

Measurement of the double- β decay half-life of ^{150}Nd and search for neutrinoless decay modes with the NEMO-3 detector

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The half-life for double- β decay of ^{150}Nd has been measured by the NEMO-3 experiment at the Modane Underground Laboratory. Using 924.7 days of data recorded with 36.55 g of ^{150}Nd , we measured the half-life for $2\nu\beta\beta$ decay to be $T_{1/2}^{2\nu} = (9.11_{-0.22}^{+0.25}(\text{stat.}) \pm 0.63(\text{syst.})) \times 10^{18}$ yr. The observed limit on the half-life for neutrinoless double- β decay is found to be $T_{1/2}^{0\nu} > 1.8 \times 10^{22}$ yr at 90% confidence level. This translates into a limit on the effective Majorana neutrino mass of $\langle m_\nu \rangle < 4.0\text{--}6.3$ eV if the nuclear deformation is taken into account. We also set limits on models involving Majoron emission, right-handed currents, and transitions to excited states.

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Experiments studying atmospheric, solar, reactor, and accelerator neutrinos have established the existence of neutrino oscillations as direct evidence for a nonzero neutrino mass. These experiments, however, cannot distinguish between Dirac or Majorana neutrinos. They also provide no information on the absolute neutrino mass scale, since oscillation experiments measure the square of the mass difference between neutrino states. The half-life of neutrinoless double- β decay ($0\nu\beta\beta$) is inversely proportional to the effective Majorana neutrino mass squared $\langle m_\nu \rangle^2$. Observation of this process would therefore directly constrain the neutrino mass scale and would be unambiguous evidence for the Majorana nature of

neutrinos. The $0\nu\beta\beta$ process also violates lepton number and is therefore a direct probe for physics beyond the standard model of particle physics.

The search for neutrinoless double- β decay of neodymium-150 (^{150}Nd) using the NEMO-3 detector is of special interest, since ^{150}Nd is a candidate isotope for SuperNEMO [1], a next-generation double- β decay experiment based on the NEMO-3 concept, and the SNO++ experiment at the Sudbury Neutrino Observatory's SNOLAB [2]. Its main advantages are the high $Q_{\beta\beta}$ value for double- β decay, $Q_{\beta\beta} = 3.368$ MeV, which lies above the typical energies for many background sources, and the large phase-space factor. The $2\nu\beta\beta$ half-life of ^{150}Nd has

previously been measured using a time projection chamber [3,4].

The NEMO-3 experiment has been taking data since 2003 in the Modane Underground Laboratory (LSM) located in the Fréjus tunnel at a depth of 4800 m water equivalent. The detector has a cylindrical shape with 20 sectors that contain different isotopes in the form of thin foils with a total surface of about 20 m² [5]. In addition to ~ 7 kg of ¹⁰⁰Mo and ~ 1 kg of ⁸²Se, the detector contains smaller amounts of other isotopes. The neodymium source foil is composed of Nd₂O₃ with an enrichment of $(91 \pm 0.5)\%$, corresponding to a ¹⁵⁰Nd mass of 36.55 ± 0.10 g. On each side of the foils is a ~ 50 cm wide tracking volume comprising a total of 6180 drift cells operated in Geiger mode with helium as the drift gas. A 25 Gauss magnetic field created by a solenoid provides charge identification. The calorimeter consists of 1940 plastic scintillators coupled to low-radioactivity photomultipliers. For 1 MeV electrons, the energy resolution (full width at half maximum, FWHM) ranges from 14.1% to 17.7%, and the timing resolution is 250 ps. A cylindrical coordinate system (r, z, ϕ) is used with the z axis pointing upward.

The data used in this Rapid communication have been recorded between February 2003 and December 2006, corresponding to 924.7 days of data taking. Signal and background events are generated with the GENBB generator and simulated using a GEANT-based simulation [6] of the detector. All Monte Carlo events are processed by the same reconstruction programs as the data. A detailed description of the analysis can be found in Ref. [7].

The $2\nu\beta\beta$ events are expected to have two electrons in the final state, and they are therefore selected by requiring two tracks with a curvature consistent with a negative charge. Each track has to be matched to a separate energy deposit in the calorimeter greater than 0.2 MeV. The z component of the distance between the intersections of each track with the plane of the foil should be less than 4 cm, and the transverse component less than 2 cm. Both tracks must originate from the first layer of the Geiger cells. The scintillator measurement of the time of flight (TOF) for both electron candidates must be consistent with the hypothesis that the event originates from the source foil. After this selection, 2789 events remain.

The background sources are divided into two categories, depending on their origin [8]. Background events originating from the radioactive impurities in the source foils are called “internal background.” β emitters can produce $\beta\beta$ -like events through three mechanisms: (i) β decay accompanied by electron conversion; (ii) Møller scattering of a β -decay electron, and (iii) β decay to an excited state followed by Compton scattering of the deexcitation photon. Another internal background source is ²⁰⁷Bi, most likely present because of a contamination of the ¹⁵⁰Nd source foil during production. This isotope decays to excited ²⁰⁷Pb through electron capture, and ²⁰⁷Pb subsequently emits two electrons via electron conversion.

The second source of background is called “external” and is caused by electrons or photons anywhere outside the source foils. The main source of external background is radon. Radon decays to ²¹⁴Bi via two α decays and one β^- decay. The decay

of ²¹⁴Bi to ²¹⁴Po is generally accompanied by one electron and several photons, which can mimic a $\beta\beta$ event through conversions. A radon purification facility was installed about halfway through the data-taking period presented in this paper. This reduces the radon-induced background for this analysis by about a factor of 6. Other external background contributions are found to be small.

The background activities are determined by measuring control decay channels that are independent of the signal topology using a full MC simulation of the background processes and the detector. A summary of the measured background activities are given in Table I.

In the $e\gamma$ channel, ²⁰⁷Pb from the ²⁰⁷Bi decays via the emission of an electron and a photon from the strongly converted energy transition in excited ²⁰⁷Pb. ¹⁵²Eu decays into excited ¹⁵²Gd through β decay, which deexcites into the ground state via photon emission. The $e\gamma$ events are selected by requiring that exactly one negatively charged particle with a track length greater than 50 cm is found in the sector containing the ¹⁵⁰Nd foil. The track must be associated with an isolated scintillator hit with energy greater than 0.2 MeV. It must originate from the ¹⁵⁰Nd foil and must have a hit in the first layer of the Geiger cells. The scintillator measurement of the TOF of the electron candidates has to be consistent with the hypothesis that the decay occurred in the source foil. The photon is identified by requiring that there is a second scintillator hit with no associated track and with energy greater than 0.2 MeV. The energy sum of all other clusters not associated with the electron or the photon must be less than 0.15 MeV. The opening angle between the electron and the photon is required to be $\cos\theta < 0.9$.

To obtain the background normalization for ²⁰⁷Bi and ¹⁵²Eu, the normalization of these background contributions is fitted to spectra of the electron energies E_e and the photon energies E_γ shown in Fig. 1. The contributions from other

TABLE I. Summary of the measured background activities, the expected number of background events, and the observed number of events for the selected data set and in the high-energy region, $E_{\text{sum}} > 2.5$ MeV.

Background	A (mBq/kg)	N_{bg}	N_{bg} for $E_{\text{sum}} > 2.5$ MeV
¹⁵² Eu	54 ± 6	19 ± 1	0
¹⁵⁴ Eu	22 ± 2	9 ± 1	0
²⁰⁸ Tl	10 ± 2	46 ± 4	3.5 ± 0.9
²²⁸ Ac	27.8 ± 5.6	52 ± 5	0
²¹² Bi	27.8 ± 5.6	32 ± 4	0
²⁰⁷ Bi	231 ± 10	138 ± 6	0
²¹⁴ Bi	3.3 ± 0.8	13 ± 3	0.6 ± 0.2
²¹⁴ Pb	3.3 ± 0.8	6 ± 1	0
⁴⁰ K	213 ± 10	66 ± 6	0
^{234m} Pa	47 ± 2	143 ± 6	0
External and radon-induced		53 ± 11	4.8 ± 0.8
⁴⁸ Ca, ⁹⁶ Zr, ¹⁰⁰ Mo		168 ± 19	0.12 ± 0.02
Sum		746 ± 30	9.0 ± 1.2
Data		2789	29

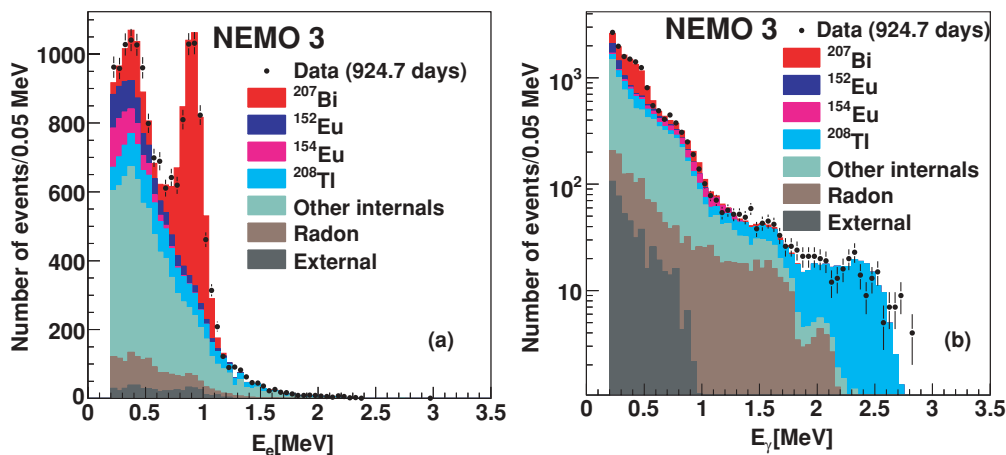


FIG. 1. (Color online) Energy distributions of the (a) electrons and (b) photons in $e\gamma$ events. The data with statistical uncertainties are compared with the sum of the expected background.

background sources are fixed in the fit. The ^{228}Ac contribution is taken from the ^{208}Tl component in the high-energy tail of the E_γ distribution, since ^{208}Tl originates from ^{228}Ac decays. The ^{212}Bi component is normalized with respect to the measurement of its decay product ^{208}Tl . The external, the radon-induced, ^{214}Bi and ^{214}Pb backgrounds are set to their independently measured values.

The isotopes ^{234m}Pa and ^{40}K undergo β decay. Their activities are therefore measured with single electron events. The same selection for the electron is applied as in the $e\gamma$ channel, apart from an additional requirement $E_e > 0.5$ MeV. The ^{234m}Pa and ^{40}K contributions are obtained from a fit of the normalization to the E_e distributions. The external background is set to the values obtained from independent measurements. The ^{207}Bi component has been measured in the $e\gamma$ channel. The E_e distribution with the fitted ^{234m}Pa and ^{40}K contributions is shown in Fig. 2. The distribution of the event vertices for the single electron events, calculated as the electron track's intersection with the source foil, shows small regions of high activity consistent with ^{234m}Pa contamination,

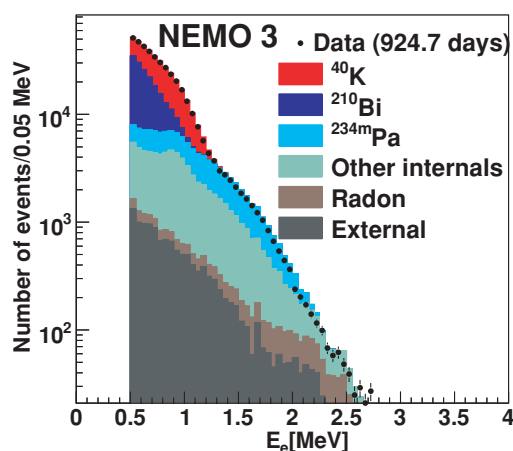


FIG. 2. (Color online) Distribution of the electron energy in single electron events. The data are compared with the sum of the expected background.

which are removed from the analysis. The activities given in Table I are measured after the removal of these regions.

Because of the resolution of the tracking detector, events from neighboring source foils (^{48}Ca , ^{96}Zr , ^{100}Mo) can be reconstructed as originating from the ^{150}Nd foil. The total number of background events from neighboring foils is estimated to be 126 ± 12 from MC simulations, where the uncertainty is dominated by the uncertainty in the half-life of these isotopes.

The distributions of the energy sum of the two electrons and the opening angle between them are shown in Fig. 3. The data are in good agreement with the sum of the background and the $2\nu\beta\beta$ signal distributions. We therefore use the data sample to measure the $2\nu\beta\beta$ half-life, $T_{1/2}^{2\nu}$, of ^{150}Nd . The efficiency of the $2\nu\beta\beta$ event selection is 7.2%. After background subtraction we obtain

$$T_{1/2}^{2\nu} = (9.11_{-0.22}^{+0.25}(\text{stat.}) \pm 0.63(\text{syst.})) \times 10^{18} \text{yr}. \quad (1)$$

The systematic uncertainty in the sum of the internal and external background is 4.3%, which translates into an uncertainty on the $2\nu\beta\beta$ half-life of 1.6%. This includes the uncertainty from the background fits and from the measurement of the activity of ^{208}Tl using two different decay channels. The uncertainty on the tracking efficiency is 5.7%. Varying the TOF requirement leads to a 1% uncertainty. An uncertainty of 3% is due to the uncertainty in the position of the ^{150}Nd foil in the detector. The uncertainty in the energy measurement was studied by smearing the individual electron energies by 2%, which yields a systematic uncertainty of 1.5% on the $2\nu\beta\beta$ half-life.

Since no significant excess is observed in the E_{sum} distribution, a limit is set on the half-life for neutrinoless double- β decay, $T_{1/2}^{0\nu}$, using the CL_s method [9]. Only the shapes and not the normalization of the full E_{sum} distribution are used to discriminate signal and $2\nu\beta\beta$ background. The normalization of the E_{sum} distribution for the other backgrounds is fixed to the value given in Table I. All limits in this paper are calculated by utilizing a likelihood fitter [10] that uses a log-likelihood ratio (LLR) test statistic method. Two hypotheses are defined, the signal-plus-background hypothesis and the background-only

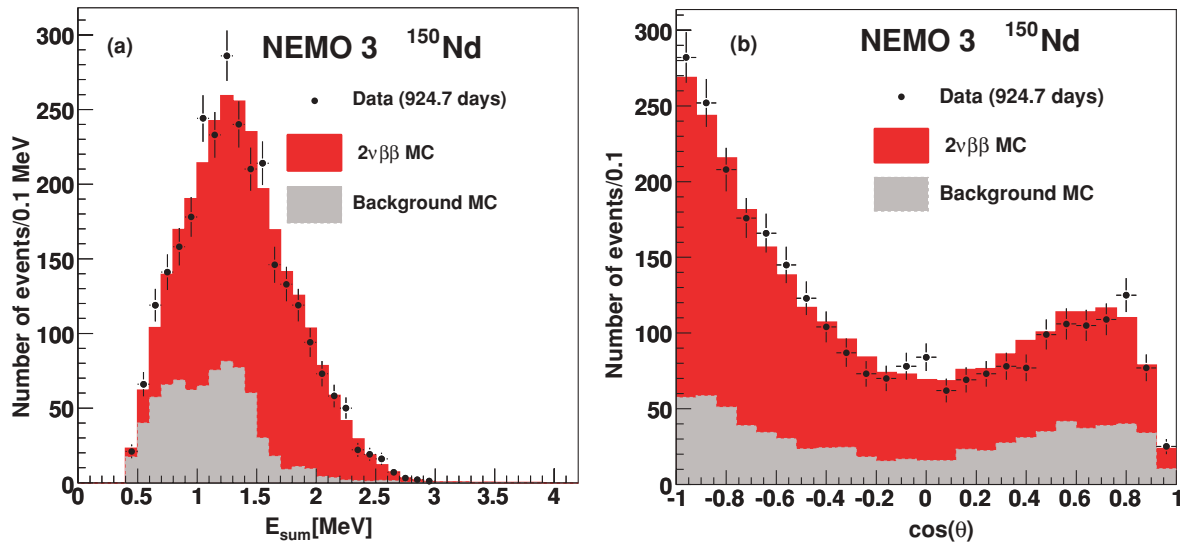


FIG. 3. (Color online) Distributions of (a) the energy sum of the two electrons, E_{sum} , and (b) the angle between the two electrons, $\cos\theta$, for data compared with the sum of the background and $2\nu\beta\beta$ signal expectations.

hypothesis. The LLR distributions are populated using Poisson simulations of the two hypotheses. Systematic uncertainties are treated as uncertainties on the expected numbers of events and are folded into the signal and background expectations via a Gaussian distribution. Correlations between systematic uncertainties are taken into account. The value of the confidence level, CL_s , is defined as $\text{CL}_s = \text{CL}_{s+b}/\text{CL}_b$, where CL_{s+b} and CL_b are the confidence levels in the signal-plus-background and background-only hypotheses, respectively. The limits are calculated by scaling the signal until $1 - \text{CL}_s$ reaches 0.9.

The total efficiency for $0\nu\beta\beta$ events after applying all selections is $(19 \pm 1)\%$. The uncertainties on the efficiency of the signal and the background are assumed to be fully correlated. The E_{sum} distribution for $E_{\text{sum}} > 2.5$ MeV is shown in Fig. 4 for data compared with the total background, which consists of internal and external backgrounds and the $2\nu\beta\beta$ expectation. A MC simulation of a $0\nu\beta\beta$ signal is also shown. Signal and background are well separated, demonstrating the advantages of using ^{150}Nd for future $0\nu\beta\beta$ searches. The observed limit on the half-life is $T_{1/2}^{0\nu} > 1.8 \times 10^{22}$ yr at 90% CL. It is consistent with the median expected limit.

This limit on the half-life is converted into a limit on the effective Majorana neutrino mass $\langle m_\nu \rangle$, using nuclear matrix elements (NME). In the currently available quasiparticle random phase approximation (QRPA)-like calculations, spherical symmetry of the nucleus has been assumed. If the upper and lower limits on the calculated NME, which also include the uncertainties in the weak coupling constant g_A , are taken into account [11], the experimental lower limit on the half-life of ^{150}Nd translates into a limit $\langle m_\nu \rangle < 1.5\text{--}2.5$ eV.

Taking into account the nuclear deformation will modify this conclusion. The suppression of the NME for ^{150}Nd has been estimated to be a factor of 2.7 in the case of nuclear deformations derived from laboratory moments [12]. This increases the upper limit to $\langle m_\nu \rangle < 4.0\text{--}6.8$ eV, which is consistent with the limit derived using the NME of a

pseudo-SU(3) model [13] and the projected Hartree-Fock-Bogoliubov (PHFB) model [14], which also include the effect of nuclear deformation. Further progress in the calculation of the NME for $0\nu\beta\beta$ decay of ^{150}Nd is therefore urgently required.

Neutrinoless double- β decay can also proceed through the emission of one or two Majorons (χ^0) [15]. These decays are characterized by the spectral index n which leads to a

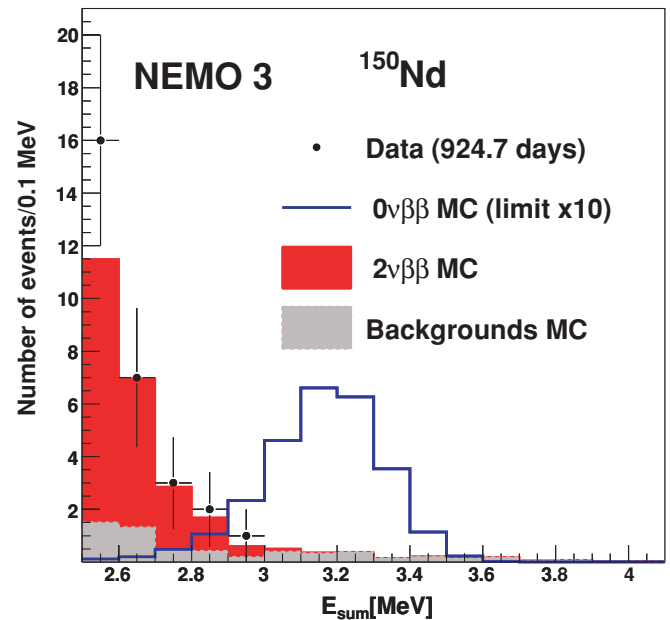


FIG. 4. (Color online) Distribution of the energy sum of the two electrons, E_{sum} , for $E_{\text{sum}} > 2.5$ MeV. The data are compared with the total background, consisting of internal and external background and the $2\nu\beta\beta$ expectation. A MC simulation of a $0\nu\beta\beta$ signal with a half-life of 1.8×10^{21} yr, corresponding to ten times the number of events expected for the observed 90% C.L. limit, is also shown.

TABLE II. 90% C.L. limits on the half-life $T_{1/2}$, in units of 10^{21} yr, for different modes of neutrinoless double- β decay.

	$0\nu\beta\beta$				Majorons			
	$0_{\text{g.s.}}^+ ((m_\nu))$	$0_{\text{g.s.}}^+ (V+A)$	2_1^+	0_1^+	$n = 1$	$n = 2$	$n = 3$	$n = 7$
Limit	18.0	10.7	2.4	0.24	1.52	0.54	0.22	0.047

modification of the energy sum distribution by a factor of $(Q_{\beta\beta} - E_{\text{sum}})^n$. We consider models with $n = 1, 3, 7$ [15] and $n = 2$ [16]. Limits on $n = 3, 7$ models are less sensitive than $n = 1, 2$, since the shape of the E_{sum} distribution is similar to the one for $2\nu\beta\beta$ decay ($n = 5$). The CL_s method is applied to the E_{sum} distribution in the same way as described previously. Since the normalization of the $2\nu\beta\beta$ background cannot be independently determined, it is left unconstrained in the fit determining the limits.

We also set limits for $0\nu\beta\beta$ processes involving right-handed currents (V+A). In addition, the $0\nu\beta\beta$ decay can also proceed through various excited states (0_1^+ or 2_1^+). Limits on all these modes of neutrinoless double- β decay are shown in Table II. They either improve previously published limits [4,17] significantly or represent the first limits for this isotope ($n = 2, 3, 7$). The limit on $n = 1$ Majoron emission can be translated into a limit on the neutrino-Majoron coupling of $g_{ee} < (0.64 - 1.05) \times 10^{-4}$ without and $g_{ee} < (1.7 - 3.0) \times 10^{-4}$ with nuclear deformation. These limits are comparable with the limits obtained for ^{82}Se and ^{100}Mo with about 9 and

70 times the exposure, defined as isotope mass multiplied by observation time [18].

In summary, we have presented the most precise measurement of the half-life of double- β decay of ^{150}Nd to date, yielding a value of $T_{1/2}^{2\nu} = (9.11_{-0.22}^{+0.25}(\text{stat.}) \pm 0.63(\text{syst.})) \times 10^{18}$ yr. This value is slightly more than two standard deviations higher than the previously measured value $T_{1/2}^{2\nu} = (6.75_{-0.42}^{+0.37}(\text{stat.}) \pm 0.68(\text{syst.})) \times 10^{18}$ yr [4]. We have significantly improved limits on the half-life of different modes of neutrinoless double- β decay for ^{150}Nd , and we have provided the first limits for several Majoron models using ^{150}Nd . Our measurements demonstrate that ^{150}Nd is an excellent candidate isotope for future double- β decay experiments.

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