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A status Report on the Double-Beta Decay Experiment NEMO 3

NEMO Collaboration*

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Abstract

The current performance of double beta decay experiments in measuring the neutrino mass is not less than 1 eV with the exception of claims from Ge experiments using favorable nuclear matrix elements. NEMO 3, a next generation detector which is currently under construction, will study ^{100}Mo, ^{82}Se and possibly ^{150}Nd. The status and expected results of this detector will be presented and compared with earlier and existing experiments, as well as the recently proposed GENIUS and CUORE experiments. Owing to kinematic factors and nuclear matrix elements, the argument is made that neutrino mass measurements by NEMO 3 with 10 kg of ^{82}Se or ^{150}Nd have the possibility of reaching a limit of 0.1 eV.

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1 Introduction

The field of double beta decay research has had great success in measuring the two neutrino decay mode, $\beta\beta 2\nu$, in several isotopes. Attention has now shifted to the zero neutrino decay modes, $\beta\beta 0\nu\chi$ and $\beta\beta 0\nu$, with and without, the emission of a Majoron. To realize this search, the detectors must be designed to address the need to study between a few and many kilogram sources. Leading this field are the multi-kilogram enriched ^{76}Ge experiments of Heidelberg-Moscow[1,2] and IGEX[3]. The hope is to discover physics which will extend the standard model or achieve lifetime limits of the order of 10^{25}y. The relevant nuclear matrix elements then define the effective neutrino mass, $< m_\nu >$.

The next experiment scheduled to come on line with plural kilograms of double beta decay sources is the NEMO 3 detector. This detector and its current construction status is presented here. A figure of merit is introduced as well to argue the likely success of this experiment.

2 Structural Design of NEMO 3

The NEMO 3 detector will be similar in function to the earlier detector, NEMO 2 [4–6] which successfully measured $\beta\beta 2\nu$ in three isotopes (see Fig. 1). More specifically, the NEMO 3 detector (Fig. 2) will operate in the Fréjus Underground Laboratory and will house up to 10 kg of double beta decay isotopes. These foils are currently being selected through a complex optimization of minimizing the background levels. To date, much attention has been focused on 10 kilograms of enriched Mo samples (97% ^{100}Mo). Also currently available are the following isotopes: 1 kg of ^{82}Se; 1 kg of ^{116}Cd; and 1 kg of ^{130}Te.

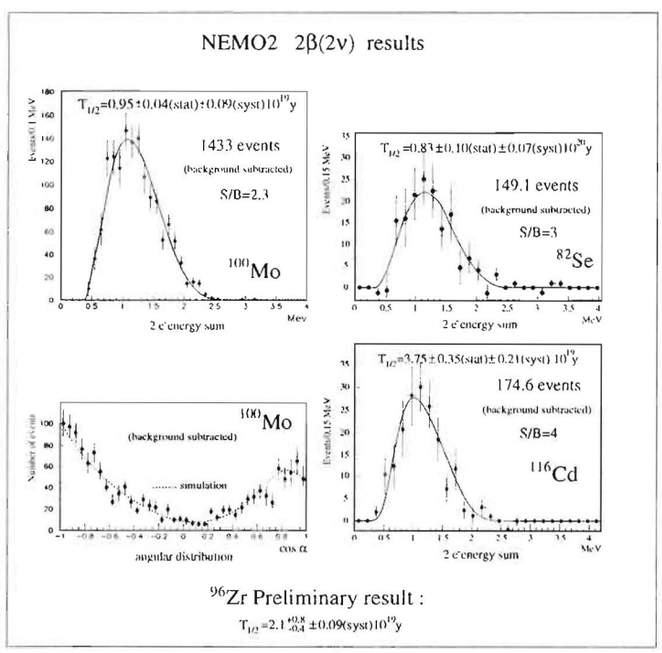

Figure 1

NEMO 3

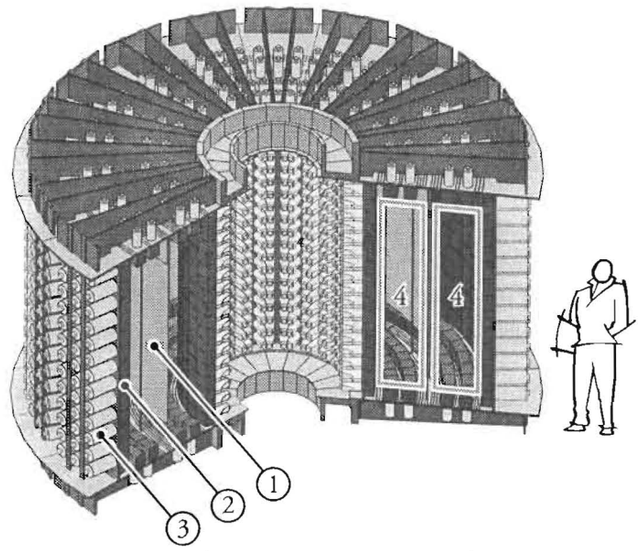

Figure 2: 1) cylindrical source foil - 2) scintillator blocks - 3) photomultiplier tubes - 4) tracking volume of drift cells.

The detector is cylindrical in design and divided into 20 equal sectors. A thin (40-50 μm) cylindrical source foil will be constructed from either a metal film or powder bound by an organic glue to mylar strips. The source will hang between two concentric cylindrical tracking volumes consisting of open octagonal drift cells operating in Geiger mode. These cells run vertically and are staged in a 4, 2, and 3 row pattern to optimize track reconstruction. The external walls of these tracking volumes are covered by calorimeters constructed with large blocks of scintillators coupled to very low radioactivity photomultiplier tubes (PMTs). The completed detector contains 6180 Geiger cells and 1940 scintillators.

3 Current Status of Construction

Of the 20 sectors required to complete the tracking and calorimeter portions of the experiment, half of the sectors will be completed by the end of July 1998 with a total of 14 completed by the end of the year. Scintillator block production by firms in Kharkov and Dubna should also be completed by the end of the year.

The design of the drift cells calls for 50 μm anode and cathode wires to prevent rapid aging. The activity in these wires is small and as background, the wires nearest the source foil will contribute to two electron events at a rate less than 10% of the background from $\beta\beta2\nu$ decays in the source foils.

The low activity 3" and 5" PMTs from Hamamatsu with associated scintillators, have an energy resolution better than that called for in the original design, 16% FWHM at 1 MeV. Currently, the resolution in the calorimeter modules associated with the vertical walls and 5" PMTs is 11% FWHM at 1 MeV, while the endcaps, which are covered with 3 inch PMTs, have 14.5% FWHM. The initial testing of all of the PMTs has been completed.

Analogue and digital readout electronics in the form of ASICs are ready for the production run. Ceramic components for the PMT bases are still being tested to identify those of the lowest radioactivity. The PMTs will be attached to the sectors after they arrive in the Fréjus laboratory, which will be at the end of 1998.

Software simulations continue to grow in detail and complexity, while a new tracking algorithm using neural networks with an elastic net has been investigated.

Additionally, a solenoid capable of producing a field of 30 gauss will surround the detector to reject pair production events. Finally, external shielding in the form of 20 cm of low activity iron will reduce gamma ray fluxes and thermal neutrons. If needed, additional shielding will be introduced to content with fast neutrons. More details on this are given below.

The current projected timeline for NEMO 3 is that in September of 1998 the placement of completed sectors will start on the frame in the Fréjus laboratory. This final stage of the construction is expected to continue until January 1, 2000. Presently, the plan is to start operating with 7 kg of ^{100}Mo and 1 kg of ^{82}Se, with some sectors filled with foils especially designed to check the background. These foils may be ^{nat}Mo, pure copper, a pair of ^{nat}Cd and ^{116}Cd, or even TeO_2 as discussed below.

4 Radiopurity of the experimental hall and detector

The experimental hall for NEMO 3 is in the Fréjus Underground Laboratory at a depth of 4800 meters of water equivalent. This reduces the cosmic ray muon flux to 4 m^{-2} per day. Vigorous flushing of the air in the hall reduces the radon levels to 10-20 Bq/m^3. The presence of ^{214}Bi decays in the detector from this level of radon contamination is below that introduced by the PMTs, thereby reducing concerns about additional reductions.

Thermal and fast neutrons in the hall are found to be at levels of 1.6×10^{-6} neutrons/s·cm^2 and 4×10^{-6} neutrons/s·cm^2, respectively. The effects of these neutrons on the earlier experiment NEMO 2 were studied with an Am-Be source and different formats and levels of shielding. A recent analysis with the software program MICAP is in good agreement with the current understanding of neutron induced backgrounds. In summary, thermal neutrons are stopped in the iron shielding while fast neutrons go through and are thermalized in the plastic scintillator blocks. The thermalized neutrons are then captured on the copper walls that support the calorimeter producing gamma rays of up to 8 MeV. MICAP simulations also generate a spectral line at 2.2 MeV suggesting that capture in the scintillators is also significant. The higher energy gammas are troublesome if they interact with the source foil by producing two electron events or pair creation. However, these rates are expected to be negligible. The magnetic field will be used to study the pair production and confirm the prediction of a negligible contribution.

Of primary importance to all $\beta\beta$ decay is the reduction of the uranium and thorium decay chains, in particular the decays of ^{214}Bi and ^{208}Tl which can generate background events which mimic $\beta\beta$ decay. Careful attention is also paid to the ubiquitous potassium.

All of the materials which have gone into the construction of the detector have been examined with HP Ge detectors at the Fréjus Underground Laboratory or at the CENBG laboratory in Bordeaux. This exhaustive examination of samples caused the rejection of numerous glues, plastics, and metals (surprisingly, some copper pieces were rejected given ^{60}Co contamination).

The activity in the mechanical pieces which frame the detector are required to be less than 1 Bq/kg. As expected, the radioactive contamination in the experiment is dominated by the low radioactivity glass in the PMTs. The total activity of all of the 0.6 tons of PMTs is, 800 Bq of ^{40}K, 300 Bq of ^{214}Bi, and 18 Bq of ^{208}Tl. These levels are three orders of magnitude below standard PMT levels. As stated earlier, there are two sources of plastic scintillators, both with very low levels of radiation. Specifically, from Dubna there are 4 tons with less than 10 Bq of ^{40}K, approximately 5.2 Bq of ^{214}Bi, and less than 2 Bq of ^{208}Tl. The one ton of Kharkov scintillators has less than 10 Bq of ^{40}K, 0.7 Bq of ^{214}Bi, and 0.3 Bq of ^{208}Tl.

One is reminded that a 75 kg human being contains 4000 Bq of ^{40}K and that a typical fingerprint contains more potassium that a 10 kg block of scintillator.

The "internal" background in the experiment is defined here as the background events coming from contamination in the foils. In the energy region of interest for $\beta\beta0\nu$ decays, there is activity from ^{214}Bi, ^{208}Tl, and the tail of the $\beta\beta2\nu$ decay distribution. The $\beta\beta2\nu$ decays ultimately define the half-life limits to which the $\beta\beta0\nu$ decays can be studied. To insure that $\beta\beta2\nu$ defines the limit, maximum levels of ^{214}Bi and ^{208}Tl were calculated. These limits are given in Table 1. For ^{100}Mo it is believed that these limits have been reached, where as for Se with a longer $\beta\beta2\nu$ decay half-life, more stringent levels are sought and will require some additional research. Note that the energetic decay of ^{150}Nd removes concerns of contamination by ^{214}Bi, but new techniques to enrich Nd will have to be developed for this to be realized.

Currently the plan is to have the ^{100}Mo source foils produced by two different processes. The first is a purification by local melting of solid Mo with an electron beam and drawing a monocrystal from the liquid portion. The monocrystal leaves behind the impurities in the slag of the melt. The crystal is then rolled into a foil for use in the detector. Some contamination was found to occur from the earlier rolling process, but a hybrid process has been developed. The hybrid process encapsulates the monocrystal in a stainless steel sheath which is rolled simultaneously into a three layer foil. The stainless steel foils are then removed.

Isotope	Events/year·10kg			mBq/kg	
	^{214}Bi	^{208}Tl	$\beta\beta2\nu$	^{214}Bi	^{208}Tl
^{100}Mo	0.4	0.4	1.1	0.3	0.02
^{82}Se	0.1	0.1	0.1	0.07	0.005
^{150}Nd	none	0.4	1.1	none	0.02

Table 1: NEMO 3 Backgrounds and Purity Criterion in the energy window [2.8 - 3.2] MeV.

The second purification method is chemical in nature and leaves the Mo in a powder form that is then used to produce foils with a binding paste and mylar strips which have been etched with an ion beam. The success of this method is currently being checked at ITEP with a chemically purified natural Mo sample. The chemical process has been most effective at ridding the samples of the U and Th decay chains. Unfortunately, the task of measuring the required limits for ^{208}Tl contamination is beyond the practical measuring limits of the HP Ge detectors in the Fréjus Underground Laboratory.

5 Isotope Selection

The NEMO 3 detector, unlike most double beta decay experiments, has the capacity to simultaneously study "source" foils of different materials. This flexibility permits comprehensive background studies. The schedule for introducing foils into the detector is still under consideration. Therefore, it is helpful to outline some of the advantages of this feature here.

The enriched samples of ^{100}Mo will initially be the primary focus of the detector. As in the study with NEMO 2, it is helpful to introduce a ^{nat}Mo foil for background studies and subtractions. This requires the knowledge that both foils are known to be very pure from HP Ge measurements.

The 1 kg of enriched ^{82}Se currently available to the collaboration may provide a $\beta\beta0\nu$ measurement below 1 eV, given a recent shell model calculations of the nuclear matrix element[7]. The possibility of getting up to 10 kg of enriched Se also exists to carry out a more extensive search as discussed below.

The use of ^{130}Te0_2 holds the interesting possibility of a $\beta\beta2\nu$ decay measurement that is not geochemical. The Q of this decay is low so the limit to which the direct measurement will reach will only test the existing lower limit of the Missouri group[8], $7\pm 2 \times 10^{20}$y.

There is a second interest in inserting ^{130}TeO_2 or even ^{nat}TeO_2, which has 34.5% ^{130}TeO_2. The effective Z of this foil is nearly the same as that of molybdenum foils. This is useful given that the external gamma ray background can give rise to pair production, double Compton scattering and Compton plus Möller scattering which are all proportional to Z^2. Thus, the background from the Mo and TeO_2 foils should give rise to similar event rates. However, in the energy region above the Q value, 2.53 MeV, Te produces no double beta decay electron pairs, so a background subtraction is possible for Mo foils given the spectrum of TeO_2.

Another approach to measuring the thermal neutron flux is to take advantage of the fact that in ^{nat}Cd there is 12.22% ^{113}Cd which has a broad neutron capture cross section of 20000 barns. In the earlier experiment, NEMO 2, the ^{113}Cd was the source of electron-gamma events and was used to confirm/measure the thermal neutron flux. Though this provides a useful diagnostic tool for studying the neutron flux, it also provides a source of two electron events within the detector which mimic double beta decay.

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6 Expected performance of NEMO 3

It is useful to compare the performance of several experiments to establish the potential success of NEMO 3. Selected for this comparison are experiments involving very different designs and experimental techniques. Starting with the best experiments today, the ^{76}Ge experiments, it is important to note that these experiments are particularly sensitive to backgrounds given their low Q value. The Heidelberg-Moscow experiment[1,2] reports a significant improvement with pulse shape discrimination (PSD) as shown in Table 2. The IGEX[3] experiment has reported similar results in the selected energy window. Looking to other studies, the ^{136}Xe experiment by Neuchâtel-Moscow-PSI[9] reported findings at the Blois '96 conference which reflected 6,000 hours of new data with an improved background in their TPC. Next it is useful to look at the bolometer experiment in search of $\beta\beta$ decay of Te. The Milano group[10] has worked with 20 crystals, 340 g each, of TeO_2 to demonstrate the feasibility of such an experiment. Though the current background is 0.48 c/keV·kg·y, significant improvements are readily available[11] as the Milano group turns its attention to backgrounds. Finally, NEMO with 14% efficiency in the window 2.8 to 3.2 MeV, is predicted to have a background of 2 events per year as indicated in Table 1. The high Q value is particularly helpful here.

To illustrate the performance of these experiments, it is helpful to consider the resolution and background of the detectors in the $\beta\beta0\nu$ decay window. A figure of merit is introduced here by multiplying the background by the resolution, to have the background cts/FWHM·kg·y. It is evident from this that the traditional argument for high resolutions in these experiments may not be so advantageous and that NEMO 3 ranks rather well.

Experiment	Background cts/keV·kg·y	Resolution	Figure of Merit cts/FWHM·kg·y
Heidelberg-Moscow			
no PSD	0.20	3.6 keV at 2 MeV	0.75
PSD	0.07	3.6 keV at 2 MeV	0.25
IGEX	0.10	3.6 keV at 2 MeV	0.36
Neuchâtel-Caltech-PSI	0.018	105 keV at 2.5 MeV	1.9
TeO_2 Bolometer	0.48	10 keV at 2.6 MeV	4.8
NEMO 3	0.0005	400 keV at 3 MeV	0.20

Table 2: Summary of Backgrounds and Figure of Merit PSD (Pulse Shape Discrimination).

The selection of which nuclear matrix element (nme) to use continues to give a broad range of results for the effective neutrino mass, $< m_\nu >$. Results are now commonly given with a variety of nme's well-suited for direct comparison. In Fig. 3 calculations for the above experiments have been performed with QRPA[12,13], Shell model[7], and SU(3)[14] nme's. It is worth noting that there seems to be a movement towards greater acceptance of shell model nme's. The projected performance with NEMO is based on 10 kg of source material with five years of running.

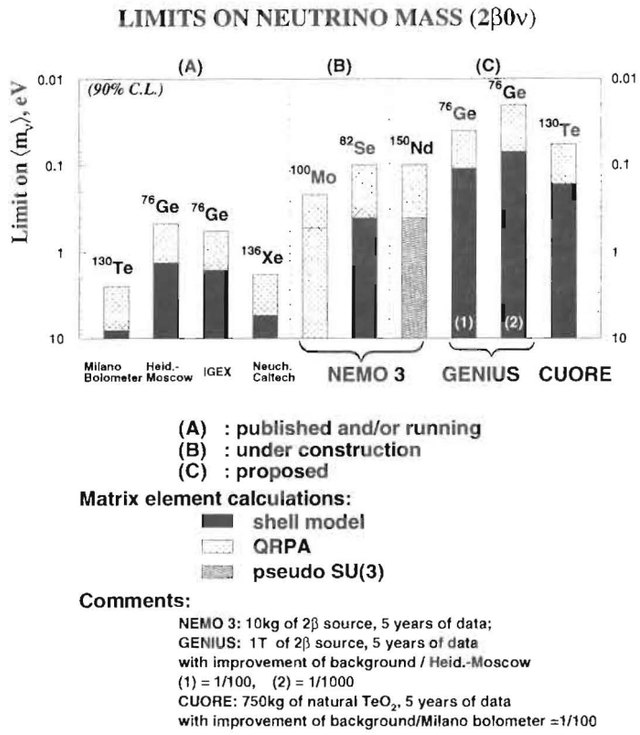

Figure 3

7 Comparison of NEMO 3 with GENIUS and CUORE

GENIUS[15] is a conceptual design of the next generation Ge experiment. Its proposed functionality far exceeds that of a double beta decay detector, but double beta decay will be the focus of the comments that follow. GENIUS, GErmanium in Nitrogen Underground Setup, is proposed to have one to ten tons of naked enriched germanium detectors suspended in a liquid nitrogen shield in a design similar to BOREXINO[16]. This ambitious proposal sights the success of several experiments in producing very low radioactivity environments while the significant increase in the mass of ^{76}Ge contributes to an improved neutrino mass limit as the square root. However, as stated in a published description, there may be trouble with ^{222}Rn in the liquid nitrogen. The level of activity required is 0.05 mBq/m^3 which is a factor of 600 better than the water shielding of BOREXINO (30 mBq/m^3). The background design criteria for GENIUS are then 0.04×10^{-3}counts/keV.y.kg versus 0.07 counts/keV.y.kg of the current Ge experiment which argues an impressive factor of 3.5 orders of magnitude reduction in the background/kg.

It is perhaps more realistic to assume some contamination will find its way into the detector by the above mentioned ^{222}Rn problem, or there will be impurities in generating such a large volume of ^{76}Ge in the Russian centrifuges, or simply be impurities in contacts and wires as they now exist. It is thus interesting to look at GENIUS if it operates with one ton Ge detectors for five years with a factor of 100 or even a 1000 improvement in the background over the current Heidelberg-Moscow experiment. This can be seen in Fig. 3 along with the projected performance of the CUORE experiment[17] which is the next generation detector for the Milano TeO_2 experiment. Here the results for CUORE assume an improvement by a factor of 100 in the background of the current experiment.

8 Conclusion

As one compares the limits on $< m_\nu >$ the playoff of different nuclear matrix elements for different isotopes becomes quite evident. The potential of NEMO 3 to bridge the gap between existing and future Ge experiments has been argued here. A figure of merit was introduced which combines the resolution and backgrounds. In this figure of merit NEMO 3 shows very strong performance.

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