Double Beta Decay Experiments

A. Piepke[a]

[a]Department of Physics and Astronomy
University of Alabama
206 Gallalee Hall
Box 870324
Tuscaloosa, AL 35487
USA

The experimental observation of neutrino oscillations and thus neutrino mass and mixing gives a first hint at new particle physics. The absolute values of the neutrino mass and the properties of neutrinos under CP-conjugation remain unknown. The experimental investigation of the nuclear double beta decay is one of the key techniques for solving these open problems.

1. Introduction

The observation of neutrino oscillations demonstrated that neutrinos have non-zero mass and that their flavor and mass eigenstates do not coincide. These measurements determine some of the elements of the neutrino-mixing matrix (often called the Maki-Nakagawa-Sakata or MNS matrix) and the quadratic difference of the masses of the mass eigenstates (see e.g. [1] and references therein). The absolute values of the neutrino masses have to be determined from kinematic mass tests, such as the evaluation of the beta spectra near their endpoint, or neutrinoless double beta decay. The latter technique is further sensitive to the properties of neutrinos under CP-conjugation. All of these fundamental but still unknown quantities are needed for a consistent and complete description of our micro-cosmos.

Double beta ($\beta\beta$) decay is a second order weak decay, converting two neutrons into two protons. It can be understood as two successive beta decays in which the intermediate nucleus is virtual. The very rare $\beta\beta$-decay becomes observable for those even-even nuclides where β-decay is either energetically forbidden or so much hindered that it does not compete. This paper will focus on two decay modes:

$$A(Z,N) \;\longrightarrow\; A(Z+2,N-2) \;+\; 2\,e^- \;+\; 2\,\overline{\nu}_e \tag{1}$$

$$A(Z,N) \;\longrightarrow\; A(Z+2,N-2) \;+\; 2\,e^-, \tag{2}$$

Z and N denote the number of protons and neutrons, and A=Z+N. $\beta\beta 2\nu$-decay (1) is allowed in the standard model of particle physics. Typical life times are of order 10^{19} y or more.

The neutrinoless ($\beta\beta0\nu$) decay mode (2) violates total lepton number, and baryon minus lepton number conservation. The existence of neutrino oscillations shows that at least the individual lepton numbers are not conserved. Here it is assumed that $\beta\beta0\nu$-decay is mediated by the emission and re-absorption of a virtual light neutrino. As the emission and absorption processes involve a spin flip, an observed decay rate would imply neutrino mass. It further requires particle and anti-particle to be identical or neutrinos to be Majorana particles. If neutrinos are Dirac-particles the decay rate has to vanish. The observation of $\beta\beta0\nu$-decay and thus demonstration of the Majorana character of neutrinos is an important goal in itself as it probes stability of matter. It does not depend on any uncertainties introduced by nuclear structure calculations.

The decay rates, $(T^{2\nu}_{1/2})^{-1}$ and $(T^{0\nu}_{1/2})^{-1}$, of $\beta\beta2\nu$ and $\beta\beta0\nu$-decay are given by Fermi's Golden Rule:

$$(T^{2\nu}_{1/2})^{-1} = G^{2\nu}(Q_{\beta\beta}, Z)\,|M^{2\nu}|^2 \tag{3}$$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q_{\beta\beta}, Z)\,|M^{0\nu}|^2\,\langle m_\nu\rangle^2, \tag{4}$$

where $G^{2\nu}(Q_{\beta\beta}, Z)$ and $G^{0\nu}(Q_{\beta\beta}, Z)$ denote the calculable phase space integrals. $M^{2\nu}$ and $M^{0\nu}$ are the nuclear matrix elements relevant for the two neutrino (1) and neutrinoless (2) channel, respectively. The phase space integrals decrease very rapidly with available decay energy $Q_{\beta\beta}$. Experimental searches for double beta decay thus usually focus on nuclides with $Q_{\beta\beta} > 2$ MeV and on beta minus decays.

$\langle m_\nu\rangle^2$ denotes an effective neutrino mass, a linear combination of the neutrino masses m_i:

$$\langle m_\nu\rangle^2 = |\sum_i^N U^2_{ei}\, m_i|^2, \tag{5}$$

where the sum runs over N neutrino flavors. U_{ei} denotes the elements of the upper row of the MNS-matrix, which contains (for N=3 and Majorana neutrinos) three independent CP phases. In general neutrino masses can cancel each other's contribution to the observable $\langle m_\nu\rangle^2$.

A measured $\beta\beta0\nu$-decay decay rate could thus be used to determine $\langle m_\nu\rangle$ if $M^{0\nu}$ is known from nuclear structure calculations. The computation of $M^{0\nu}$ is difficult, resulting in a considerable spread of values when comparing different nuclear models. The comparison of measured and calculated $M^{2\nu}$-values has traditionally served to indirectly test the nuclear modeling of second order weak decays. $M^{2\nu}$ has by now been measured for some 10 different nuclides for this purpose. Another article in this volume will be dedicated to the discussion of theoretically calculated nuclear matrix elements.

$\langle m_\nu\rangle$ values derived this way are believed to be uncertain to within a factor of 2 to 3 due to the nuclear model uncertainties [3].

2. Mass Scale and Oscillation Experiments

What are reasonable expectations for $\langle m_\nu\rangle$ based on the neutrino oscillation data? The following discussion will assume three light neutrinos. It will hence ignore the so-called LSND evidence for neutrino oscillations which would require the existence of a fourth non-interacting (sterile) neutrino [1]. It should be noted that this working *assumption* may need to be revisited once the results of the mini-Boone experiment become public. This project is being conducted to either confirm or refute the LSND evidence.

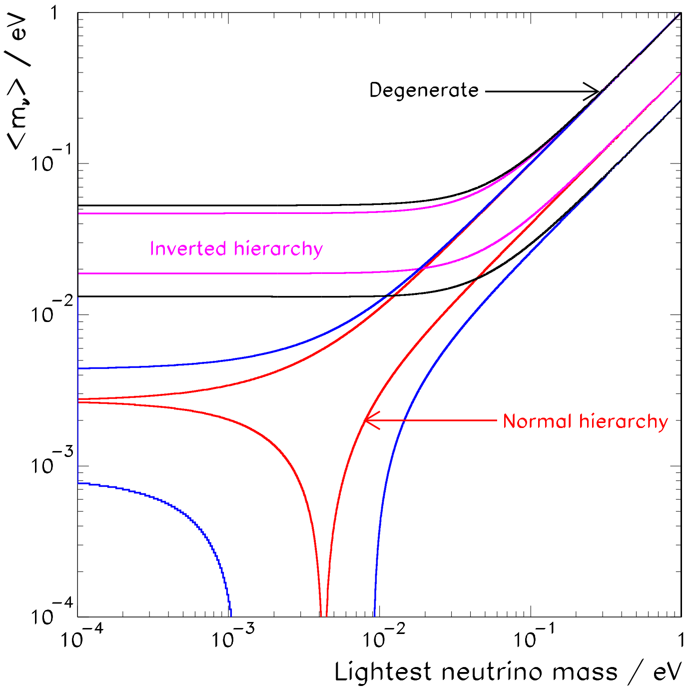

Figure 1. Effective mass as a function of the smallest neutrino mass. The inner parameter band was calculated using $sin^2\theta_{13} = 0$, and assuming all oscillation parameters are known with infinite accuracy. The outer ban was obtained by setting $sin^2\theta_{13} = 0.028$, at its current limit, and using the oscillation parameter errors given in [1].

Several recent reviews have been devoted to the discussion of double beta decay (see e.g. [3]). Neutrino flavor mixing is usually expressed through three rotations in flavor space, characterized by three rotational angles θ_{12} (determined by solar and reactor oscillation experiments), θ_{13}, and θ_{23} (determined by atmospheric and accelerator oscillation experiments). Using the notation of ref. [2] $\langle m_\nu \rangle$ may be expressed as:

$$\langle m_\nu \rangle \;=\; \left| m_1\, cos^2\theta_{12}\, cos^2\theta_{13} + m_2\, sin^2\theta_{12}\, cos^2\theta_{13}\, e^{i(\alpha_2-\alpha_1)} + m_3\, sin^2\theta_{13}\, e^{i(-\alpha_2-2\delta)} \right|, \tag{6}$$

where δ, α_1, and α_2 denote the CP-phases. Only δ results in CP-violating effects, observable e.g. in neutrino oscillations. α_1 and α_2 are observable only in $\beta\beta0\nu$-decay. Neutrino oscillations experiments allow for three different neutrino mass scenarios: degenerate, hierarchical and inverse hierarchical. Degenerate neutrino masses are characterized by: $m_1 \approx m_2 \approx m_3$. In the case of a hierarchical scheme we have: $m_1 < m_2 \ll m_3$, for an inverse hierarchical arrangement: $m_3 \ll m_1 < m_2$. The quadratic mass differences ($\Delta m^2_{ij} \equiv m^2_i - m^2_j$) are known from oscillation experiments. Equation (6) can be used to express the effective neutrino mass as a function of the smallest neutrino mass and CP-phases:

$$\begin{aligned} \langle m_\nu \rangle &= \Big| m_1\, cos^2\theta_{sol}\, cos^2\theta_{13} \pm \sqrt{m_1^2 + \Delta m^2_{sol}}\; sin^2\theta_{sol}\, cos^2\theta_{13} \\ &\quad \pm \sqrt{m_1^2 + \Delta m^2_{atm}}\; sin^2\theta_{13} \Big| \qquad (7) \\ \langle m_\nu \rangle &= \left| \sqrt{m_3^2 + \Delta m^2_{atm}}\, [1 + (-1 \pm 1)\, sin^2\theta_{sol}]\, cos^2\theta_{13} \pm m_3\, sin^2\theta_{13} \right|, \qquad (8) \end{aligned}$$

for the hierarchical (m_1 lowest mass) and inverse hierarchical (m_3 lowest mass) case, respectively. Figure (1) depicts the dependence of $\langle m_\nu \rangle$ on the minimal neutrino mass for these two cases. Even if the lightest neutrino is massless $\langle m_\nu \rangle$ remains finite. A *measurement* of $\langle m_\nu \rangle$ would thus allow to identify which mass scenario is realized in nature. Total destructive interference of the neutrino masses can only occur in case of a hierarchical scheme and only in a narrowly tuned range of the minimal neutrino mass. Even if only a mass limit can be obtained one can learn something important if the experiments are sensitive to $\langle m_\nu \rangle > 10$ meV. In this case an inversely hierarchical neutrino mass scheme would be excluded, at least for Majorana neutrinos. The width of the inner parameter band, shown in figure (1), is cause by the unknown CP-phases and thus irreducible. The outer band is due to the experimental uncertainties of the oscillation experiments and the unknown value of $sin^2\theta_{13}$ and its CP-phase. Running $\beta\beta$-experiments, sensitive to $\langle m_\nu \rangle > 200$ meV can probe the degenerate mass scenario.

The observation of neutrino oscillations thus nicely determines the sensitivity requirements for a new generation of $\beta\beta$-experiments. A considerable number of interesting new approaches is being developed world wide to take advantage of this scientific opportunity. The next chapter will discuss some of these developments.

3. Experimental Approach

Double beta decays of interest to experimentalists are typically resulting in an energy release of around 2 MeV (^{48}Ca has with 4.27 MeV the largest decay energy). Many forms of natural, cosmogenic and anthropogenic radioactivity result in a similar low energy signature constituting potential background. The fact that even the longest lived natural radioactivity has live-times some 10 to 14 orders of magnitude shorter than $\beta\beta$-decay is the main experimental challenge: background control. $\beta\beta$-experiments have to be constructed from materials containing as little radioactivity as possible. The construction of such an experiment requires, in practical terms, the right analytical tools to identify these materials: low background γ-ray spectroscopy, neutron activation analysis, mass spectroscopy, alpha counting are some of them. Required analytical sensitivities are of order μBq/kg or better. Low activity materials do not necessarily have desirable properties for the construction of a detector. This often introduces engineering challenges as well.

Cosmic radiation is a further source of background. This is the reason why *all* $\beta\beta$-experiments are conducted underground. The most sensitive ones in very deep under-

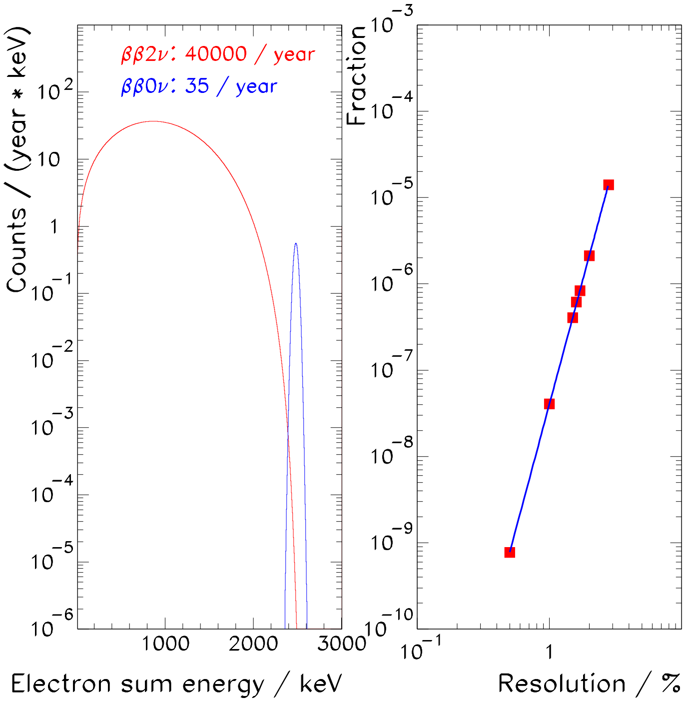

Figure 2. The left panel shows the distribution of electron sum energies for ^{136} Xe. The total number of events has been normalized to reasonable expectation values. The distributions have been folded with a 1% (σ at Q-value) energy resolution, assumed to follow a $\sqrt{E}$ dependence. In this example less than 0.002 $\beta\beta2\nu$-background counts would fall into a $\pm2\sigma$-analysis interval around the $\beta\beta0\nu$-peak. The right panel shows the fraction of $\beta\beta2\nu$-scattered into $\beta\beta0\nu$-analysis energy interval as a function of the fractional energy resolution in %. The fit corresponds to a power law of 5.8th power.

ground sites to sufficiently suppress the penetrating muonic component. For intermediate-Z metallic construction materials such as e.g. Fe and Cu activation by the cosmic radiation is an important issue. To limit those cosmogenic activities careful exposure management is essential. No “off the shelf” materials of unknown production vintage can be used as they may be loaded with activation products.

The $\beta\beta$-modes (1) and (2) result in the emission of 4 and 2 light particles, respectively. The statistical distribution of the electron sum energy, shown in figure 2, will thus be continuous in process (1) and discrete in process (2). $\beta\beta$-decay experiments are usually designed to measure the energy or summed energy of the decay electrons in order to identify the decay channel. Good energy resolution is thus key in suppressing $\beta\beta0\nu$-background. An interesting example for such background is $\beta\beta2\nu$-events scattered into the $\beta\beta0\nu$-analysis interval. The right panel of figure 2 shows, for ^{136}Xe, $\beta\beta2\nu$-leakage as a function of fractional energy resolution. This particular background depends in the

5.8^{th} power on the energy resolution, as shown in the right panel of figure 2. Next generation experiments will need to have sufficient resolution to suppress this second order background, which is otherwise irreducible.

Most $\beta\beta$-unstable isotopes constitute about 10% or less of the isotopic mixture. Among the candidates with a decay energy of more than 2 MeV ^{130}Te has with 34.5% the highest, and ^{48}Ca with 0.19% the lowest isotopic abundsance, respectively. For any given element being studied in a $\beta\beta$-detector the entire isotope inventory is sensitive to background while only a fraction of it decays. To optimize the signal-to-background ratio most experiments are conducted using detector material isotopically enriched in the isotope of interest. In many cases the enrichment constitutes the the largest expense. In case of a background limited experiment the half life limit, to be obtained after the counting time t, in the presence of a background B [counts / keV y kg], is given by:

$$T^{0\nu}_{1/2} \;\sim\; a\,\varepsilon\,\sqrt{\frac{M\,t}{\Delta E\,B}}, \tag{9}$$

where a denotes the abundance of the decaying isotope, ε the detection efficiency, M the detector mass [kg], and ΔE the energy resolution at the decay energy. This half live limit is a convenient measure for the experimental sensitivity. Isotopic enrichment and high detection efficiency are thus the most effective tools for optimizing the sensitivity. $1/\sqrt{T^{0\nu}_{1/2}} \sim \langle m_\nu \rangle$ results in a very slow gain in sensitivity as far as optimization of the other parameters is concerned. It should be noted that in case of a background free experiment $T^{0\nu}_{1/2} \sim M\ t$. Such a scenario is thus very advantageous. Next generation experiments are trying to achieve this condition in order to make the most of the very expensive enriched isotope.

Experiments can be grouped into two general categories: calorimetric and tracking. The first approach, in which the decaying material constitutes the sensitive medium, optimizes sensitivity by means of energy resolution and simplicity of design. Only a limited amount of information about every given event is collected. The choice of decaying isotope is limited to those materials that can be used to build a detector. In the latter approach track reconstruction is utilized to separate, off-line, double beta decays from single beta decays and photon induced events. The first generation of $\beta\beta$-decay experiments were sensitive to the atomic species born in the decay. These measurements were thus inclusive in a sense that they could not distinguish which of the decay modes produced the isotope of interest. Minerals, which accumulated the decay product over geological time scales, were used in these pioneering experiments, often called “geo-chemical”. Because of the inability to demonstrate the presence of the interesting $\beta\beta0\nu$-decay mode this approach as fallen out of fashion.

3.1. Running Experiments

Most existing experiments have been planned and build before the neutrino oscillation data clearly defined the mass scale. As a consequence their sensitivity is limited to testing the degenerate mass scenario.

3.1.1. The Heidelberg-Moscow Experiment and the Evidence for $\beta\beta0\nu$-decay

The Heidelberg-Moscow Experiment, conducted by a German-Russian collaboration, has been the longest running experiment in the field [4]. Data has been collected in the

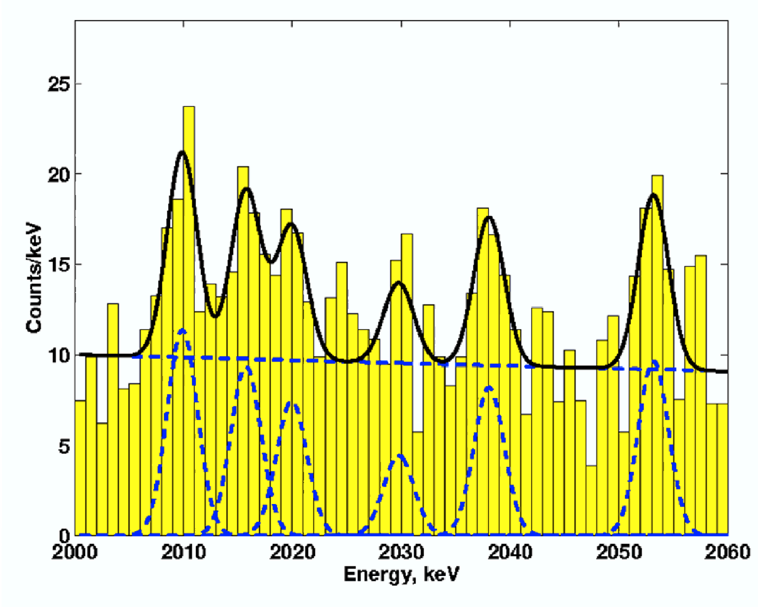

Figure 3. This figure has been taken from ref. [4]. The entire data set, corresponding to an exposure of 71.7 kg y, is displayed along with the claimed $\beta\beta0\nu$-peak at 2038.07 ± 0.44 keV.

Gran Sasso underground lab in Italy from 1990 to 2003. A total of 11 kg of of isotopically enriched (a=0.86) Ge has been used in form of calorimetric semiconductor detectors. The energy resolution at the decay energy of $Q_{\beta\beta} = 2039.01 \pm 0.05$ keV is with $\Delta E/Q_{\beta\beta}$=0.2% the best in the field. For part of their data set the group utilized a novel "pulse shape analysis" allowing them to discriminate single site $\beta\beta$-events from multiple site γ-induced background. The resulting background of 0.11 counts / keV y kg is one of the lowest reported in the literature. The use of solid state detectors further results in an excellent electron detection efficiency of ε =0.96.

2001 part of the collaboration published evidence for the observation of a $\beta\beta0\nu$-decay signal [5]. This initial evidence let to a lively discussion within the neutrino community. 2004 more data and an improved analysis was presented [4]. The $\beta\beta0\nu$-peak is now reported to have $4.2\,\sigma$ significance, thus greatly strengthening their initial claim. Figure (3) shows the data along with its proposed interpretation. The measured decay rate corresponds to $\langle \mathrm{m}_\nu \rangle = 0.44^{+0.14}_{-0.20}$ eV (errors stated at $3\,\sigma$ c.l.) using the matrix element calculation in [6]. If indeed correct, this would correspond to a degenerate neutrino mass scenario and establish the Majorana character of neutrinos. Independent experimental verification of this effect is needed to either confirm or refute this claim. The experiment has been discontinued in 2003.

Another experiment using isotopically enriched Ge detectors, called IGEX [7], did not observe evidence for $\beta\beta0\nu$-decay. Using the same matrix element [6] their data implies $\langle \mathrm{m}_\nu \rangle < 0.38$ eV, thus excluding part of the allowed range.

3.1.2. NEMO III

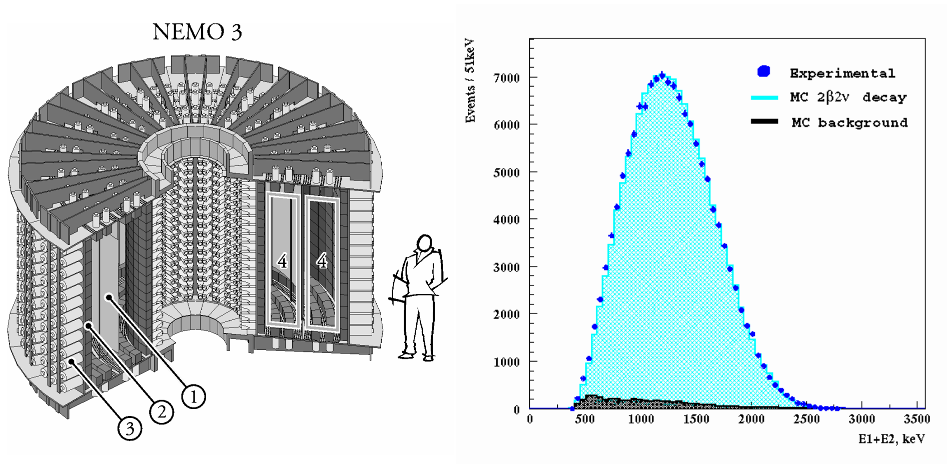

Figure 4. This figure has been taken from reference [8]. The left panel shows the NEMO3 detector: 1-source foils, 2-plastic scintillators, 3-low activity PMTs, and 4-the tracking detector, composed of 6180 Geiger cells. The right panel shows the measured ^{100}Mo $\beta\beta 2\nu$-spectrum.

NEMO III is being conducted by groups from France, Russia, USA, Czech Republic, Finland, UK, and Japan in the Frejus underground lab in France. [8]. It is currently the most advanced tracking detector. The group has been extremely successful in measuring various $\beta\beta 2\nu$-decay rates. The tracking capability of NEMO3 eliminates almost all background in this kind of measurement. Figure (4), taken from figures 1 and 3 of reference [8], shows the detector and a textbook example for a virtually background free $\beta\beta 2\nu$-measurement of ^{100}Mo.
$\beta\beta 0\nu$-decay could, thus far, not be observed by NEMO3. The absence of an effect in ^{100}Mo allows to state a range of limits $\langle \mathrm{m}_\nu \rangle < 0.8$ to 1.2 eV, using different nuclear matrix elements [8]. If the matrix element calculation [6] utilized to derive the $\beta\beta 0\nu$-evidence is used one gets $\langle \mathrm{m}_\nu \rangle < 2.0$ eV from the NEMO3 constraint. NEMO3 is thus only starting to challenge the $\beta\beta 0\nu$-evidence discussed before.
The $\beta\beta 0\nu$-sensitivity of NEMO3 has thus far been limited by airborne ^{222}Rn and its relatively modest energy resolution of $\Delta E/Q_{\beta\beta}$=7.8% (for ^{100}Mo). While the collaboration is in the process of eliminating the Radon background, the resolution cannot be easily improved and will thus constitute the ultimate limitation. The NEMO3 group hopes to reach a Majorana mass sensitivity of about 200 meV within 5 year of running.
The NEMO collaboration is exploring a larger follow-up experiment named Super NEMO.

3.1.3. Cuoricino

Another article in this volume will be devoted to this project. Only a very brief discussion will thus be given here. Cuoricino is using 40 kg of TeO_2 in form of bolometric calorimeters. It is the largest running double beta decay experiment to date. The high isotopic abundance of ^{130}Te does not require isotopic enrichment, a unique feature among next generation projects. Good background conditions, along with excellent energy resolution allow the group to derive $\langle m_\nu \rangle < 0.37$ to 1.9 eV, from the non-observation of a $\beta\beta0\nu$-decay signal in Te [9]. This project is a precursor of a planned larger experiment called Cuore which is being developed to test the degenerate and inversely hierarchical neutrino mass scenarios.

3.2. Next Generation Experiments

Many groups have recognized that Majorana neutrino mass searches at the few tens meV scale present an excellent physics opportunity. How large such next generation experiments ultimately have to be in order to be able to unambiguously demonstrate an effect, obviously depends on the mass scenario realized in nature and the technical parameters of the project. The product of phase space and matrix element, as given by nuclear models, has to be reasonable. The isotopic abundance should not be too small in order to keep costs within limits.

Should the claimed evidence for double beta decay [4] be confirmed, then a few hundred kg of source strength would suffice. If this is not the case then the inverted mass scenario requires experiments containing several tons of decaying isotope. Testing the hierarchical mass pattern would require many tons of source strength.

The following sections will give a *subjective* selection of projects currently being developed. For a comprehensive listing of all relevant projects see [3]. The somewhat uncertain nature of the matrix element calculations would make it desirable to study several different nuclides in the next generation of large experiments. If an effect can indeed be observed then the comparison of derived effective neutrino masses would allow a consistency check of the nuclear models. It is hoped that the funding agencies in the US, Europe and Asia will take this consideration into account when deciding what project to fund.

3.2.1. Majorana

Groups from the US, Russia and Japan formed the Majorana collaboration, with the goal to study Majorana neutrino masses with a sensitivity of 50 meV [10]. A few hundred enriched crystals are to be operated in clusters. Segmentation and pulse shape analysis will be used as tools for active background reduction. Low-mass metal cryostats will be used to cool the crystals. This technology is well developed and the collaboration, having many years of experience in building low background detectors, sees this as one of their main advantages for timely progress.

The energy resolution of Ge detectors is excellent. Leakage of $\beta\beta2\nu$-events into the $\beta\beta0\nu$-analysis window is thus not an issue. Activation of the cryostat and detector material during above ground processing is, however, a serious issue. Underground detector production and underground production of the Copper cryostat parts by way of electroforming are being explored to answer these challenges. The collaboration is working on a prototype detector to provide proof of principle.

3.2.2. Gerda

The German-Russian-Italian collaboration [11] plans to utilize the ∼17 kg high resolution, isotopically enriched Ge semiconductor detectors, left over from the concluded

Heidelberg-Moscow and IGEX experiments. The experiment is to be conducted in the Gran Sasso underground laboratory in Italy. An innovative shielding configuration in which the Ge crystals are suspended in ultra pure liquid nitrogen is being envisaged. Only a minimal amount of passive support materials near the crystals will be needed. The detailed background analysis of the Heidelberg-Moscow experiment yielded evidence that the main source of background there was due to impurities in the detector cryostats and passive shielding. The Gerda design thus addresses this background component. A composite shielding configuration, utilizing an external lead shield as well as an active (scintillating) liquid Argon shield are being considered.

In its initial phase the project is expected to confirm or refute the double beta decay evidence for ^{76}Ge. It is planned to expand the source strength by additional 20 kg of enriched Ge. Depending on the outcome of the initial phase the detector could be enlarged to accommodate a ton of enriched Ge to probe the inversely hierarchical mass scheme. The Gerda and Majorana collaboration are considering to join forces for such a large final project phase.

3.2.3. EXO

The US-Swiss-Russian-Canadian EXO collaboration is planning to use 10 tons of isotopically enriched ^{136}Xe to build a redundant and background-free detector using good energy resolution, pattern recognition and the identification of the atomic species produced by the double-beta decay [12].

Xenon offers some advantages over other isotopes. As a noble gas it can be cost effectively enriched by ultra-centrifugation. Xenon can further be used as an ionization detector [13]. The spatial resolution of the TPC allows active background recognition. Xenon further scintillates in the UV with a light yield comparable to NaI. The EXO collaboration showed, using a liquid Xenon detector, that a microscopic anti-correlation of the ionization and scintillation signals can be utilized to improve the energy resolution of Xenon detectors [14]. The resulting projected energy resolution at the decay energy is with 1 to 1.5% (in units of σ) still inferior to that of Ge semiconductor detectors. For ^{136}Xe this energy resolution is sufficient to suppress $\beta\beta 2\nu$-background to negligible levels. ^{136}Xe has the longest $\beta\beta 2\nu$-half life among all high Q-value $\beta\beta$-unstable nuclides (at least factor 6.5 longer than e.g. ^{76}Ge). The ^{136}Xe $\beta\beta$-decay Q-value is with $Q_{\beta\beta} = 2481$ keV slightly higher than that of e.g. ^{76}Ge.

EXO plans to add to the low background, high resolution, tracking measurement of the decay electrons the simultaneous detection of the emerging ^{136}Ba ion. This introduction of a new independent observable would help to greatly reduce background.

The final state atom tagging is possible because of the simple and well known atomic spectroscopy of Ba^{+} ions. Such spectroscopy has enabled the observation of individual ions illuminated with appropriate wavelengths since about 20 years. The specific wavelengths needed to produce atomic fluorescence ensure extreme selectivity of this technique. In EXO the Xenon will be used as an active target in a Time Projection Chamber (TPC) either in liquid (LXe) or gas (GXe) phase. In the GXe case the laser beams would be steered to the location where a candidate decay has occurred. In the LXe case the Ba-ion candidate would be extracted and brought into an ion trap where the fluorescence would be observed. The possibility of observing the fluorescence of the Ba directly in the liquid

is also being investigated by one of the EXO groups. While R&D is proceeding at different institutions for both liquid and gas phase TPC, a LXe TPC for 200 kg of ^{136}Xe is being built as a prototype and as a first step toward the very large detector. The construction of this advanced 200 kg enriched LXe prototype, initially without the Ba-tagging, is well under way. The enriched Xenon is at hand.
Ultimately EXO plans to test Majorana neutrino masses as small as 10 to 40 meV using this scheme that should ensure extremely high background rejection power. High Ba detection efficiency and good energy resolution will have to be demonstrated. This sensitivity covers neutrino masses derived from the atmospheric mass spitting. A degenerate or inversely hierarchical neutrino mass pattern could thus be tested with EXO.

4. Conclusion

The investigation of the neutrino-less double beta decay is one of *the* exciting new frontiers of neutrino physics. The detection of this decay would establish new physics. Knowledge of the neutrino mass splittings allows to quantify sensitivity goals for a new generation of experiments. Should a degenerate or inversely hierarchical mass pattern be realized in nature then these projects should have a fair chance to observe an effect, if neutrinos are Majorana particles. A subjective selection of these projects has been presented together with a general discussion of major experimental challenges that have to be addressed. Based on this rather optimistic projection it is clear that new projects have to be designed to un-ambiguously demonstrate that any decay signal is indeed due to double beta decay.

REFERENCES

1. M. Maltoni et al., hep-ph/0405172.
2. S. Eidelman et al., Phys. Lett. B 592 (2004) 1.
3. S.R. Elliott and J.Engel, hep-ph/0405078, J. Phys. G 30 (2004) R183.
4. H.V. Klapdor-Kleingrothaus, et al., Phys. Lett. B 586 (2004) 198.
5. H.V. Klapdor-Kleingrothaus, et al., Mod. Phys. Lett. 16 (2001) 2409.
6. A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus, Europhys. Lett. 13 (1990) 31.
7. C.E. Aalseth et al., Phys. Rev. D65 (2002) 092007.
8. R. Arnoldt et al., hep-ex/0410021, JETP Lett. 80 (2004) 429.
9. C. Arnaboldi, et al., Phys. Lett. B 584 (2004) 260.
10. R. Gaitskell et al., nucl-ex/0311013.
11. I. Abt et al., hep-ex/0404039.
12. M. Danilov et al., Phys. Lett. B 480 (2000) 12.
13. R. Luescher et al., Phys. Lett. B 434 (1998) 407.
14. E. Conti et al., Phys. Rev. B 68 (2003) 054201.