events.

Limits on the neutrinoless double beta decay are set with CL_s method using a binned log-likelihood ratio (LLR) test statistics [8]. With ^{100}Mo data the upper 90% C.L. limit on a possible $0\nu\beta\beta$ decay contribution of 17 events is established. The MC evaluated $0\nu\beta\beta$ efficiency is $\epsilon_{0\nu}$=13%. This gives the lower limit on the half-life $T_{1/2}^{0\nu}(^{100}Mo) > 1.0 \times 10^{24} yr$ (90% C.L.). In case of ^{82}Se there are 9 events excluded at 90% C.L., efficiency $\epsilon_{0\nu}$=14%, which corresponds to the lower limit $T_{1/2}^{0\nu}(^{82}Se) > 3.2 \times 10^{23} yr$ (90% C.L.).

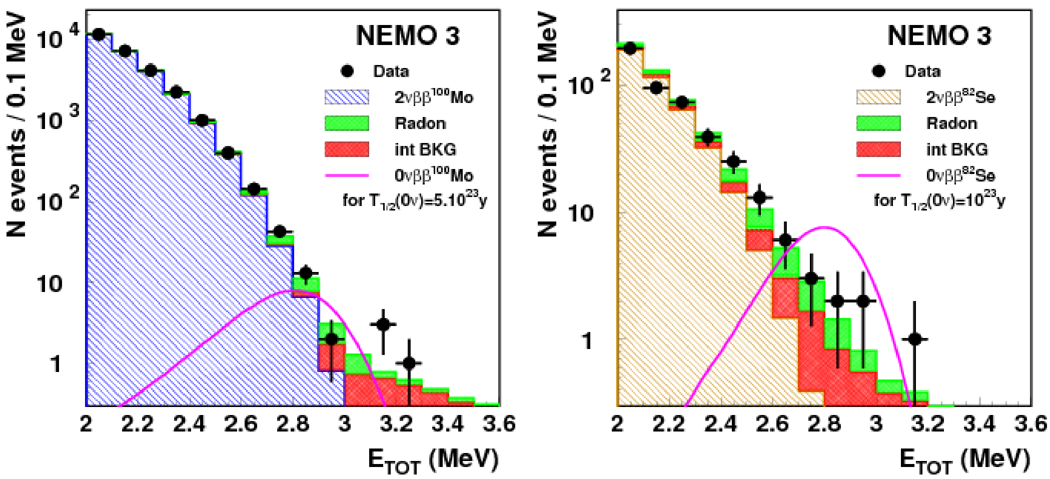

Figure 3. Distribution of the energy sum of two electrons for ^{100}Mo (left) and ^{82}Se (right), 1647 d data.

According to the recent result of different theoretical NME calculations [9, 10, 11, 12, 13, 14] the lower half-life limit obtained for ^{100}Mo corresponds to the upper limit on the effective Majorana neutrino mass interval $\langle m_\nu \rangle < 0.31 - 0.96$ eV, it is less restrictive for ^{82}Se $\langle m_\nu \rangle < 0.94 - 2.6$ eV. The reached NEMO-3 sensitivity on the neutrino mass is close to that of Heidelberg-Moscow collaboration [15], IGEX [16] and CUORICINO [17].

5. Conclusion

After the end of the data taking, the NEMO-3 collaboration would publish soon the final results of the NEMO-3 experiment. A demonstrator of the SuperNEMO experiment should be installed in the Laboratoire Souterrain de Modane : with 7 kg of ^{82}Se and 2 years of data taking, it should exclud or confirm Klapdor's claim of evidence and demonstrate the ability to reach an ultra-low background level, necessary for the next generation experiments.

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[1] IOP Publishing is to grateful Mark A Caprio, Center for Theoretical Physics, Yale University, for permission to include the `iopart-num` BibTeXpackage (version 2.0, December 21, 2006) with this documentation. Updates and new releases of `iopart-num` can be found on `www.ctan.org` (CTAN).
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