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NEMO 3, A DETECTOR TO INVESTIGATE THE NEUTRINO MASS IN THE 0.1 eV RANGE

NEMO Collaboration

Contributed paper to Neutrino 94 Conference
Eilat, Israel, May 29-June 3, 1994

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Abstract

The objective of the proposed experiment is to investigate double-beta decay without the emission of neutrinos. A variety of emitters will be studied (^{100}Mo, ^{116}Cd, ^{96}Zr and ^{150}Nd). The research program which is currently in progress is the next generation experiment to supersede NEMO 2 and will again use Geiger drift cells for tracking and plastic scintillators as calorimeters. The first double-beta decay source (10 kg of ^{100}Mo) to be studied will be capable of achieving a half-life of the order of 10^{25}y for the zero-neutrino double-beta process corresponding to a neutrino mass of a few times 0.1 eV and a lifetime of 10^{23}y for the Majoron emission which corresponds to a coupling constant of 10^{-5}. A description of the detector is given and performance predictions presented with simulations for all modes of double-beta decay.

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1. GENERAL INTRODUCTION

The aim of the proposed experiment is to investigate double-beta decay without the emission of neutrinos. This research is one of the principal topics in neutrino physics, which is a subfield of particle physics with cosmological and astrophysical implications. Since the first observations of the electronic neutrino in a nuclear reactor, the muonic neutrino in 1962 in an accelerator, and then the demonstration of the tau neutrino in 1974 using an e^+e^- storage ring, much has been learned about the detailed structure of its interaction with matter, particularly with the discovery of neutral currents in 1973 by A. Lagarrigue's team at CERN. In contrast, we know much less about the neutrino's intrinsic properties.

A fundamental problem is whether neutrinos are massless. No principle excludes the possibility of massive neutrinos and modifications to the standard model may provide a natural explanation for the minuteness of the neutrino mass. In this case the neutrino constitutes its own antiparticle (the Majorana neutrino).

Double-beta decay without neutrino emission, $\beta\beta0\nu$, can be observed if the neutrino is a massive Majorana particle. It is proposed that there is an exchange of neutrinos between two neutrons in the same nucleus leading to the emission of two electrons. The Majorana mass term enables transitions through the $V - A$ interaction alone. The observation of $\beta\beta0\nu$ radioactivity would then prove the Majorana nature of the neutrino.

Investigation of $\beta\beta0\nu$ in transitions to a 2^+ excited state is also possible using a Majorana mass term if the $V + A$ interaction exists. Other mechanisms may contribute to the double-beta decay process without neutrino emission, in particular the emission of a Majoron, the boson associated with the spontaneous symmetry breaking of lepton number. Research on this process imposes additional constraints on the experiment, as it involves a three body decay spectrum in the final state with the Majoron not being detected. To fully understand the double-beta decay process, the three different decay modes must be investigated. This is the objective of NEMO (Neutrino Experiments in MOlybdenum).

In all double-beta decays, which are second order weak interactions, certain nuclei may transform themselves into daughter nuclei by emitting two electrons accompanied by two undetected neutrinos ($\beta\beta2\nu$). Studies of the isotopic abundances in samples using geochemical methods have suggested the existence of ^{82}Se, ^{130}Te and more recently ^{96}Zr double-beta decay. The first direct experimental observation by the detection of two electrons in the final state, was claimed in 1987 by M. Moe's team at U.C. Irvine in ^{82}Se and later in ^{100}Mo. Other calorimetric-type experiments have observed ^{76}Ge decay [1].

The proposed experiment aims to investigate the Majorana neutrino mass down to the level of 0.1 eV, thus considerably improving the sensitivity of present day experiments. Bearing in mind the uncertainty in the nuclear matrix elements for the process, such a mass limit corresponds to neutrinoless double-beta decay in the ^{100}Mo nucleus with a half-life of the order of 10^{25} years.

The choice of nuclei to be studied is constrained by several parameters which are the transition Q value, the nuclear matrix elements of the transitions $\beta\beta0\nu$ and $\beta\beta2\nu$, the background in the energy region close to Q, the possibility of reducing the radioactivity of the material studied to acceptable levels, and finally the natural isotopic abundance of the candidate. Basing the choice on nuclear matrix element data is undesirable since current theoretical calculations are not definitive. In contrast, the Q value is an important parameter for all discussions of backgrounds. Therefore, an important consideration used in the selection of a double-beta decay candidate has been to identify isotopes whose Q values are above the 2.614 MeV gamma transition, which is an important background and is produced in the decay of ^{208}Tl. From a preliminary list of double-beta decay candidates, five nuclei with an isotopic abundance greater than 2 % (which allows for enrichment) satisfy this criterion: ^{100}Mo, ^{116}Cd, ^{82}Se, ^{96}Zr and ^{150}Nd. Particular efforts have been made by the NEMO collaboration to study ^{100}Mo, but the proposed experiment is not limited to this nucleus alone, since the source can be changed in the detector.

Independence of the source and detector has been a primary concern in the design of this experiment. It follows that if an excess of events is observed, which could be due to $\beta\beta0\nu$ in a small statistics experiment, then the ability to study four other nuclei would be crucial for confirmation and would reduce the dependence of the interpretation on the nuclear matrix elements of the forbidden process. The allowed process, $\beta\beta2\nu$, constitutes the ultimate background in the search for $\beta\beta0\nu$ in the experiment which has an energy resolution of several percent. Although it might appear that the rarer the allowed process, the better the candidate nucleus, in fact the choice is complicated by possible correlations between the two nuclear matrix elements of the allowed process and the forbidden process which are not currently known. The hypothesis that there exists a scale factor between the two nuclear matrix elements cannot be excluded.

Measurements of double-beta decay with a half-life as long as 10^{25} years is difficult. The measurement requires not only considerable knowledge and understanding of natural and cosmogenic radioactive backgrounds in the materials from which the detector itself is made, but also backgrounds induced by the radioactivity of the walls and atmosphere in the underground laboratory where the experiment will operate. An effective purification process for molybdenum has been tested and is available and well understood, while a study of cadmium is still underway. Current simulations involving background contamination give insight on restrictions to the detector geometry and levels of contamination in materials used in its construction. Correspondence between expected and actual performance has been demonstrated in the experimental results from our research and development program. Since 1988, the NEMO collaboration has step-by-step studied different background sources and has identified techniques and designs to provide suitable rejection criteria.

Two prototypes, NEMO 1[2] and NEMO 2[3] have been constructed and run to demonstrate the feasibility of the techniques. The approach has been to develop detection equipment which enables complete characterization of two-electron decays, including reconstruction of trajectories, direction of propagation, measurement of energy, and tagging of photons. All technical choices have been made with the consideration that a possible extrapolation by a factor of ten in the size of the detector would still be practical. Particular attention was given to low levels of radioactivity in the materials employed in the construction of the prototypes. At present, only the photomultiplier tubes have not been optimized for low levels of radioactivity and improvements in this area are near completion. Measurements of samples of enriched and natural molybdenum have been made over the past four years with ultra low radioactivity germanium detectors specially developed to measure levels of ^{214}Bi and ^{208}Tl contamination to the order of a mBq/kg (milli-Becquerel per kg).

Special attention was given to the measurements of radioactivity in the metallic foils placed in the center of the NEMO 2 detector. Gamma-ray cascades were detected and a comparison was made with results of gamma-ray spectroscopy. The effects and signature of a neutron flux in the Fréjus Underground Laboratory was studied by placing a neutron source near but outside the shielding of the detector. Similarly the effects of radon in the laboratory atmosphere have been measured and techniques to remove the radon are under investigation. The proof of understanding the backgrounds has been the measurement of the $\beta\beta 2\nu$ half-life of ^{100}Mo. The NEMO 2 detector performed this measurement with an enriched molybdenum metallic foil (172 g)[4].

Development of NEMO 3 which is the next generation detector was begun more than one year ago[5, 6]. It reflects a 10 fold enhancement of NEMO 2 in order to probe a half-life of 10^{25} years for the $\beta\beta 0\nu$ process and 10^{22} years for $\beta\beta 2\nu$. The detector has a cylindrical geometry which enables a solid angle acceptance which approaches 4π. A weak magnetic field of 30 Gauss is supplied by a solenoid surrounding the detector to improve background rejection. Electron energies are measured by plastic scintillators which are also used for time-of-flight measurements. The scintillator's thickness was chosen to obtain the necessary efficiency for tagging gamma rays from natural radioactivity. Finally, the scintillators also permit the observation of de-excitation gammas of the daughter nuclei produced by $\beta\beta 2\nu$ and $\beta\beta 0\nu$ decay. Lead and iron shields protect the detector from non airborne ambient radioactivity in the Fréjus Underground Laboratory. The expected performance of NEMO 3 for $\beta\beta 2\nu$ and $\beta\beta 0\nu$ will be discussed in the context of different levels of background contamination.

2. GENERAL PROPERTIES OF NEMO 3

The NEMO 3 experiment is a detector designed to be sensitive enough to measure a double-beta decay half-life limit of 10^{25} y for the $\beta\beta 0\nu$ decay, 10^{23} y for the $\beta\beta M^0$ decay, and 10^{22} y for the $\beta\beta 2\nu$ decay.

The research and development program to study Geiger cells has clearly shown that three dimensional track reconstruction is possible. The reconstruction is based on the avalanche propagation along the sense wire with all the wires/cells in the same direction. Therefore a compact cylindrical geometry with a large solid angle acceptance detector is an efficient configuration for the NEMO 3 detector. Accordingly, the source will be a cylindrical foil 2.8 m in diameter, 2 m in height and 50 μm thick, with a total mass of roughly 10 kilograms of enriched isotopes. Sources will be interchanged to study different isotope candidates.

Two concentric tracking volumes will surround the source foil in a fashion similar to that in NEMO 2. To accomodate the increased height of the detector the length of the wires in the tracking volume will be increased by a factor of three. There will also be an improvement in the transparency of the detector by decreasing the field wire diameter of the drift cell from 100 μm to 30 μm. As in NEMO 2 the time and energy measurements are provided by arrays of plastic scintillators. The main change in this aspect of the experiment is the increased number of plastic scintillators (1940 units) and their thickness (10 cm). The increased thickness is instrumental in providing greater efficiencies for tagging γ rays. Moreover, the fine granularity of these counters allows for robust detection of $2e + \gamma$ events coming from decays of the excited states.

An important finding in the research and development program was the need for a magnetic field. Consequently, a solenoid surrounding the detector will provide a 30 Gauss field parallel to the foil axis. The magnetic field will be used to identify the signature of positron-electron pairs produced in the source by high energy gamma rays. Curvature measurements also permit an extra rejection factor for incoming electrons and reveal the presence of simple beta emitters such as ^{90}Sr and ^{234m}Pa. Finally, $\beta^+\beta^+$ decays can also be studied.

In the detector an electron will be identified as a track with nine measurements along its trajectory. Each measurement provides three coordinates that will make it possible to unambiguously reconstruct the track. The energy of each electron is measured by the plastic scintillators associated with a track's end point. A photon is identified as a single or cluster of triggered scintillators with no associated tracks. Alpha particles can be identified as straight tracks stopping in the gas. It is worthwhile to point out that the NEMO 3 detector will be detecting multi-particle events in the low energy domain of natural radioactivity.

3. DESCRIPTION OF THE NEMO 3 DETECTOR

3.1 Source

The general layout of the NEMO 3 detector is shown in Fig. 1. The detector is segmented into 20 sectors (Fig. 2) which permits easy servicing of the detector and access to patchwork source foils. Currently the proposed source foil is 10 kg of ^{100}Mo. Monitoring the external background can again be done with an OFHC copper "source" foil as in NEMO 2.

3.2 Tracking

The Geiger drift cells are the same as in NEMO 2 but the length of the cells are increased by a factor of three. All the cells are vertical and as such parallel to the axis of the cylinder. The previous prototypes demonstrated that the longitudinal coordinate of the particle track can be measured by the plasma propagation time induced in the Geiger regime. The accuracy in the transverse and longitudinal position measurements are the same as that measured in NEMO 1 and NEMO 2, $\sigma_T = 0.5$ mm and $\sigma_L = 5$ mm.

3.3 Energy and TOF measurements

Energy and TOF measurements will be performed as in NEMO 2 by plastic scintillators covering the two vertical surfaces of the active tracking volume. To further enhance the acceptance efficiency, the end caps will be equipped with scintillators in the spaces between the Geiger cell layers.

The photon detection efficiency will be improved by increasing the thickness of the plastic scintillator (10 cm instead of 2 cm as in NEMO 2). The front face of the scintillator (20 cm $\times$ 20 cm) is larger than in NEMO 2 (12 cm $\times$ 12 cm) corresponding to a compromise between resolution and an affordable number of PMTs. The expected energy and time resolution (FWHM) are 16% and 700 ps at 1 MeV.

3.4 Magnetic field and shielding

As it has been shown in NEMO 1 and NEMO 2 with neutron sources, the high energy γ-rays induced by neutron capture in the detector create e^+e^- pairs in the 3 to 8 MeV energy region. The 30 Gauss magnetic field induces a unique signature for the e^+e^- events. Additionally, the magnetic field will provide an extra rejection factor for incoming electrons.

Studies with NEMO 1 have shown that an effective shield for the attenuation of γ-rays and neutrons is a combination of 5 cm of lead surrounded by 20 cm of low activity iron.

4. THE NEMO 3 DETECTOR SIMULATION

The simulation of the detector was accomplished with GEANT (version 3.15) to predict the detector's performance in the various decay channels of interest. For each channel studied and in the study of background sources, 10^5 to 10^6 decays were generated and analysed.

4.1 Detector characteristics

The foil thickness of 50 μm corresponds to 10 kg of ^{100}Mo. However, calculations show that the results are not very sensitive to the foil thickness. In order to speed up the computations, the wires of the Geiger cells (30 μm field shaping and 100 μm sense wires) were not included in the simulation's geometry. This is of negligible importance when considering ratios of events generated by the different processes. The magnetic field was fixed at 30 Gauss and the $FWHM$ energy resolution of the scintillation counters is taken as $0.16\sqrt{E}$ (E in MeV).

4.2 Kinematics

For the $\beta\beta$ decays of ^{100}Mo to the ground state of ^{100}Ru, events were generated according to the Primakoff-Rosen approximation which was tested and shown to be adequate in the following studies, thus:

$$\begin{aligned} dw &\approx (1+qt_1)[1+q(1-t_1)]^2(1-\beta_1\beta_2\cos\theta)dt_1 d\cos\theta & (\beta\beta 0\nu) \\ dw &\approx (1-t_1-t_2)^5(1+qt_1)^2(1+qt_2)^2(1-\beta_1\beta_2\cos\theta)dt_1 dt_2 d\cos\theta & (\beta\beta 2\nu) \end{aligned} \quad (1)$$

where $q = Q/m_ec^2$, $t = T/Q$ and $T = T_1 + T_2$ with T_1 and T_2 being the kinetic energies and with β_1 and β_2 the velocities of the electrons. Here $\cos\theta$ is the cosine of the angle between the two electrons. The generated energy sum spectrum for the $\beta\beta 2\nu$ events is shown in Fig. 3.a. The angular distributions for $\beta\beta 0\nu$ and $\beta\beta 2\nu$ events are presented in Figs. 4.

4.3 Tracking of the particles through the detector

In the analysis of the tracking volume efficiency, the following physical processes were taken into account for e^+ and/or e^-: multiple scattering, δ ray production and ionization, bremsstrahlung, positron annihilation. For photons the analysis of the interactions involve the photoelectric effect, Compton scattering and pair production.

4.4 Selection of two electron events

An electron is defined as a track connecting the source foil and a scintillator without having its path re-cross the foil. For $\beta\beta$ decay to the ground state an event should have no more than two electrons and have no detected photon. The photon detection threshold is 20 keV to guarantee a high detection efficiency for X-rays associated with background events.

If an event satisfies the above criteria a threshold of 300 keV is applied to the electron signal. This cut does not significantly affect the detection efficiency. In addition a soft time of arrival difference cut of 5 ns is applied to the two electrons to reject through going particles which do not originate in the foil.

Figs. 3(b,c) shows the summed electron energy spectra for $\beta\beta 2\nu$ and $\beta\beta 0\nu$, respectively. Figs. 4(c,d) represent the cosine of the angle between the two electrons for the same channels. The distortion of the cos θ distributions is mainly due to scattering in the molybdenum foil and the geometrical acceptance of the detector.

5. SENSITIVITY OF THE EXPERIMENT

5.1 Decay of ^{100}Mo to the ground state of ^{100}Ru

Assuming a $\beta\beta 2\nu$ half live of 10^{19}y, and data collection for 2.5 years with a source of enriched ^{100}Mo of 10 kg, Fig. 5 shows a scaled signal for $\beta\beta 0\nu$ for the arbitrary value $T_{1/2}$ ($\beta\beta 0\nu$) of 10^{23}y. For the decay with Majoron emission the grey histogram of Fig. 6 represents the corresponding two electron summed energy distribution. In this case the $\beta\beta 2\nu$ background is more important than in the case of the $\beta\beta 0\nu$ decay. The lower limit for the half-life which can be reached for the $\beta\beta M^0$ decay mode is 10^{23}y which is calculated using a summed energy cut at 2.5 MeV.

5.2 Decay of ^{100}Mo to the excited states of ^{100}Ru

Although the decay rate is strongly dependent on the transition energy, which is obviously lower for a decay to an excited state, the possibility of detecting the emission of the two electrons in coincidence with the de-excitation gamma ray(s) is helpful in the rejection of background events. However events decaying to the 2_1^+ level ($\beta\beta$ $(0^+ \to 2_1^+), E_\gamma$ = 540 keV) are also selected by the coincidence of two electrons and one photon ($2e + \gamma$ channel). The energy of the photon must be larger than 100 keV to reject bremsstrahlung photons and smaller than 600 keV to account for the finite energy resolution of the scintillator counters. The photon must be in a counter which is not the same as those triggered by the electrons. In the case of the decay to the 0_1^+ level ($\beta\beta$ $(0^+ \to 0_1^+), E_\gamma = 591$ keV and 540 keV), two photons are sought in the same energy range as in the previous case.

$0^+ \to 2_1^+$ transition

Although the $0^+ \to 2_1^+$ $\beta\beta 2\nu$ decay mode is less favored because of the cancellation of the phase space integral, the simulation of such decays in the detector was studied. Fig. 7 shows the shape of the summed electron energy spectrum together with the spectrum produced by $0^+ \to 0_1^+$ $\beta\beta 2\nu$ events where an extra photon originates from bremsstrahlung and is detected with an energy larger than 100 keV. The calculations show that a limit on the half-life of about 3.10^{22}y can be achieved for the $0^+ \to 2_1^+$ $\beta\beta 2\nu$ transition.

The detector's configuration is particularly well suited for the detection of the $\beta\beta 0\nu$ $(0^+ \to 2_1^+)$ decay as shown in Fig. 8 which reveals a detection efficiency as high as 14% where the background from the $0^+ \to 0^+ \beta\beta 2\nu$ decay mode is strongly suppressed. Given a cutoff at 2.1 MeV on the summed energy, the efficiency for detecting a background decay ($\beta\beta 2\nu$) is only 10^{-6}. Thus NEMO 3 should reach a lower limit of 3.10^{24}y for the half-life of $\beta\beta 0\nu$ ($0^+ \rightarrow 2_1^+$).

$0^+ \rightarrow 0_1^+$ transition

For the sake of completeness there was an investigation of the $\beta\beta 2\nu$ and $\beta\beta 0\nu$ modes in the transition to the 0_1^+ excited state. Here the event selection requires the detection of two gamma rays with energies between 100 and 600 keV along with two electrons. These channels are almost background free except from possible internal background. Given a summed energy cut around 1 Mev to avoid internal background, half-life limits of 2.10^{22}y for the $\beta\beta 2\nu$ mode and 10^{24}y for the $\beta\beta 0\nu$ mode can be achieved.

6. INTERNAL BACKGROUND CONTRIBUTION WITHIN THE ^{100}Mo

The presence of impurities in the molybdenum foil may give rise to two-electron events which imitate $\beta\beta$ decay. In particular β decaying nuclei can produce a second electron by internal conversion from the excited daugter nucleus or by direct Mϕller scattering.

6.1 Background in the $\beta\beta 0\nu$ decay to the ground state

Two nuclei with large Q values may produce backgrounds in the 3 Mev region. These are ^{214}Bi ($Q = 3.270$ MeV) and ^{208}Tl ($Q = 4.992$ MeV). In order to estimate the acceptable levels of ^{214}Bi and ^{208}Tl in the molybdenum foil the behavior of the decays of these nuclei in the detector have been simulated. A program describing all possible cascades of ^{214}Bi and ^{208}Tl has been used to generate the kinematics of the events.

Fig. 9 represents the summed energy spectrum of the events with only two electrons detected ($2e + 0\gamma$ channel) from ^{214}Bi. It shows that an activity of 0.4 mBq/kg produces 1.2 events above 2.8 MeV per year. Fig. 10 is the corresponding figure for ^{208}Tl. An activity of 2.10^{-2} mBq/kg leads to 1.2 events per year in the energy interval 2.8 to 3.3 MeV.

6.2 Background in the decay mode to the excited state

When the ^{100}Mo $\beta\beta$ decays to an excited state the smaller energy requires a lowering of the summed electron energy cut. As a consequence, additional nuclei present in the foil may contribute to the background. Fig. 11a gives the probability that a β decay of a given nucleus can mimic a $\beta\beta$ decay to the 2_1^+ excited state which has the $2e + 1\gamma$ signature. Fig. 11b is the corresponding figure for the decays which mimic $\beta\beta$ decay to the 0_1^+ excited state with the $2e + 2\gamma$ signature.

The expected limits on the different channels are summarized in Tab. 1. These limits take into account the presence of 2.10^{-2} mBq/kg of ^{208}Tl and 0.4 mBq/kg of ^{214}Bi. The limits are only improved by 10% to 40% if the ^{214}Bi activity is reduced from 0.4 mBq/kg to 0.04 mBq/kg.

Decay mode	Half-life (years)
$\beta\beta 2\nu$ $(0^+ \rightarrow 2_1^+)$	3.10^{22}
$\beta\beta 0\nu$ $(0^+ \rightarrow 2_1^+)$	3.10^{24}
$\beta\beta 2\nu$ $(0^+ \rightarrow 0_1^+)$	2.10^{22}
$\beta\beta 0\nu$ $(0^+ \rightarrow 0_1^+)$	1.10^{24}

Table 1: Half-life limits on $\beta\beta$ decay to the excited states assuming 2.10^{-2} mBq/kg of ^{208}Tl and 0.4 mBq/kg of ^{214}Bi.

7. SOURCE ACTIVITY MEASUREMENT BY NEMO 3

As demonstrated in the NEMO 2 detector it is capable of measuring its own internal background activity in the foil. In NEMO 3, with a 10 kg source, a close to 4π solid angle acceptance, and a much higher photon tagging efficiency, the very low levels of internal activity will be measured with good accuracy. This internal background is detected via the $e\gamma$, $e\gamma\gamma$, $e\gamma\alpha$ and $e\gamma\gamma\alpha$ events.

7.1 The $e\gamma$ channel

The ^{214}Bi and ^{208}Tl spectra of Fig. 12 show a strong difference in their behavior at high energies. Given ^{208}Tl activity of 2.10^{-2} mBq/kg and selecting events with $E_\gamma > 2.4$ MeV and $E_e + E_\gamma > 3$ MeV, 95 events/y are measured while 0.4 mBq/kg of ^{214}Bi produces only 11 events/y. Other nuclei such as ^{60}Co, ^{212}Bi, ^{228}Ac, and ^{234m}Pa do not contribute because of their lower energy photon spectra. For measurements of ^{214}Bi contamination, E_γ cuts of 1.4 MeV to 2.0 MeV with an activity of 0.4 mBq/kg produces 1340 events/y while ^{208}Tl contributes 55 events/y given 2.10^{-2} mBq/kg. Note also that the other four nuclei mentioned above contribute negligeably even at 2.10^{-2} mBq/kg.

7.2 The $e\gamma\gamma$ channel

The spectra of the most energetic gammas are shown in Fig. 13 for ^{214}Bi and ^{208}Tl. It is evident that their behavior is different in the high energy region. A simple cut of $E_{\gamma_{max}} > 1.8$ MeV eliminates all the ^{214}Bi contribution and other nuclei which are to be taken into account in ^{208}Tl studies. Given this cut, one still gets 118 events/y for 2.10^{-2} mBq/kg. As far as the ^{214}Bi activity measurement is concerned, the contributions due to ^{208}Tl and ^{60}Co have to be minimized, this is done with the cuts $0.9 < E_e <$ 1.4 MeV and $E_{\gamma_1} + E_{\gamma_2} < 1.5$ MeV. So for 0.4 mBq/kg of ^{214}Bi, 415 events/y are obtained while the contributions of ^{208}Tl (2.10^{-2} mBq/kg) and ^{60}Co (2 mBq/kg) are respectively 15 events/y and 30 events/y. The use of both channels, for internal activity measurements provides a cross check on the method and an estimation of the accuracy in each case. The external backgrounds coming from ^{208}Tl and ^{214}Bi, via external photons are expected to be negligible in particular in the $e\gamma\gamma$ channel.

7.3 Channels $e\gamma\alpha$ and $e\gamma\gamma\alpha$

The detection of ^{214}Bi using the delayed α particle of ^{214}Po ($T_{1/2} = 164\ \mu s$) will provide NEMO 3 with different methods for measuring the level of contamination of the source foil. The very low background in these two channels has been checked in NEMO 2 and allows the measurement of the same order of contamination of the source foil (0.4 mBq/kg of ^{214}Bi).

8. EXTERNAL BACKGROUND SENSITIVITY

The "external background" is defined as events produced by γ-ray sources located outside the central foil. It is known from γ-ray spectroscopy that the main component of the external radioactivity comes from the PMTs and to a less extent from the radon gas circulating around the tracking chamber.

In contrast to the internal background, the external background cannot be simulated accurately for two reasons. The precise locations of the radioactive sources are not known, and the computing time rapidly becomes prohibitive. Limited studies have been made using the GEANT program and assuming that the external events are only produced by the radioactivity in the glass of the PMTs. In these studies there is agreement to within $\approx 30\%$ for the counting rate, and good agreement between the calculated and the experimental energy spectra for the NEMO 2 detector.

The energy spectra of the external background in the 2e and $e\gamma$ channels have been measured in the NEMO 2 experiments using very pure copper foils. As expected the final 2e spectrum, corresponding to a run of 6000 h, does not have events above 2.2 MeV. This result implies that the external background is not a background for the $\beta\beta0\nu(0^+ \rightarrow 0^+)$ process. Below 2.2 MeV the shape of the spectrum and the total counting rate of ≈ 0.10 counts/h ($S/B = 3$) becomes troublesome for the $\beta\beta2\nu$ process, and limits the sensitivity of the present NEMO 2 detector to a $\beta\beta2\nu$ half-life of around 3.10^{19} y. At the end of 1993, new 3" EMI PMTs (50 units), built with a low radioactivity glass, replaced the existing tubes in the NEMO 2 detector. Calculations have shown that this change should improve the ability to detect $\beta\beta2\nu$ by more than an order of magnitude ($S/B \approx 1$ for $T_{1/2} \approx 10^{21}$ y).

In the NEMO 3 detector, one expects $\approx 8.10^5$ detected $\beta\beta2\nu$ events in a year given 10 kg of enriched molybdenum (> 95%), a detection efficiency of 20% for 2e events, and a half-life of 10^{19} y. Assuming 1000 low radioactivity 5" PMTs ($\approx$ 500 g glass each), the γ flux impinging on the central foil can be estimated to be $\approx 10^5$ γ/h. These γ-rays will generate 2e events mainly through the Compton effect and then by Mϕller scattering since the double Compton effect is negligible (factor of $\approx$ 10 lower). The e^+e^- events are rejected by the magnetic field. Simulations with the GEANT code have shown that $\approx$ 700 external 2e events are expected in one year, which leads to a S/B ratio of ≈ 1 for a half-life $T_{1/2}$ $(\beta\beta2\nu) = 10^{22}$ y. Note, that an additional rejection ($\approx$ 50%) of the external background events is also given by tagging γ-rays.

The above discussion has been made keeping in mind that the measurement of the $\beta\beta2\nu$ spectrum assumes an energy threshold as low as possible (400 keV in NEMO 2 and NEMO 3 for the total event energy). However, the analysis of the NEMO 2 data with enriched and natural molybdenum has shown that when using an energy cut $E_{tot} >$ 1.5 MeV both the internal and external background rates become negligible as compared to the $\beta\beta2\nu$ counting rate. Since this ratio will increase by at least one order of magnitude with the use of low activity PMTs, it is deduced that a half-life of 10^{22} y can easily be measured with the NEMO 3 detector.

If the use of low activity PMTs strongly reduces the external background rate, it is noted that the activity of the radon gas could be a serious limitation, unless the air ventilation system of the Fréjus laboratory is controlled and the detector is surrounded by a radon tight shield. However, the fact that in NEMO 3 the scintillators are within the gas filled tracking chamber, there will be a reduction in the influence of radon in comparison with the NEMO 2 detector.

Concerning the neutron and high energy γ-rays, they mainly produce e^+e^- pairs which are rejected via charge track recognition in the magnetic field.

9. SENSITIVITY OF THE NEMO 3 DETECTOR TO STUDIES OF $\beta\beta0\nu$ IN OTHER NUCLEI

The handy feature of NEMO 3 which permits different source foils to be introduced to the detector invites a discussion and prediction of the efficiency of the experiment in $\beta\beta0\nu$ studies of ^{96}Zr and ^{150}Nd. The Q values for these two candidates are 3.35 MeV and 3.67 MeV respectively. In the region beyond 3 MeV there are no events generated by the decay of ^{214}Bi while the contribution from ^{208}Tl persists. However, the background contribution from ^{208}Tl in the energy region of interest for $\beta\beta0\nu$ in ^{96}Zr and ^{150}Nd is reduced by a factor of approximately two when compared with the corresponding window for $\beta\beta0\nu$ searches in ^{100}Mo.

In terms of an effective neutrino mass, while taking into account the range of nuclear matrix elements, a limit of 0.15 eV can be reached in five years with 1 kg of ^{96}Zr and ^{150}Nd. To measure a signal, at the 95% CL a source of 5 kg of ^{96}Zr or ^{150}Nd studied for five years, will provide a 0.2 eV neutrino mass measurement given negligible backgrounds.

10. CONCLUSIONS OF THE NEMO 3 SIMULATION

In summary, the expected half-life limits attainable with the NEMO 3 detector in the channels discussed previously, are presented in Tab. 2. These limits, obtained with 10 kg of ^{100}Mo and five years of data collection, take into account the presence of internal impurities at a level of 2.10^{-2} mBq/kg of ^{208}Tl (equivalent to one ppt of ^{232}Th if the decay chain is in equilibrium) and 0.4 mBq/kg of ^{214}Bi (equivalent to ten ppt of ^{238}U if the decay chain is in equilibrium).

Mode	Channel	$T_{1/2}$ (y) at 90% CL	Parameters and Limits	
$\beta\beta0\nu\ (0^+ \to 0^+)$	$2e$	$5\,10^{24}$	$<m_\nu>$ (eV)	0.07 - 0.45
			$<\lambda>$ ($\times10^7$)	3.3 - 4.4
			$<\eta>$ ($\times10^9$)	2.3 - 2.6
$\beta\beta M^0$	$2e$	$1\,10^{23}$	$<g_M>$ ($\times10^5$)	0.5 - 3.3
$\beta\beta0\nu\ (0^+ \to 2^+)$	$2e+\gamma$	$3\,10^{24}$	$<\lambda>$ ($\times10^6$)	2
$\beta\beta0\nu\ (0^+ \to 0^+_1)$	$2e+2\gamma$	$1\,10^{24}$	$<\eta>$ ($\times10^6$)	2

Mode	Channel	$T_{1/2}$ (y) at 90% CL
$\beta\beta2\nu\ (0^+ \to 2^+)$	$2e+\gamma$	3.10^{22}
$\beta\beta2\nu\ (0^+ \to 0^+_1)$	$2e+2\gamma$	2.10^{22}

Table 2: NEMO 3 expected limits for 10 kg of ^{100}Mo observed for five years and with a ^{208}Tl and ^{214}Bi contamination at the level of 2.10^{-2} mBq/kg and 0.4 mBq/kg, respectively.

A two sigma effect from a null signal is expected for the $\beta\beta0\nu$ decay if the half-life is lower than $3.\,10^{24}$ y. The $\beta\beta2\nu$ signal will lead to about a million events per year for the ^{100}Mo, while for another nuclei the process will be above the background ($S/B \geq 1$) if the half-life is lower than 10^{22} y generating at least a thousand events per year. The angular distribution of the two outgoing electrons can be studied if the foil thickness is decreased from 50 μm to 10 μm to reduce the multiple scattering effects. The precise measurement of the $\beta\beta 2\nu$ will be useful in understanding the nuclear matrix elements involved, a necessary step in the interpretation of the $\beta\beta 0\nu$ process.

In terms of half-life limits, the improvements are two to three orders of magnitude when compared to present limits on ^{100}Mo. It is possible to obtain an order of magnitude improvement on the effective mass of the neutrino $<m_\nu>$ as well as on the right-handed current parameters $(<\lambda>, <\eta>)$, over the present ^{76}Ge result. The Majoron coupling constant $(<g_M>)$ limit can be improved by an order of magnitude relative to the ^{76}Ge result. The present limit is derived from the geochemical ^{108}Te experiment and can be reached with NEMO 3. Concerning the $\beta\beta 0\nu$ decay induced by photino, zino and gluino exchange, NEMO 3 can improve the limits on squark mass by only a factor of three compared to present $\beta\beta 0\nu$ constraints. Using the $\beta\beta\tilde{\nu}\tilde{\nu}$ mode it is possible to push the $M_{\tilde{Z}}$ limit to 10 GeV which is one order of magnitude better than the present ^{128}Te limit.

Finally, it has been demonstrated with NEMO 2 that the detector can measure very low levels of ^{208}Tl and ^{214}Bi contamination in the source foil via the two channels $e\gamma$ and $e\gamma\gamma$ within a reasonable time scale.

11. CONCLUSION

Double-beta decay experiments play a particularly interesting role in providing the answers to questions on the nature of the neutrino. Of paramount importance is the identification of the neutrino as a Dirac particle or Majorana particle. The proposed experiment is designed to study this problem with the potential to measure a Majorana neutrino mass of 0.1 eV. To do this requires a considerable increase in the scale of the experiment over the current state-of-the-art experiments. The experiment will not only be sensitive to transitions between ground states (0^+ to 0^+) but also between the ground state and an excited state (0^+ to 2^+). The latter probes right-handed currents with a substantial increase in sensitivity over present-day experiments. Finally, NEMO 3 is particularly well suited to investigate the Majoron, and it should push the limit of the coupling constant to values between 10^{-5} and 10^{-6}.

In the traditionally allowed double-beta decay, any nuclei with a half-life shorter than 10^{21} years can be readily measured. For these nuclei, several thousand events can be collected each year and high statistics studies of the energy and angular distribution spectrum can be achieved. The limits to these studies should be around 10^{22} years, beyond which events from unavoidable backgrounds reach the same order of magnitude as the signal. Investigations of the $\beta\beta 2\nu$ process to excited states can similarly be undertaken for half-life measurements up to a few times 10^{22} years. The detector proposed here will be able to study a large number of candidate nuclei, among which are ^{116}Cd, ^{82}Se, ^{100}Mo, ^{96}Zr and ^{150}Nd. These nuclei are privileged because of their high transition Q values which are of higher energy than most natural radioactive backgrounds. Also, the study of several nuclei will reduce concerns and perhaps shed some light on the uncertainty in nuclear matrix element calculations.

The results of the research and development program have been extremely encouraging. The two-electron event spectrum from backgrounds operating in or on the OFHC copper sheet studied in NEMO 2 did not exceed 2.2 MeV. Tests with a neutron source have shown that magnetic field rejection is essential to identify and reject e^+e^- pairs produced by high energy gamma rays. This identification of the event signatures associated with contamination has made it possible to achieve unambiguous measurements of the two neutrino double-beta decay half-life for ^{100}Mo.

The techniques employed in the two prototypes have been shown to be reliable after 20,000 hours of data collection. The same techniques can be implemented without major problems on a detector scaled up by a factor of ten in terms of the number of detector channels.

The greatest concern on the feasibility of the experiment is the capacity of the NEMO 3 detector to measure extremely low levels of contamination from ^{214}Bi and in particular ^{208}Tl. Measurements to recognize these decays can be performed in two channels, the $e\gamma$ and $e\gamma\gamma$ channels. A sensitivity of 2.10^{-2} mBq/kg in ^{208}Tl in detecting several hundred events, ensures reliable background verification. The same type of approach led to the development of ultra-low background germanium crystals for double-beta decay experiments, the instrument itself serving to quantify the background. The level of radiopurity achieved in the recent production of 2 kg of enriched molybdenum has been shown to be excellent for low levels of ^{214}Bi, but improved chemical or physical purification is required for ^{208}Tl. The NEMO collaboration is working on this important problem.

The NEMO collaboration is capable of completing this program, as it brings together a wealth of experience in nuclear and particle physics. While the French members initiated this research program, the Russian groups from ITEP in Moscow, JINR in Dubna, the Ukrainian group from INR in Kiev, and the US group from MHC have been working in this field for many years and have considerable knowledge and experience. In addition, the chance to work with several kilograms of enriched isotopes produced in Russia is an extraordinarily rare opportunity to carry out this fundamental research. For the past ten years, France has had an excellent underground laboratory at Modane, the Fréjus Laboratory, which is well protected from cosmic radiation, easily accessible, and well equipped. The first experiments in Modane on double-beta decay were conducted in 1985, and this has led to the development of ultra-low background germanium detectors which today make it possible to quantitatively study all the materials required for the experiment. Other research fields have also benefited from these developments. The NEMO 3 experiment requires very low-radioactivity photomultiplier tubes, and the cooperative efforts with the manufactures to engineer these tubes will clearly aid others given the inevitable advances.

Discovery of neutrino physics by the direct measurement of the neutrino mass using this relatively simple process would mean a leap forward in the field beyond the strict limits of the standard model of particle physics. NEMO 3 hopes to contribute such progress.

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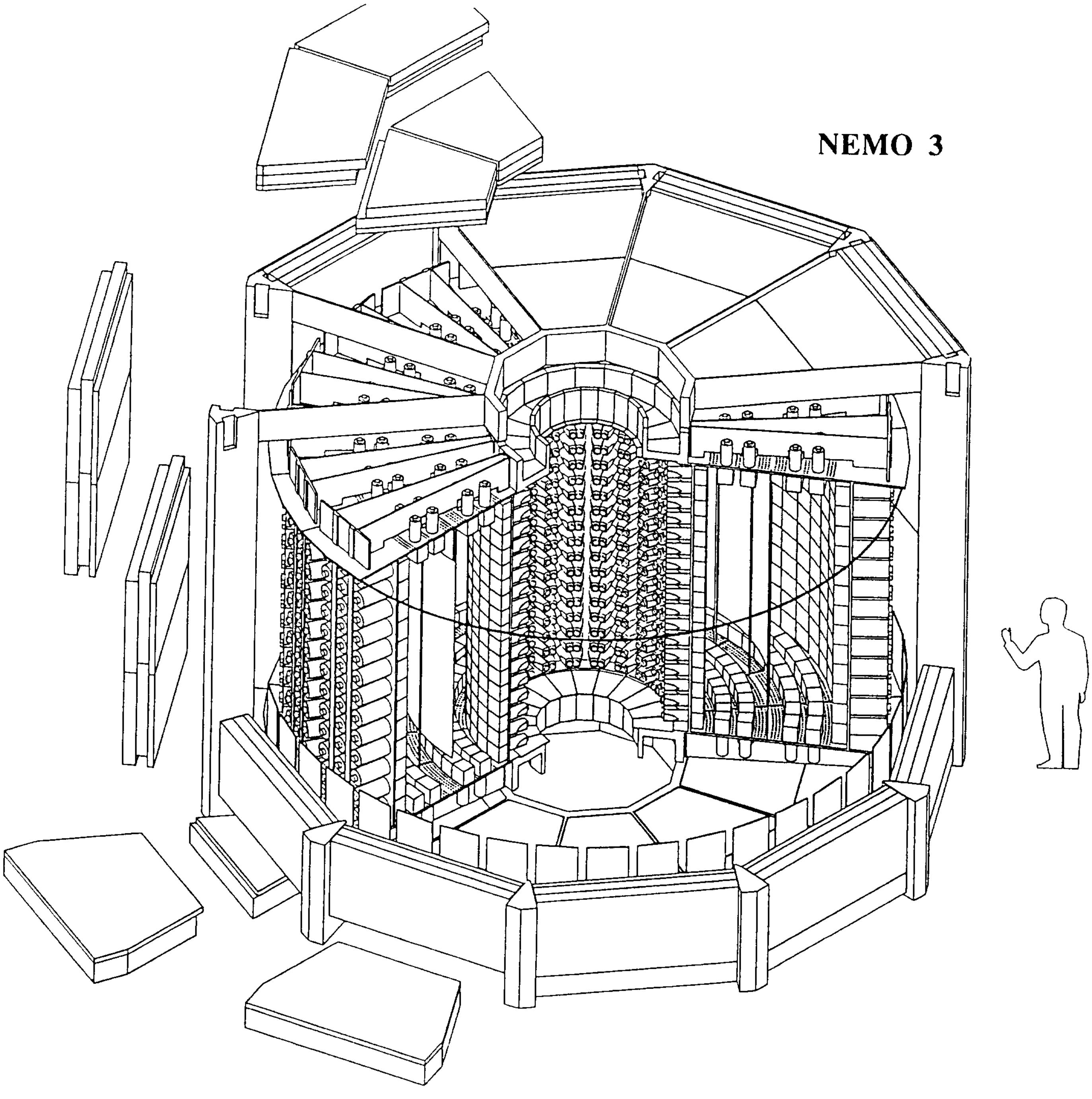

Figure 1: General layout of NEMO 3

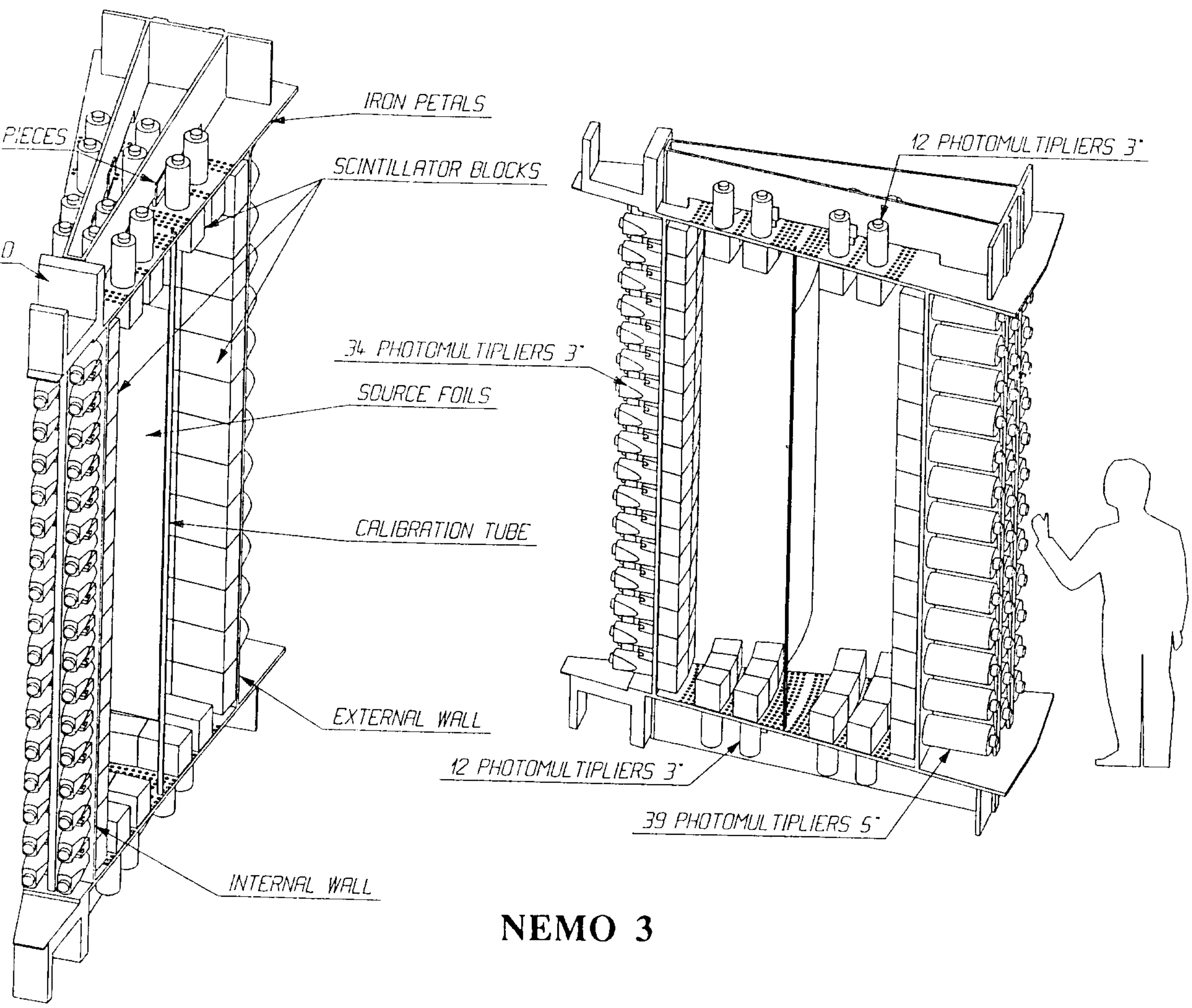

Figure 2: One sector of NEMO 3 with details on the ^{100}Mo source foil, scintillator blocks, photomultipliers. The Geiger cells are located between the internal and external walls.

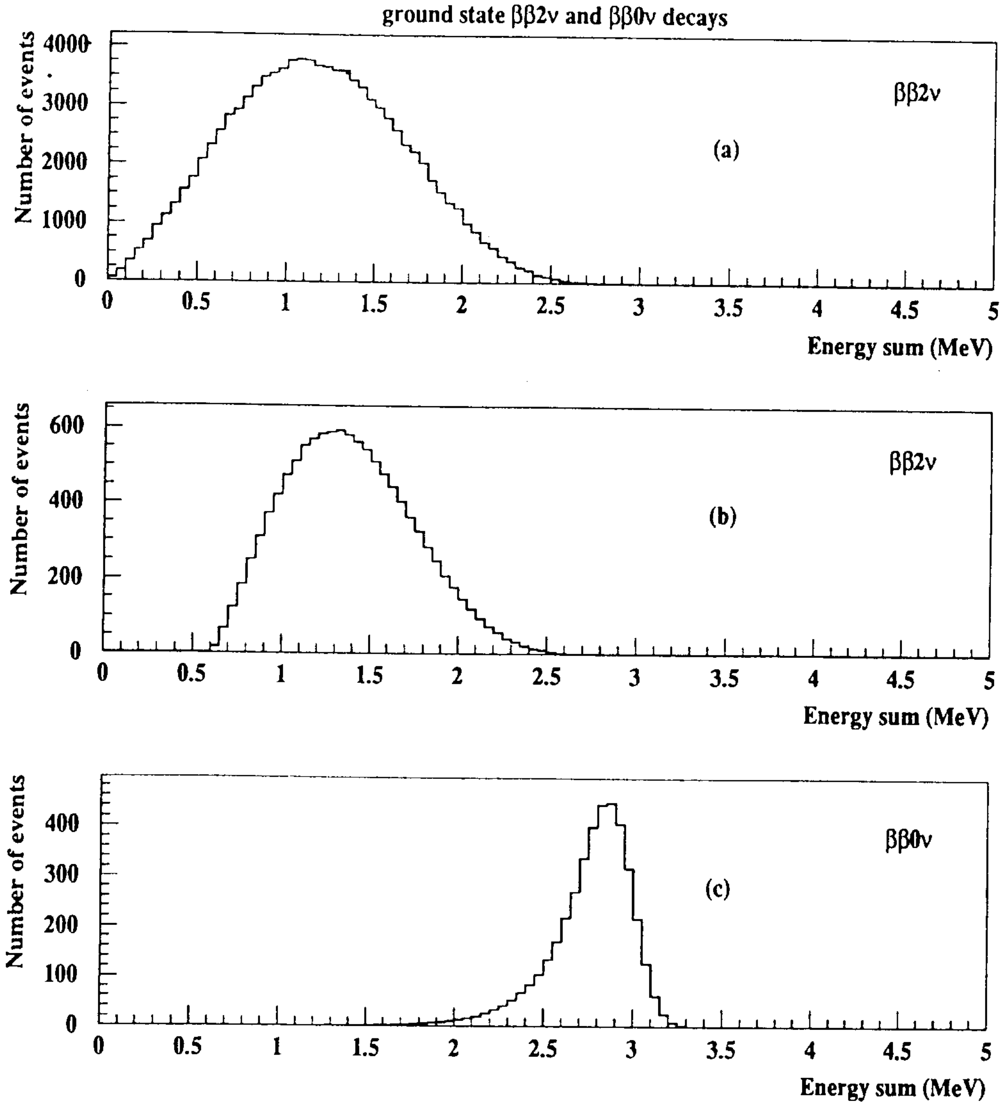

Figure 3: 2e energy sum spectra for: (a) generated $\beta\beta2\nu$ decays (b) $\beta\beta2\nu$ decays after detector simulation and event selection, (c) $\beta\beta0\nu$ decays after detector simulation and event selection.

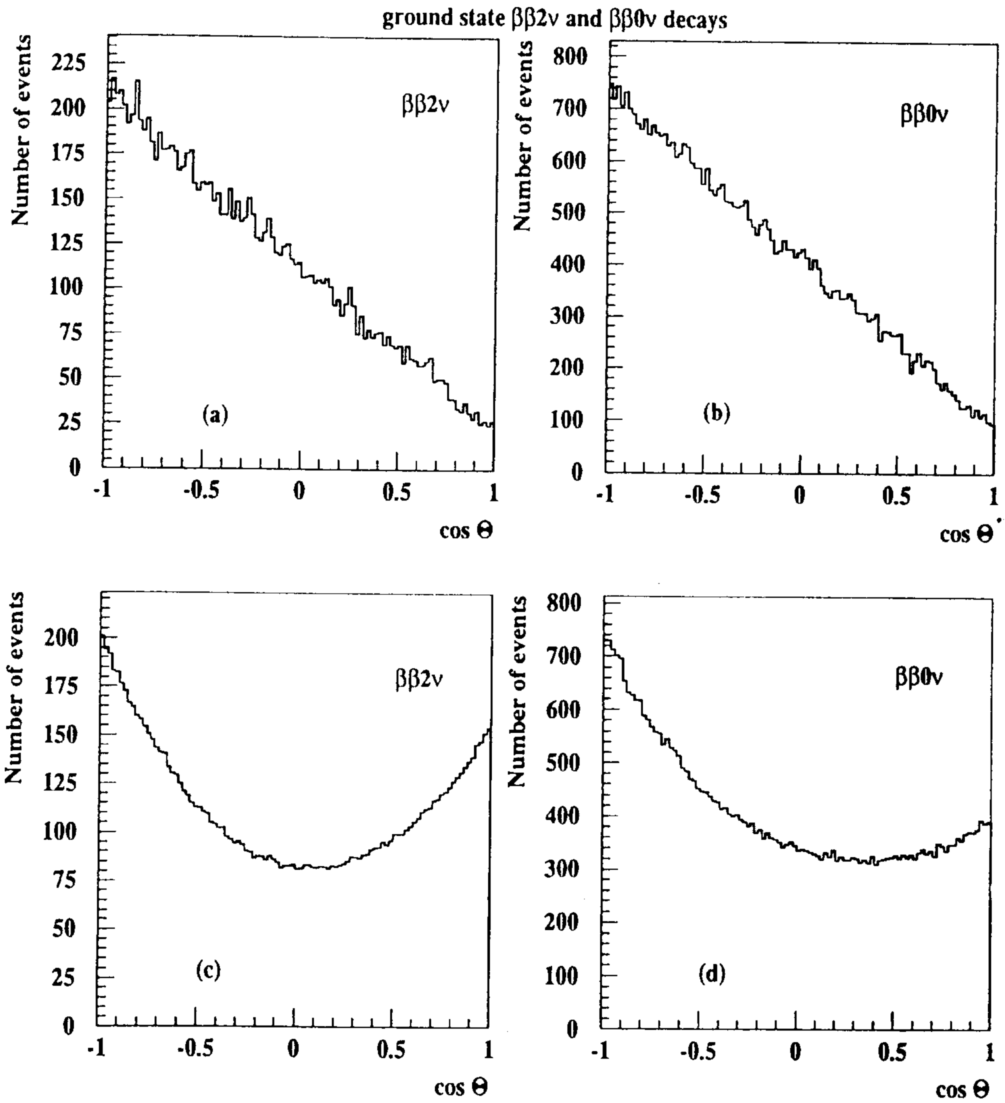

Figure 4: Cosine of the angle between the two electrons for: (a) generated $\beta\beta2\nu$ decays, (b) generated $\beta\beta0\nu$ decays, (c) $\beta\beta2\nu$ decays after detector simulation and event selection, (d) $\beta\beta0\nu$ decays after detector simulation and event selection.

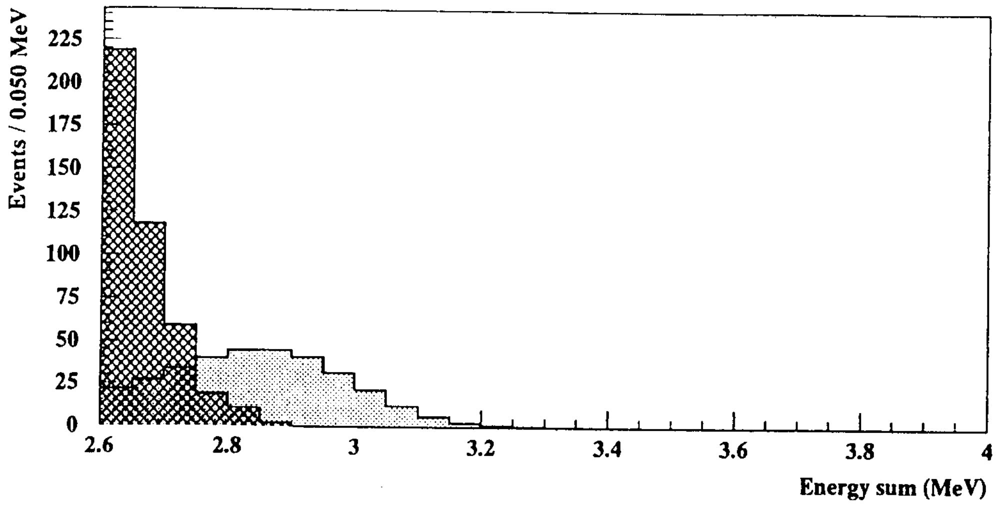

Figure 5: Contribution to the summed energy spectrum for $\beta\beta2\nu$ decays (cross hatched histogram) and $\beta\beta0\nu$ decays (grey histogram). Number of generated events are respectively 10^7 and 10^6. Rescaling has been done on the figure to display a $T_{1/2}(\beta\beta2\nu) = 10^{19}$y and $T_{1/2}(\beta\beta0\nu) = 10^{23}$y for 2.5 years of data collection and a 10 kg source of enriched ^{100}Mo.

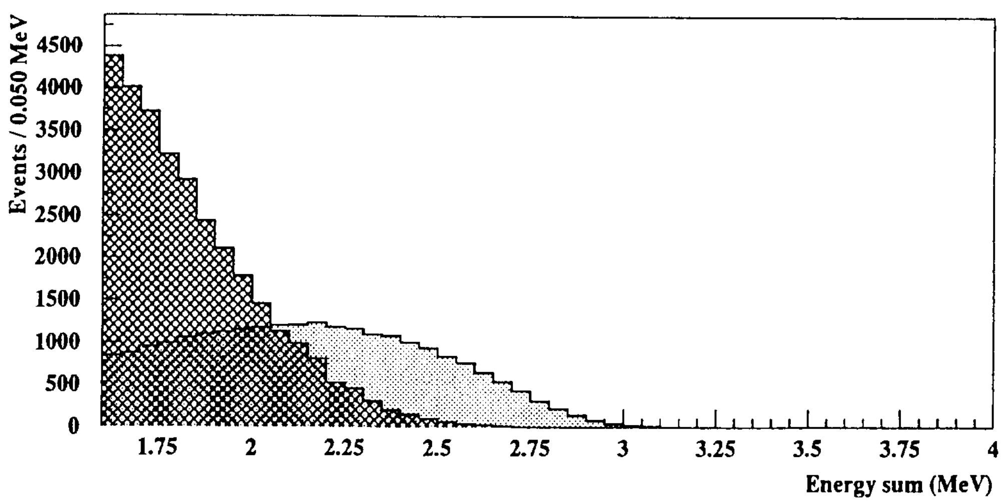

Figure 6: $\beta\beta M^0$ decay mode: Contributions to the summed energy spectrum $\beta\beta2\nu$ decays (cross hatched histogram) $\beta\beta M^0$ decays (grey histogram). For 10^6 generated events and rescaling corresponding to $T_{1/2}$ $(\beta\beta2\nu) = 10^{19}$y and $T_{1/2}$ $(\beta\beta M^0) = 10^{20}$y with 3 months of data collection and a 10 kg source of enriched molybdenum.

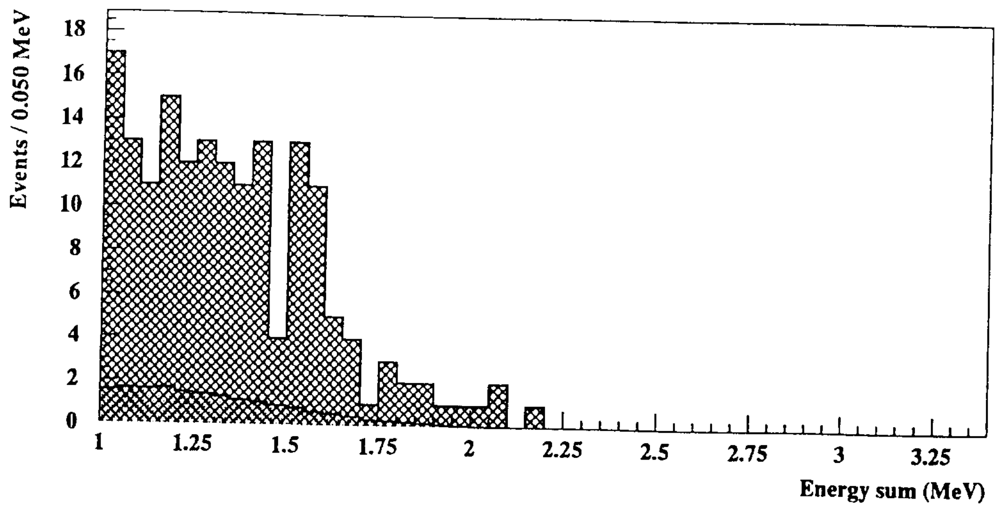

Figure 7: ($0^+ \rightarrow 2_1^+$) $\beta\beta 2\nu$ decay mode: Contributions to the summed energy spectrum for ($0^+ \rightarrow 0^+$) $\beta\beta 2\nu$ decays (cross hatched histogram) and ($0^+ \rightarrow 2_1^+$) $\beta\beta 2\nu$ decays (grey histogram). Generated events are 10^6 and rescaling corresponds to $T_{1/2}$ ($\beta\beta 2\nu$) = 10^{19}y and $T_{1/2}(0^+ \rightarrow 2_1^+)$ $\beta\beta 2\nu = 10^{22}$y with 3 months of data collection and a 10 kg source of enriched molybdenum).

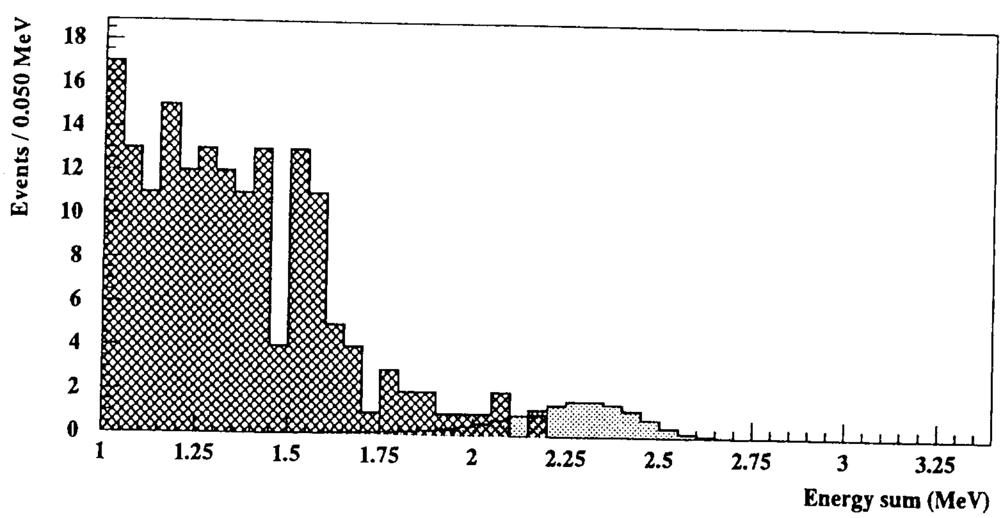

Figure 8: ($0^+ \rightarrow 2_1^+$) $\beta\beta 0\nu$ decay mode: Contribution to the summed energy spectrum for 10^6 generated events ($0^+ \rightarrow 0^+$) $\beta\beta 2\nu$ decays (cross hatched histogram) and 10^6 generated ($0^+ \rightarrow 2_1^+$) $\beta\beta 0\nu$ decays (grey histogram). Rescaling has been done for $T_{1/2}$ ($\beta\beta 2\nu$) = 10^{19}y and T ($0^+ \rightarrow 0^+$) $\beta\beta 2\nu$ = 10^{23}y with 3 months of data collection and a 10 kg source of enriched molybdenum).

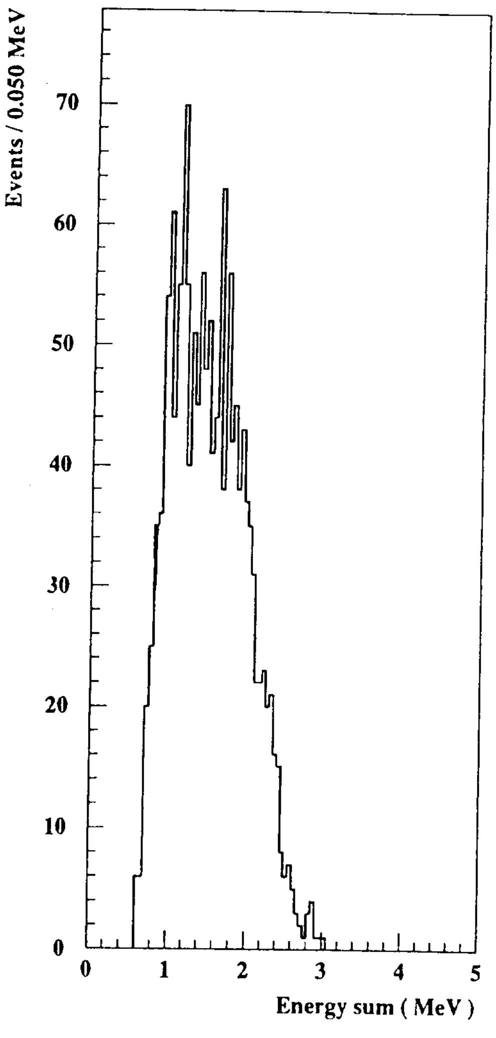

Figure 9: Energy spectrum for the $2e$ channel for ^{214}Bi

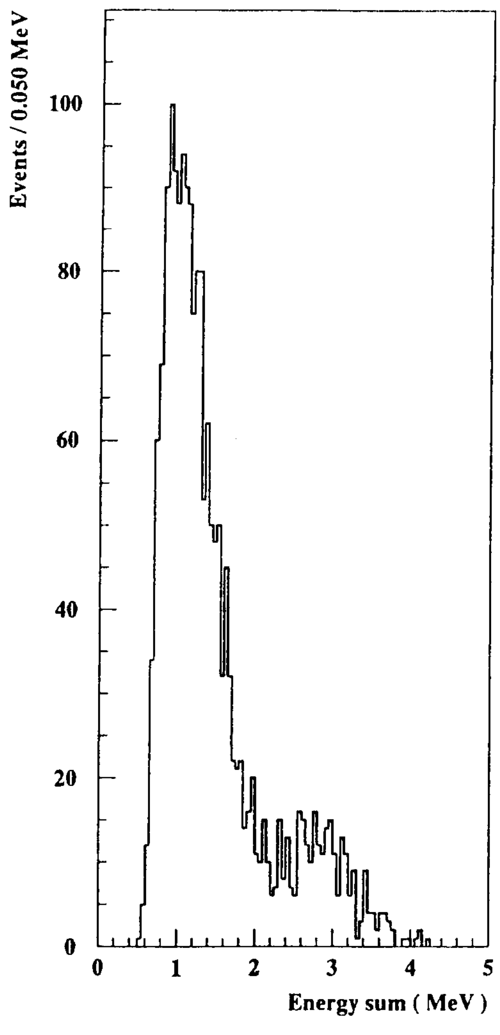

Figure 10: Energy spectrum for the $2e$ channel for ^{208}Tl

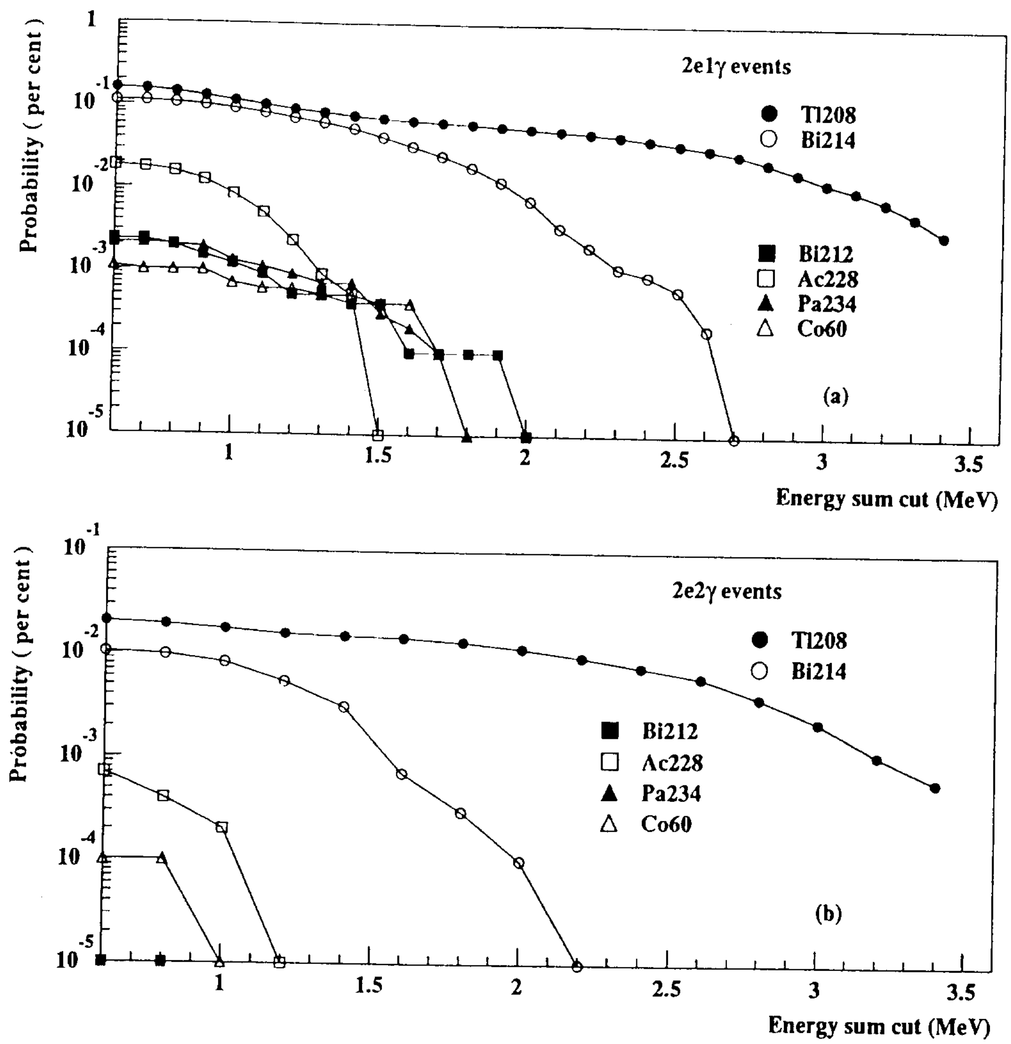

Figure 11: Probability for a β decaying nucleus to mimic $\beta\beta$ decays into the excited states of ^{100}Ru: (a) for decays into the 2_1^+ level, (b) for decays into the 0_1^+ level. The various curves correspond to the probabilities for the nuclei indicated in the figures.

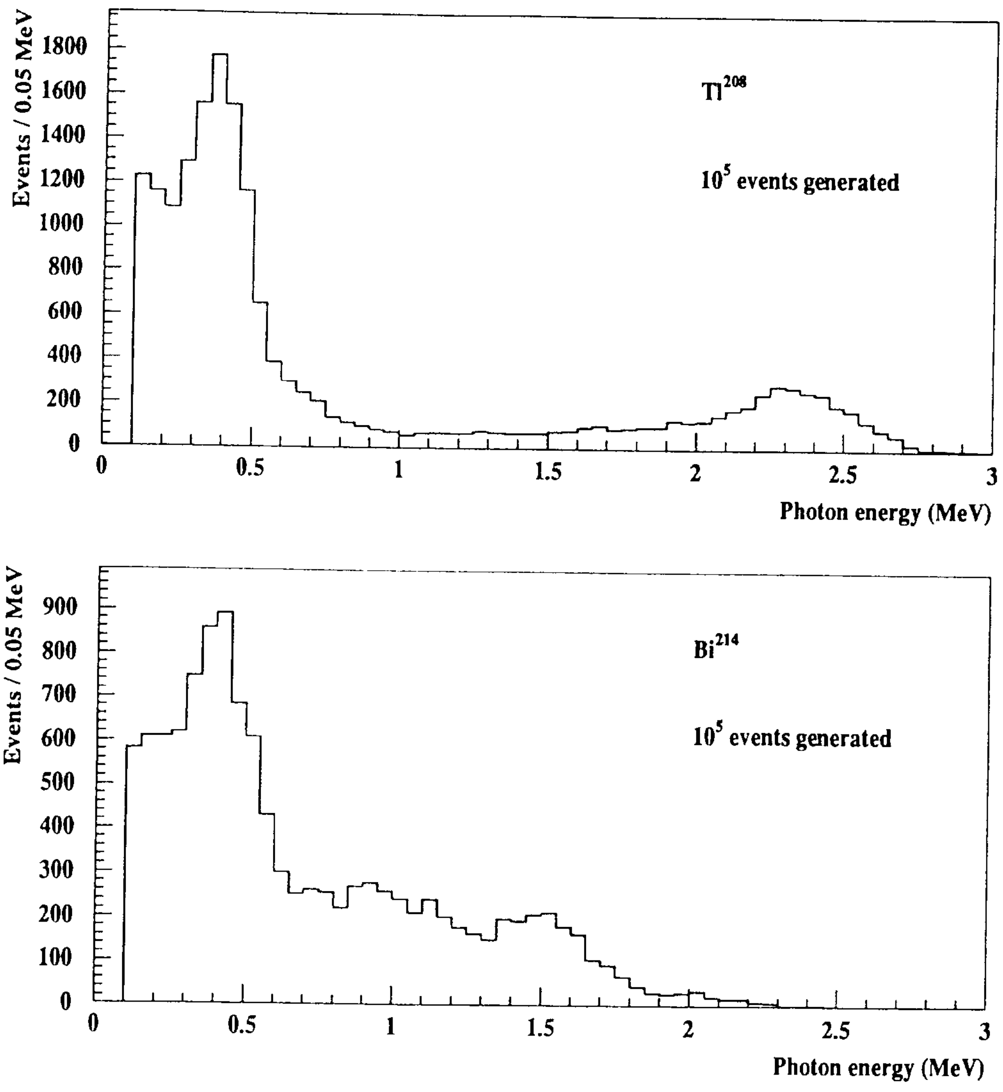

Figure 12: $e\gamma$ channel: Simulated photon energy spectra for ^{208}Tl and ^{214}Bi. The different behaviors of the high energy tail of the spectra allow for a good estimate of the contribution of both nuclei.

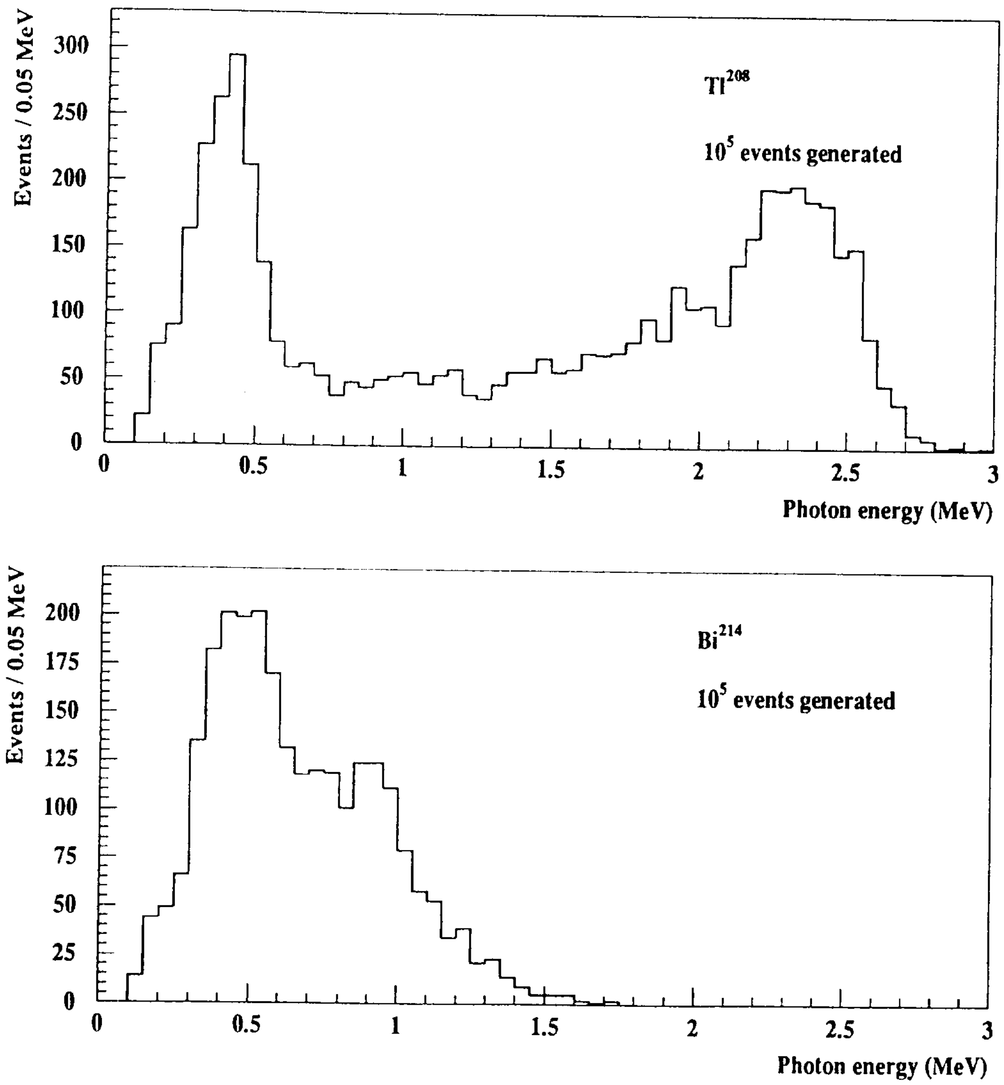

Figure 13: $e\gamma\gamma$ channel: Simulated energy spectra for the most energetic photons from ^{208}Tl and ^{214}Bi. The shape of the spectra is different from that of the $e\gamma$ channel presented in figure 12.