Results from NEMO-3.

Robert L. Flack on behalf of the NEMO-3 collaboration.

Department of Physics and Astronomy, University College London, Gower Street, LONDON, WC1E 6BT, UK

E-mail: robflack@hep.ucl.ac.uk

Abstract. The NEMO-3 experiment is located in the Modane Underground Laboratory (LSM) and has been taking data since 2003 with seven isotopes. It is searching for the double beta decay process with two ($2\nu\beta\beta$) or zero ($0\nu\beta\beta$) neutrinos emitted in the final state. Precision measurements of the half-life of the isotopes due to $2\nu\beta\beta$ decay have been performed and new results for $T^{2\nu}_{1/2}(^{96}\mathrm{Zr}) = [2.3 \pm 0.2(\mathrm{stat}) \pm 0.3(\mathrm{syst})] \cdot 10^{19}\mathrm{y}$, $T^{2\nu}_{1/2}(^{48}\mathrm{Ca}) = [4.4^{+0.5}_{-0.4}(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \cdot 10^{19}\mathrm{y}$ and $T^{2\nu}_{1/2}(^{150}\mathrm{Nd}) = [0.920^{+0.025}_{-0.022}(\mathrm{stat}) \pm 0.072(\mathrm{syst})] \cdot 10^{19}\mathrm{y}$ are presented here. Measurements of this process are important for reducing the uncertainties on the nuclear matrix elements. No evidence for $0\nu\beta\beta$ decay has been found and a 90% Confidence Level lower limit on the half-life of this process is derived. From this an upper limit can be set on the effective Majorana neutrino mass using the most recent nuclear matrix elements (NME) calculations.

1. Introduction

The objective of the NEMO 3 experiment is to search for the double beta decay process with two ($2\nu\beta\beta$ decay) or zero ($0\nu\beta\beta$ decay) neutrinos in the final state in the seven different $\beta\beta$ isotopes listed in Table 1. The experimental search for $0\nu\beta\beta$ decay is of major importance in particle physics. If this process is observed then it will reveal the Majorana nature of the neutrino ($\nu \equiv \bar{\nu}$) and may allow an access to the absolute neutrino mass scale.

The process $0\nu\beta\beta$ decay also violates the principle of lepton number conservation and is, therefore, a direct probe for physics beyond the standard model. In the case of the neutrino-mass mechanism the $0\nu\beta\beta$ decay rate can be written as

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

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, $Q^5_{\beta\beta}$.

The $2\nu\beta\beta$ decay process is a rare second order weak interaction process. The accurate measurement of its rate of decay is important since it constitutes the ultimate background in the search for $0\nu\beta\beta$ decay signal and is a valuable input for the theoretical calculations of the NME.

2. The NEMO 3 detector

The detector [1] is located in the LSM in the Frejus tunnel at the depth of 4800 m w.e. It is cylindrical with thin source foils ($\sim 50\,\mathrm{mg/cm^2}$) situated in the middle of the tracking volume surrounded by the calorimeter. The source foils are composed of almost 10 kg of enriched $\beta\beta$ isotopes, listed in Table 1. Observation of the $\beta\beta$ decay is accomplished by fully reconstructing the tracks of the two electrons and measuring their energy. A tracking chamber containing 6180 open drift cells, operating in the Geiger mode, provides a vertex resolution of about 1 cm and a 25 G magnetic field is used to curve the tracks for charge identification. A calorimeter consisting of 1940 plastic scintillator blocks with photomultiplier readout gives an energy resolution of 14 – 17%/$\sqrt{\mathrm{E\,(MeV)}}$ FWHM. A time resolution of 250 ps allows excellent suppression of the external background due to electrons crossing the detector. The detector is capable of identifying e^-, e^+, γ and α particles and allows good discrimination between signal and background events. The detector is covered by two layers of shielding against external γ rays and neutrons.

3. Event selection and background model

The $\beta\beta$ events are selected by requiring two reconstructed electron tracks with a curvature corresponding to the negative charge, originating from a common vertex in the source foil. The energy of each electron measured in the calorimeter should be higher than 200 keV. Each track must be incident upon a separate scintillator block and the time difference of the two PMT signals is compared to the estimated time as if the two electrons had originated from a common vertex.

The background can be classified in three groups: external one from incoming γ, radon inside the tracking volume and internal radioactive contamination of the source. All three were estimated from the NEMO-3 data with events of various topologies. In particular, radon was measured with $e\gamma$ and $e\alpha$ events and internal ^{214}Bi with $e\alpha$. The $e\gamma\gamma$, and $e\gamma\gamma\gamma$ events are used to measure the ^{208}Tl activity requiring the detection of the 2.615 MeV γ-ray typical of the ^{208}Tl β decay. Single electron events are used to measure the foil contamination by β-emitters. The external background is measured with the events with the detected incoming γ-ray producing an electron in the source foil. The external background is checked with two-electron events originating from pure copper and natural tellurium foils. Measurements performed with an HPGe detector and radon detectors are used to verify the results.

4. Results

Measurements of the $2\nu\beta\beta$ decay half-lives have been performed for the seven isotopes available in NEMO-3 and for completeness previous results as well as new results are given in Table 1. New preliminary results based on higher statistics than used previously are presented here for the three isotopes, ^{48}Ca, ^{96}Zr and ^{150}Nd .

Table 1. NEMO-3 results of $2\nu\beta\beta$ decay half-life measurements for seven isotopes.

Isotope	Mass (g)	$Q_{\beta\beta}$ (keV)	Signal/Background	$T_{1/2}$ [10^{19} years]
^{100}Mo	6914	3034	40	0.711 $\pm$ 0.002 (stat) $\pm$ 0.054 (syst) [2]
^{82}Se	932	2995	4	9.6 $\pm$ 0.3 (stat) $\pm$ 1.0 (syst) [2]
^{116}Cd	405	2805	7.5	2.8 $\pm$ 0.1 (stat) $\pm$ 0.3 (syst) [3]
^{150}Nd	37.0	3367	2.8	$0.920^{+0.025}_{-0.022}$(stat) $\pm$ 0.072 (syst)
^{96}Zr	9.4	3350	1.	2.3 $\pm$ 0.2 (stat) $\pm$ 0.3 (syst)
^{48}Ca	7.0	4272	6.8	$4.4^{+0.5}_{-0.4}$(stat) $\pm$ 0.4 (syst)
^{130}Te	454	2529	0.25	76 $\pm$ 15 (stat) $\pm$ 8 (syst) [3]

The measurement of the ^{96}Zr half-life was performed using the data collected for 925 days. A total of 678 events was selected, with an expectation of 328 background events. The largest background contribution is due to the internal ^{40}K contamination of the sample. The distributions of the sum of the energies of the two electrons and their angular separation are shown in Fig. 1, demonstrating good agreement between the data and the Monte Carlo simulation. The $2\nu\beta\beta$ efficiency is estimated to be 7.6%. The measured half-life is $\mathrm{T}^{2\nu}_{1/2}(^{96}\mathrm{Zr}) = [2.3 \pm 0.2(\mathrm{stat}) \pm 0.3(\mathrm{syst})] \cdot 10^{19}\mathrm{y}$.

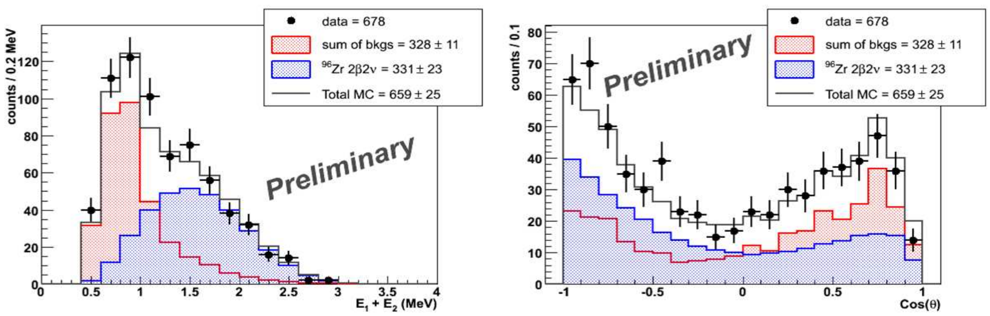

Figure 1. The sum of the energies of the two electrons and their angular separation for two-electron events for ^{96}Zr.

The measurement of the ^{48}Ca half-life was performed using the data collected for 943 days. A total of 133 events was selected, with 17 background events expected. The two-electron energy sum distribution and single-electron energy spectrum are presented in Fig. 2. The ^{48}Ca sample is known to be contaminated with ^{90}Sr ($\mathrm{T}_{1/2}$=28.79 y, Q_β=0.546 MeV). Its daughter ^{90}Y ($\mathrm{T}_{1/2}$=3.19 h, Q_β=2.282 MeV) is the major background source in this case. An activity of approximately 1700 mBq/kg was measured for ^{90}Y using single-electron events. Both ^{90}Sr and ^{90}Y are essentially pure β^- emitters and imitate $\beta\beta$ events through Möller scattering. To suppress this background contribution, events with the energy sum greater than 1.5 MeV and $\cos(\Theta_{\mathrm{ee}}) < 0$ are selected. The $2\nu\beta\beta$ efficiency is 3.3%, and the measured half-life is $\mathrm{T}^{2\nu}_{1/2}(^{48}\mathrm{Ca}) = [4.4^{+0.5}_{-0.4}(\mathrm{stat}) \pm 0.4(\mathrm{syst})] \cdot 10^{19}\mathrm{y}$.

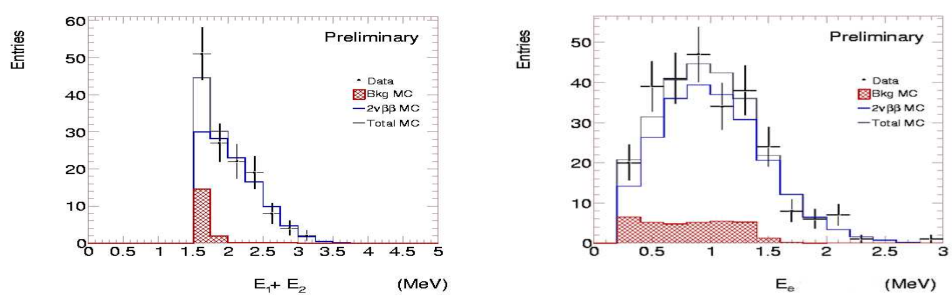

Figure 2. The energy sum and single-electron energy spectra for two-electron events from ^{48}Ca.

The measurement of the ^{150}Nd half-life was performed using the data collected within 939 days. A total of 2853 events was selected, with 765 background events expected. The distributions of the sum of the energies of the two electrons and their angular separation are shown in Fig. 3, demonstrating good agreement between the data and the Monte Carlo simulation. The $2\nu\beta\beta$ efficiency is estimated to be 7.6% and the half-life is measured to be $\mathrm{T}^{2\nu}_{1/2}(^{150}\mathrm{Nd}) = [0.920^{+0.025}_{-0.022}(\mathrm{stat}) \pm 0.062(\mathrm{syst})] \cdot 10^{19}\mathrm{y}$.

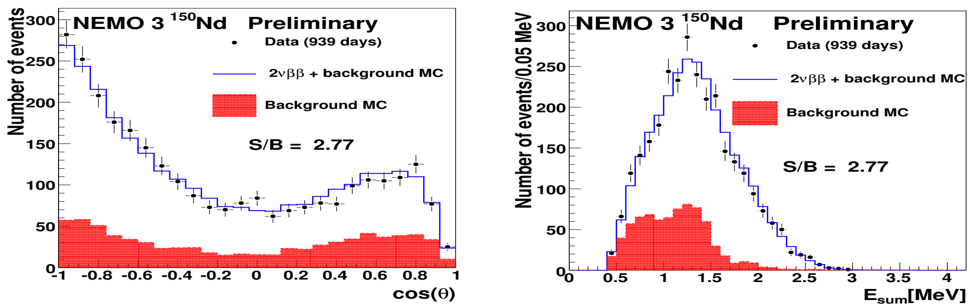

Figure 3. The distributions of the angular separation and energy sum spectra for two-electron events from ^{150}Nd.

In the case of the mass mechanism, the $0\nu\beta\beta$ decay signal is expected to be a peak in the energy sum distribution at the position of the transition energy $Q_{\beta\beta}$ (with a long non-Gaussian tail due to energy losses in the source foil). Since no excess is observed at the tail of the distribution for ^{96}Zr, see Fig. 1 (left), nor for ^{48}Ca, Fig. 2 (left), limits are set on the neutrinoless double beta decay $T^{0\nu}_{1/2}$ using the CLs method [4]. A lower half-life limit is translated into an upper limit on the effective Majorana neutrino mass $\langle m_\nu \rangle$ (see Eq. 1). The following results are obtained using the NME values from [5, 6] for ^{96}Zr and from [7] for ^{48}Ca: $T^{0\nu}_{1/2}(^{96}\mathrm{Zr}) > 8.6 \cdot 10^{21}$ y (90% C.L.), $\langle m_\nu \rangle < 7.4 - 20.1$ eV and $T^{0\nu}_{1/2}(^{48}\mathrm{Ca}) > 1.3 \cdot 10^{22}$y (90% C.L.), $\langle m_\nu \rangle < 29.7$ eV.

Similarly a limit has been set for $\langle m_\nu \rangle$ for ^{150}Nd. It is complicated by whether the deformation of the nucleus is taken into account. The limit has been calculated for both scenarios: $T^{0\nu}_{1/2}(^{150}\mathrm{Nd}) > 1.8 \cdot 10^{22}$y (90% C.L.) with $\langle m_\nu \rangle < 1.7 - 2.4$ eV using QRPA model (no deformation) [8] and $\langle m_\nu \rangle < 4.8 - 7.6$ eV using SO(3) model (with deformation) [9].

All of these limits should be compared with the one set previously by NEMO-3 of $\langle m_\nu \rangle < 0.8 - 1.3$ eV for ^{100}Mo [2].

5. Conclusion

No evidence was found for $0\nu\beta\beta$ decay and limits on the neutrino mass, $\langle m_\nu \rangle$, have been set. New measurements for the half-lives due to $2\nu\beta\beta$ decay for the three isotopes, ^{48}Ca, ^{96}Zr and ^{150}Nd has been presented. The NEMO-3 experiment continues taking data but will eventually be superceded with a new experiment called SuperNEMO. The baseline design of SuperNEMO envisages using 100 kg of ^{82}Se or ^{150}Nd to reach a sensitivity to the Majorana neutrino mass of $0.05 - 0.1$ eV.

References

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