Pis'ma v ZhETF, vol. 80, iss. 6, pp. 429 – 433

Study of 2β-decay of ^{100}Mo and ^{82}Se using the NEMO3 detector

R. Arnold[▼], *C. Augier*[•], *J. Baker*[▽], *A. Barabash*[1)+], *V. Brudanin*[△], *A. J. Caffrey*[▽], *V. Egorov*[△], *J. L. Guyonnet*[▼], *F. Hubert*[+], *Ph. Hubert*[+], *L. Jenner*[♦], *C. Jollet*[▼], *S. Jullian*[•], *A. Klimenko*[△], *O. Kochetov*[△], *S. Konovalov*[+], *V. Kovalenko*[△], *D. Lalanne*[•], *F. Leccia*[+], *I. Linck*[▼], *C. Longuemare*[*], *G. Lutter*[+], *Ch. Marquet*[+], *F. Mauger*[*], *H. W. Nicholson*[▲], *H. Ohsumi*[◇], *F. Piquemal*[+], *J-L. Reyss*[□], *R. Saakyan*[♦], *X. Sarazin*[•], *F. Scheibling*[▼], *Yu. Shitov*[△], *L. Simard*[•], *A. Smolnikov*[△], *I. Štekl*[■], *J. Suhonen*[∘], *C. S. Sutton*[▲], *G. Szklarz*[•], *V. Timkin*[△], *J. Thomas*[♦], *V. Tretyak*[△], *V. Umatov*[+], *L. Vála*[■], *I. Vanyushin*[+], *S. Vasiliev*[△], *V. Vasilyev*[+], *V. Vorobel*[★], *Ts. Vylov*[△]

[+] *CENBG, IN2P3-CNRS et Université de Bordeaux, 33170 Gradignan, France*

[*] *LPC, IN2P3-CNRS et Université de Caen, 14032 Caen, France*

[△] *Joint Institute for Nuclear Research, 141980 Dubna, Russia*

[□] *CFR, CNRS, 91190 Gif sur Yvette, France*

[▽] *INEEL, Idaho Falls, ID 83415, USA*

[∘] *JYVÄSKYLÄ University, 40351 Jyväskylä, Finland*

[+] *Institute of Theoretical and Experimental Physics, 117218 Moscow, Russia*

[•] *LAL, IN2P3-CNRS et Université Paris-Sud, 91405 Orsay, France*

[▲] *MHC, South Hadley, Massachusetts 01075, USA*

[▼] *IReS, IN2P3-CNRS et Université Louis Pasteur, 67037 Strasbourg, France*

[■] *IEAP CTU, Prague, Czech Republic*

[★] *Charles University, Prague, Czech Republic*

[◇] *SAGA University, Saga, Saga 840-8502, Japan*

[♦] *University College London, London, UK*

Submitted 2 August 2004

After analysis of 5797 h of data from the detector NEMO3, new limits on neutrinoless double beta decay of ^{100}Mo ($T_{1/2} > 3.1 \cdot 10^{23}$ y , 90% CL) and ^{82}Se ($T_{1/2} > 1.4 \cdot 10^{23}$ y , 90% CL) have been obtained. The corresponding limits on the effective majorana neutrino mass are: $\langle m_\nu \rangle < (0.8 - 1.2)$ eV and $\langle m_\nu \rangle < (1.5 - 3.1)$ eV, respectively. Also the limits on double-beta decay with Majoron emission are: $T_{1/2} > 1.4 \cdot 10^{22}$ y (90%CL) for ^{100}Mo and $T_{1/2} > 1.2 \cdot 10^{22}$ y (90% CL) for ^{82}Se. Corresponding bounds on the Majoron-neutrino coupling constant are $\langle g_{ee} \rangle < (0.5 - 0.9) \cdot 10^{-4}$ and $< (0.7 - 1.6) \cdot 10^{-4}$. Two-neutrino 2β-decay half-lives have been measured with a high accuracy, $T_{1/2}^{^{100}\mathrm{Mo}} = [7.68 \pm 0.02(\mathrm{stat}) \pm 0.54(\mathrm{syst})] \cdot 10^{18}$ y and $T_{1/2}^{^{82}\mathrm{Se}} = [10.3 \pm 0.3(\mathrm{stat}) \pm 0.7(\mathrm{syst})] \cdot 10^{19}$ y.

PACS: 14.80.Mz, 23.40.−s

Interest in neutrinoless double beta decay ($2\beta0\nu$) has seen a significant rebirth in recent years after evidence for neutrino oscillations was obtained from the results of atmospheric [1] and solar [2 – 6] neutrino experiments (see, for example, the discussions in [7 – 9]).

This observation of oscillations was recently confirmed by the KamLAND experiment with reactor antineutrinos [10] and by the new SNO result [11]. These results are an impressive proof that neutrinos have a non-zero mass. However, the experiments studying neutrino oscillations are not sensitive to the nature of the neutrino mass (Dirac or Majorana?) and provide no information on the absolute scale of the neutrino masses, since such experiments are sensitive only to the difference, Δm^2. The detection and study of $2\beta0\nu$ decay may clarify the following problems of neutrino physics (see discussions in [12 – 14]): (i) neutrino nature; is the neutrino a Dirac or a Majorana particle?, (ii) absolute neutrino mass scale (a measurement or a limit on m_1), (iii)

[1)] e-mail: Alexander.Barabash@itep.ru

the type of neutrino mass hierarchy (normal, inverted, or quasidegenerate), (iv) CP violation in the lepton sector (measurement of the Majorana CP-violating phases).

The main goal of the NEMO3 experiment is to study neutrinoless double beta decay of different isotopes (^{100}Mo, ^{82}Se etc.) with a sensitivity of up to $\sim 10^{25}$ y, which corresponds to a sensitivity for the effective Majorana neutrino mass at the level of $\sim$ $(0.1-0.3)$ eV [15]. The planned sensitivity for double beta decay with Majoron emission is $\sim 10^{23}$ y (the sensitivity for the coupling constant of Majoron to neutrino $\langle g_{ee}\rangle$ is at the order of $\sim 10^{-5}$). In addition, one of the goals is a precise study of $2\beta2\nu$ decay for a number of nuclei (^{100}Mo, ^{82}Se, ^{116}Cd, ^{150}Nd, ^{130}Te, ^{96}Zr and ^{48}Ca) with high statistics and to study all major characteristics of the decay.

NEMO3 is a tracking detector, which in contrast to ^{76}Ge experiments [16, 17], detects not only the total energy deposition but also other important parameters of the process. These include the energy of individual electrons, their angular distribution, the event vertex coordinates in the source plane, etc. This provides a unique opportunity to monitor and reject backgrounds. Since June of 2002 NEMO3 has been running in the Frejus Underground Laboratory (France) located at a depth of 4800 m.w.e.

The detector has a cylindrical shape and consists of 20 identical sectors (see Fig.1). A thin ($\sim$30–60 mg/cm^2) source is placed in the center of the detector which contains 2β-decaying nuclei and has a total area of 20 m^2 and a mass of about 10 kg. In particular, it includes 7.1 kg of enriched Mo (average enrichment is 98%, the total mass of ^{100}Mo is 6.914 kg) and 0.962 kg of Se (enrichment is 97%, the total mass of ^{82}Se is 0.932 kg). To investigate the external background a part of the source is made of very pure natural materials (TeO_2 – 0.767 kg and Cu – 0.621 kg). The level of contamination of the sources with radioactive impurities was obtained from measurements using low-background HPGe-detectors.

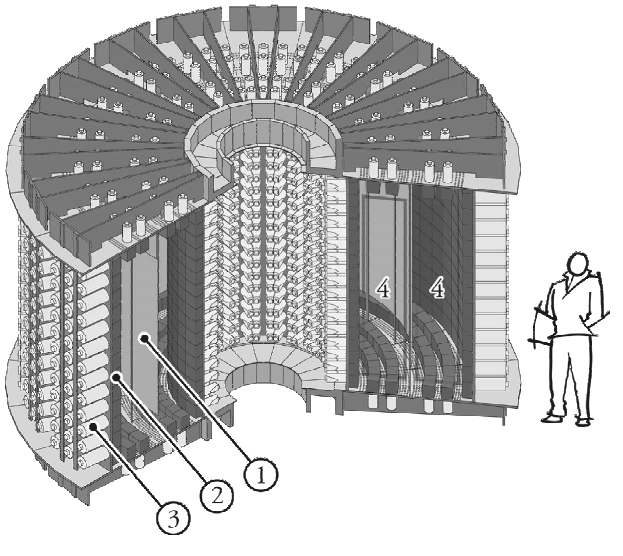

Fig.1. The NEMO3 detector. *1* – source foil; *2* – plastic scintillator; *3* – low radioactive PMT; *4* – tracking chamber (6.180 octagonal Geiger cells)

The basic detection principles of NEMO3 are the following. The energy of the electrons is measured with plastic scintillators coupled to PMTs (1940 individual counters), while the tracks are reconstructed from the information obtained with drift Geiger cells (6180 cells). The tracking volume of the detector is filled with a mixture of $\sim$95% He, 4% alcohol, 1% Ar and 0.15% water at 20 mbar above atmospheric pressure. In addition, a magnetic field of 25 Gauss parallel to the detector's axis is created by a solenoid surrounding the detector. The magnetic field is used to identify electron-positron pairs to suppress the background associated with these events.

The main characteristics of the detector's performance are the following. The energy resolution of the scintillation counters lies in the interval of 14–17% (FWHM for 1 MeV electrons). The time resolution is 250 ps for an electron energy of 1 MeV. The reconstruction accuracy of a two electron (2e) vertex is around 1 cm. The characteristics of the detector are studied in special calibration runs with radioactive sources. The energy calibration is carried out using ^{207}Bi with conversion electrons at energies 0.482 and 0.976 MeV, and ^{90}Sr with the end-point of the β spectrum at 2.283 MeV. The vertex reconstruction accuracy for $2e^-$ events was determined in measurements with ^{207}Bi. The time-of-flight properties were determined via measurements with ^{60}Co where two γ-quanta are emitted simultaneously, ^{207}Bi for which two electrons are emitted simultaneously and neutron sources which provide high energy electrons crossing the detector.

The detector is surrounded by a passive shield made of 20 cm of steel, 30 cm of water contained in tanks covering the vertical exterior of the detector and wood and paraffin on the top and bottom. The level of radioactive impurities in the construction materials of the detector and the passive shield was tested with low-background HPGe detectors.

From June to December of 2002 a number of calibration and test measurements were carried out, as was the first data taken for double beta decay studies. Since 14 February 2003 the detector has been routinely taking double beta decay data. The calibrations with the radioactive sources are carried out every 1.5 months. Calorimeter stability is checked daily using a laser system between calibrations. A detailed description of the detector and its characteristics is presented in [18].

In this paper we present the results for ^{100}Mo and ^{82}Se. Only part (5797 h of measurement) of the available data has been analyzed.

Double beta decay of ^{100}Mo. 2e-events with a common vertex at the source have been selected. For 2e-events, an electron was defined as a track between the source foil and a fired scintillation counter with the energy deposited being greater than 200 keV. The track curvature must be consistent with a negatively charged particle. The time-of-flight measurement should be consistent with the hypothesis of two electrons leaving the source from a common vertex simultaneously. In order to suppress the ^{214}Bi background, which is followed by a ^{214}Po α-decay, it is required that there are no delayed Geiger cell hits close to the event vertex or the electron track (within a delay of up to 700 μs). A typical 2e-event is shown in Fig.2.

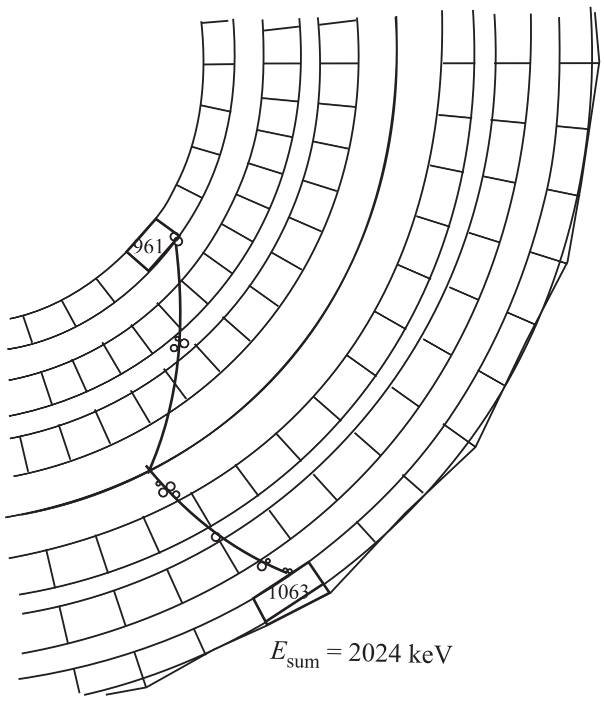

Fig.2. A view of a reconstructed 2e-event in NEMO3. Sum energy of the electrons is 2024 keV, energy of electrons in the pair is 961 keV and 1063 keV

Fig.3 shows the $2\beta2\nu$ energy spectrum for ^{100}Mo. The total number of useful events (after background subtraction) is ~141000. The signal-to-background ratio is

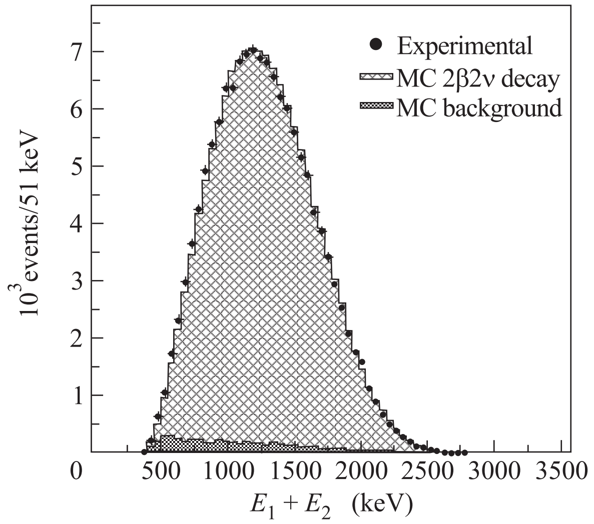

Fig.3. $2\beta2\nu$ spectrum of ^{100}Mo, background subtracted

40/1, while it is 100/1 for energies above 1 MeV. This means that the background is negligible. The detection efficiencies which included the selection cuts were estimated by Monte Carlo (MC) simulations. This was done for two models of the ^{100}Mo decay. The first one is the higher state dominance (HSD) mechanism and the second is the single state dominance (SSD) mechanism (see ref. [19]). For the SSD mechanism it is assumed that the decay goes via the lowest 1^+ state of ^{100}Tc [20]. The detection efficiencies calculated by MC simulations were 5.68% for the SSD mechanism and 6.33% for the HSD mechanism. Correspondingly, the following results were obtained for the ^{100}Mo half-life:

$$T_{1/2} = [7.68 \pm 0.02(stat) \pm 0.54(\mathrm{syst})] \cdot 10^{18}\ y\ (\mathrm{SSD}),$$

$$T_{1/2} = [8.57 \pm 0.02(stat) \pm 0.6(\mathrm{syst})] \cdot 10^{18}\ y\ (\mathrm{HSD}).$$

A preliminary analysis of the experimental single electron energy spectrum favors the SSD hypothesis. However, at the moment this question remains open and requires further studies. Both values are in agreement with the world mean value from other experiments: $(8 \pm 0.7) \cdot 10^{18}$ y [21, 22].

$2\beta0\nu$-decay. The energy range 2.65–3.2 MeV has been investigated. The information about the electron's energies and their angular distribution in 2e-events can be used to improve the selection of candidate events and thus, improve the NEMO3 sensitivity [23]. Introducing a higher threshold of 900 keV for each electron, one gets 13 candidate events in this energy window. This is in agreement with our expectations from the background (18.8 events) coming mainly from ^{222}Rn (13 events) plus the $2\beta2\nu$ contribution (5.8 events). The calculated $2\beta0\nu$ efficiency is 8.2%. As a result a limit has been

set at $T_{1/2} > 3.1 \cdot 10^{23}$ y (90% CL), which is better than the best previous measurement ($T_{1/2} > 5.5 \cdot 10^{22}$ y [24]). Using the nuclear matrix elements (NME) from [25–27], the following range of limits on the neutrino mass has been derived: $\langle m_\nu \rangle < (0.8 - 1.2)$ eV. This range can be compared with that of the ^{76}Ge experiment [16] (using the same nuclear matrix elements [25–27]), $\langle m_\nu \rangle < (0.33{-}0.84)$ eV.

For neutrinoless double beta decay caused by the right current admixture (λ term) in weak interactions the 2.8–3.2 MeV energy window was used. An additional cut on the electron energies, $|E_1 - E_2| > 800$ keV [23], allows an extra background suppression. In this case there are only 3 candidate events in the 2.8–3.2 MeV window with 2.8 (2.0+0.8) expected. With an efficiency of 4.2% this gives $T_{1/2} > 1.8 \cdot 10^{23}$ y (90% CL) and $\langle \lambda \rangle < (1.5 - 2.0) \cdot 10^{-6}$, using the NME from [28].

$2\beta0\nu\chi$ decay. The energy interval 2.65–3.2 MeV has been studied. Introducing a threshold of 750 keV for each electron one gets only 18 events (13.7+8 are expected with an efficiency of 0.49%) and the half-life limit yields $T_{1/2} > 1.4 \cdot 10^{22}$ y (90% CL). This value is better than the previous one ($T_{1/2} > 5.8 \cdot 10^{21}$ y [29]) and the corresponding limit on the Majoron-neutrino coupling constant (NME from [25–27]) is $\langle g_{ee} \rangle < (0.5 - 0.9) \cdot \cdot 10^{-4}$. This is one of the best limits for the majoron coupling constant.

Double beta decay of ^{82}Se. The energy spectrum of $2\beta2\nu$-events for ^{82}Se is shown in Fig.4. A higher threshold of 300 keV was used in order to improve the signal-to-background ratio. The total number of useful

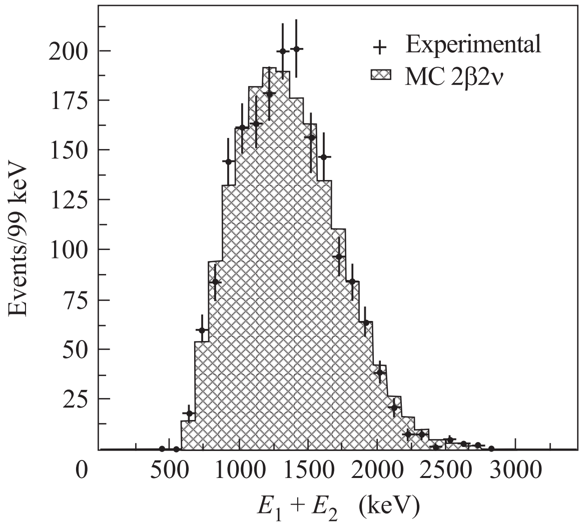

Fig.4. $2\beta2\nu$ spectrum of ^{82}Se, background subtracted

events after the background subtraction is ~ 1800. The signal-to-background ratio is approximately 4 to 1. The detection efficiency has been calculated by MC calculations to be 6.02%. The ^{82}Se half-life value obtained is,

$$T_{1/2} = [10.3 \pm 0.3(\mathrm{stat}) \pm 0.7(\mathrm{syst})] \cdot 10^{19} y.$$

This value is in agreement with our previous measurement with NEMO2 [30] and with the world average value of $(9 \pm 1) \cdot 10^{19}$ y [22].

$2\beta0\nu$-decay. Three events have been detected in the interval 2.65–3.2 MeV. The expected background in this energy windows is 5.3 events. Again this background is mainly due to ^{222}Rn. Efficiency of 15.8% gives a limit for the ^{82}Se 0ν-decay of $T_{1/2} > 1.4 \cdot 10^{23}$ y (90% CL), which is better than the previous value by one order of magnitude ($T_{1/2} > 1.4 \cdot 10^{22}$ y at 90% CL [31]). The corresponding limit on the effective neutrino mass, using NME from [25–27] is $\mathrm{m}_\nu < (1.5{-}3.1)$ eV.

For neutrinoless double beta decay caused by the right current admixture (λ term) in weak interactions, the 2.65–3.2 MeV energy window was used and a cut on the electron energy, $|E_1 - E_2| > 800$ keV [23] was applied. The number of events is zero and the efficiency is 8.5%. This gives $T_{1/2} > 1.1 \cdot 10^{23}$ y (90% CL) and $\langle \lambda \rangle < (3.2 - 3.8) \cdot 10^{-6}$, using the NME from [32, 33].

$2\beta0\nu\chi$-decay. The energy interval 2.3-3.2 MeV was studied. The number of selected events is 39, while 40 is the estimated background. Using the efficiency estimated by MC calculations (4.2%) the following limit was obtained, $T_{1/2} > 1.2 \cdot 10^{22}$ y. (90% CL). This is better than the previous best limit ($T_{1/2} > 2.4 \cdot 10^{21}$ y [30]). Using this result and the NME from [25–27] one gets the corresponding limit for the Majoron-neutrino coupling constant $\langle g_{ee} \rangle < (0.7 - 1.6) \cdot 10^{-4}$.

Presently, the NEMO3 tracking detector is continuing to collect data. At the same time, work is in progress to improve the detector's performance, background conditions and data analysis techniques. In particular a radon barrier tent has been installed and a radon trapping factory will be in operation in autumn of 2004, which will help reduce the ^{222}Rn background by a factor of 10–100. It is believed that the sensitivity of the experiment can be increased significantly in the near future.

The authors would like to thank the Modane Underground Laboratory staff for their technical assistance in running the experiment. Portions of this work were supported by a grant from INTAS N 03051-3431 and a grant NATO PST.CLG.980022.

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