Neutrinoless double beta decay and direct searches for neutrino mass

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(Dated: September 16, 2004)

Study of the neutrinoless double beta decay and searches for the manifestation of the neutrino mass in ordinary beta decay are the main sources of information about the absolute neutrino mass scale, and the only practical source of information about the charge conjugation properties of the neutrinos. Thus, these studies have a unique role in the plans for better understanding of the whole fast expanding field of neutrino physics.

PACS numbers: 11.30.Fs, 14.60.-z, 23.40.-s

I. EXECUTIVE SUMMARY

The physics addressed by this research program seeks to answer many of the Study's questions:

1. Are neutrinos their own anti-particles?
2. What are the masses of the neutrinos?
3. Do neutrinos violate the symmetry CP?
4. Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the Universe?
5. What do neutrinos have to tell us about the intriguing proposals for new models of physics?

Only the research covered within this working group can answer the first and second of these fundamental questions. Among the ways to measure the neutrino mass, three are notable because they are especially sensitive: double-beta decay, tritium beta decay, and cosmology. Consequently, we have focused our report and recommendations on them.

• Observation of the neutrinoless double-beta decay ($0\nu\beta\beta$) would prove that the total lepton number is not conserved and would establish a non vanishing neutrino mass of Majorana nature. In other words, observation of the $0\nu\beta\beta$ decay, independent of its rate, would show that neutrinos, unlike all the other constituents of matter, are their own antiparticles. There is no other realistic way to determine the nature - Dirac or Majorana, of massive neutrinos. This would be a discovery of major importance, with impact not only on this fundamental question, but also on the determination of the absolute neutrino mass scale, and on the pattern of neutrino masses, and possibly on the problem of CP violation in the lepton sector, associated with Majorana neutrinos. There is a consensus on this basic point which we translate into the recommendations how to proceed with experiments dedicated to the search of the $0\nu\beta\beta$ decay, and how to fund them.

• To reach our conclusion, we have to consider past achievements, the size of previous experiments, and the existing proposals. There is a considerable community of physicists worldwide as well as in the US interested in pursuing the search for the $0\nu\beta\beta$ decay. Past experiments were of relatively modest size. Clearly, the scope of future experiments should be considerably larger, and will require advances in experimental techniques, larger collaborations and additional funding. In terms of $\langle m_{\beta\beta}\rangle$, the effective neutrino Majorana mass that can be extracted from the observed $0\nu\beta\beta$ decay rate, there are three ranges of increasing sensitivity, related to known neutrino-mass scales of neutrino oscillations.

• The ∼100-500 meV $\langle m_{\beta\beta}\rangle$ range corresponds to the quasi-degenerate spectrum of neutrino masses. The motivation for reaching this scale has been strengthened by the recent claim of an observation of $0\nu\beta\beta$ decay in ^{76}Ge; a claim that obviously requires further investigation. To reach this scale and perform reliable measurements, the size of the experiment should be approximately 200 kg of the decaying isotope, with a corresponding reduction of the background.

This quasi-degenerate scale is achievable in the relatively near term, ∼ 3-5 years. Several groups with considerable US participation have well established plans to build ∼ 200-kg devices that could scale straight-forwardly to 1 ton (Majorana using ^{76}Ge, Cuore using ^{130}Te, and EXO using ^{136}Xe). There are also other proposed experiments worldwide which offer to study a number of other isotopes and could reach similar sensitivity after further R&D. Several among them (*e.g.* Super-NEMO, MOON) have US participation.

By making measurements in several nuclei the uncertainty arising from the nuclear matrix elements would be reduced. The development of different detection techniques, and measurements in several nuclei, is invaluable for establishing the existence (or lack thereof) of the $0\nu\beta\beta$ decay at this effective neutrino mass range.

• The ∼20-55 meV range arises from the atmospheric neutrino oscillation results. Observation of $\langle m_{\beta\beta}\rangle$ at this mass scale would imply the inverted neutrino mass hierarchy or the normal-hierarchy ν mass spectrum very near the quasi-degenerate region. If either this or the quasi-degenerate spectrum is established, it would be invaluable not only for the understanding of the origin of neutrino mass, but also as input to the overall neutrino physics program (long baseline oscillations, search for CP violations, search for neutrino mass in tritium beta decay and astrophysics/cosmology, etc.)

To study the 20-50 meV mass range will require about 1 ton of the isotope mass, a challenge of its own. Given the importance, and the points discussed above, more than one experiment of that size is desirable.

• The ∼2-5 meV range arises from the solar neutrino oscillation results and will almost certainly lead to the $0\nu\beta\beta$ decay, provided neutrinos are Majorana particles. To reach this goal will require ∼100 tons of the decaying isotope, and no current technique provides such a leap in sensitivity.

• The qualitative physics results that arise from an observation of $0\nu\beta\beta$ decay are profound. Hence, the program described above is vital and fundamentally important even if the resulting $\langle m_{\beta\beta}\rangle$ would be rather uncertain in value. However, by making measurements in several nuclei the uncertainty arising from the nuclear matrix elements would be reduced.

• Unlike double-beta decay, beta-decay endpoint measurements search for a kinematic effect due to neutrino mass and thus are "direct searches" for neutrino mass. This technique, which is essentially free of theoretical assumptions about neutrino properties, is not just complementary. In fact, both types of measurements will be required to fully untangle the nature of the neutrino mass. Excitingly, a very large new beta spectrometer is being built in Germany. This KATRIN experiment has a design sensitivity approaching 200 meV. If the neutrino masses are quasi-degenerate, as would be the case if the recent double-beta decay claim proves true, KATRIN will see the effect. In this case the $0\nu\beta\beta$-decay experiments can provide, in principle, unique information about CP-violation in the lepton sector, associated with Majorana neutrinos.

• Cosmology can also provide crucial information on the sum of the neutrino masses. This topic is summarized in a different section of the report, but it should be mentioned here that the next generation of measurements hope to be able to observe a sum of neutrino masses as small as 40 meV. We would like to emphasize the complementarity of the three approaches, $0\nu\beta\beta$, β decay, and cosmology.

Recommendations:

We conclude that such a double-beta-decay program can be summarized as having three components and our recommendations can be summarized as follows:

1. A substantial number (preferably more than two) of 200-kg scale experiments (providing the capability to make a precision measurement at the quasi-degenerate mass scale) with large US participation should be supported as soon as possible.
   ◦ Each such experiment will cost approximately $10M-$20M and take 3-5 years to implement.

2. Concurrently, the development toward ∼1-ton experiments (*i.e.* sensitive to $\sqrt{\Delta m^2_{\rm atm}}$) should be supported, primarily as expansions of the 200-kg experiments. The corresponding plans for the procurement of the enriched isotopes, as well as for the development of a suitable underground facility, should be carried out. The US funding agencies should set up in a timely manner a mechanism to review and compare the various proposals for such experiments which span research supported by the High Energy and Nuclear Physics offices of DOE as well as by NSF.
   ◦ Each such experiment will cost approximately \$50M-\$100M and take 5-10 years to implement.

3. A diverse R&D program developing additional techniques should be supported.
   The total cost of this described program will be approximately \$250M over a 10 year period.

• In addition to double-beta decay, other techniques for exploring the neutrino mass need to be pursued also. We summarize these recommendations as follows.

1. Although the KATRIN is predominately a European effort, there is significant US participation. The design and construction of this experiment is proceeding well and the program should continue to be strongly supported.

2. Research and development of other techniques for observing the neutrino mass kinematically should be encouraged.

II. INTRODUCTION

The standard model of electroweak interactions, developed in the late 1960's, incorporated neutrinos as left-handed massless partners of the charged leptons. The discovery of the third generation of quarks and leptons completed the model, and made it possible, in addition, to incorporate also a description of CP violation. Later efforts to unify the strong and electroweak interactions led to the development of Grand Unified Theories which provided a natural framework for neutrino masses, and motivated many experiments in the field. Studies of e^+e^- annihilation at the Z-resonance peak have determined the invisible width of the Z boson, caused by its decay into unobservable channels. Interpreting this width as a measure of the number of neutrino active flavors, one can, quite confidently, conclude that there are just three active neutrinos with masses of less than $M_Z/2$.

In parallel, the understanding of big-bang nucleosynthesis and the discovery of the cosmic microwave background illustrated the important role of neutrinos in the history of the early universe. Those developments also led to the possibility that neutrinos, with small but finite mass, could explain the existence of dark matter. Although it now appears that neutrinos are not a dominant source of dark matter in the universe, the experimental evidence obtained in the last decade for finite neutrino masses and mixing between generations is strong and compelling. Those discoveries, the first evidence for 'physics beyond the Standard Model' gives us an intriguing glimpse into the fundamental source of particle mass and the role of flavor in the scheme of particles and their interactions. The scale of neutrino mass differences motivates experimental searches for the neutrinoless double beta decay and end-point anomalies in beta decay described in this report.

Despite the recent triumphs of neutrino physics, several fundamental questions remain to be answered to advance the field itself and its impact in general on the whole particle and nuclear physics, as well as astrophysics and cosmology. The studies of neutrinoless double beta decay and end-point anomalies in beta decay, in particular, are essential and unique in their potential to answer the first two of them and plays an important and equally unique role in the remaining ones:

- Are neutrinos their own anti-particles?
- What are the masses of the neutrinos?
- Do neutrinos violate the symmetry CP?
- Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the Universe?
- What do neutrinos have to tell us about the intriguing proposals for new models of physics?

The present report is structured as follows: In this introductory section we provide the "Goal of the field" statement first in which we stress the fundamental importance of the distinction between the Dirac and Majorana neutrinos, and its relation to the existence of the neutrinoless double beta decay ($0\nu\beta\beta$).

In the next section "$0\nu\beta\beta$ and β decays and Oscillations" we briefly summarize the status of the neutrino oscillation studies and the values of the corresponding mass differences Δm^2_{ij} and mixing angles. Next we discuss the relations and constraints provided by the results of oscillation studies and the neutrino mass parameters extracted from $0\nu\beta\beta$ and β decay experiments. We also show how this research fits into the larger picture of the whole neutrino field described in the other reports of this APS study. Moreover, we stress the importance of Majorana neutrinos for leptogenesis, i.e. for the explanation of the (tiny) baryon/photon ratio and the present excess of baryons over antibaryons.

For $0\nu\beta\beta$, the process that is observable only in heavy nuclei, the understanding of the nuclear structure plays an essential role in extracting the neutrino effective mass from the observed rate. We discuss the nuclear structure aspects in the section titled "Nuclear Structure Issues" and comment on the existing uncertainties as well as on the prospects of reducing them.

The rest of the report deals with the experiments. In the section titled "Experimental Prospects for $\beta\beta$" we summarize the situation in experimental $\beta\beta$ and briefly describe the numerous proposals. A similar treatment for β decay is discussed in "Experimental Prospects for β Decay". The relationship between cosmology and neutrino mass is described in the final section "Cosmology and Neutrino Mass". We end with a conclusion section.

Throughout the report we often use results reported in earlier reviews by some of us [1–4].

At present, we do not know the absolute scale of the neutrino mass. There is an upper limit, of $\sim$ few eV from combining the limits from the tritium β decay with the Δm^2 values from the oscillation studies. For some, but not all, of the neutrinos there is also a lower limit, simply $\sqrt{\Delta m^2}$. These limits show that neutrinos, while massive, are very much lighter than the other fundamental constituents of matter, the charged leptons and quarks. While we do not understand the mass values of any fermion, the huge difference in masses of neutrinos and all charged fermions clearly requires an explanation. The usual one, like the see-saw mechanism, ties the neutrino mass with some very high mass scale. It also suggests that neutrinos, unlike all other fermions, are Majorana particles, i.e. they are their own antiparticles.

The research discussed here, if successfull, would show whether these ideas are true or not. As stated already in the executive summary, observation of the $0\nu\beta\beta$ decay would prove that the total lepton number is not conserved and would establish a nonvanishing neutrino mass of Majorana nature. In other words, observation of the $0\nu\beta\beta$ decay, independently of its rate, would show that neutrinos, unlike all the other constituents of matter, are their own antiparticles. There is no other realistic way to determine the nature - Dirac or Majorana, of massive neutrinos. This would be a discovery of major importance, comparable to the already discovered oscillations of atmospheric, solar and reactor neutrinos, and as important as a discovery of CP violation involving neutrinos. It would have impact not only on this fundamental question, but also on the determination of the absolute neutrino mass scale, and on the pattern of neutrino masses, and possibly on the problem of CP-violation in the lepton sector, associated with Majorana neutrinos.

At the same time, beta-decay endpoint measurements search for a kinematic effect due to neutrino mass and therefore are frequently referred to as "direct searches" for neutrino mass. This technique, which is essentially free of theoretical assumptions about neutrino properties, is not just complementary to the search of $0\nu\beta\beta$ decay. In fact, both types of measurements will be required to fully untangle the nature of the neutrino mass.

The following sections describe the status of the field, and plans for further experiments. Determining the absolute neutrino mass scale, and finding whether neutrinos are indeed Majorana particles and thus that the lepton number is not conserved, would represent a major advance in our understanding of particle physics.

$0\nu\beta\beta$ AND β DECAY AND OSCILLATIONS

Status of oscillation searches

As is well known, the concept of neutrino oscillations is based on the assumption that the neutrinos of definite flavor $(\nu_e, \nu_\mu, \nu_\tau)$ are not necessarily states of a definite mass $\nu_1, \nu_2, \nu_3 ....$ Instead, they are generally coherent superpositions of such states,

$$|\nu_\ell\rangle = \sum_i U_{\ell i} |\nu_i\rangle \ . \tag{1}$$

When the standard model is extended to include neutrino mass, the mixing matrix U is unitary. As a consequence the neutrino flavor is no longer a conserved quantity and for neutrinos propagating in vacuum the amplitude of the process $\nu_\ell \to \nu_{\ell'}$ is

$$A(\nu_\ell \to \nu_{\ell'}) = \sum_i U_{\ell i} e^{-i\frac{m_i^2 L}{2E}} U^*_{\ell' i} \ , \tag{2}$$

The probability of the flavor change for $\ell \neq \ell'$ is the square of this amplitude, $P(\nu_\ell \to \nu_{\ell'}) = |A(\nu_\ell \to \nu_{\ell'})|^2$. It is obvious that due to the unitarity of U there is no flavor change if all masses vanish or are exactly degenerate. The idea of oscillations was discussed early on by Pontecorvo [5, 6] and by Maki, Nakagawa and Sakata [7]. Hence, the mixing matrix U is often associated with these names and the notation U_{MNS} or U_{PMNS} is used.

The formula for the probability is particularly simple when only two neutrino flavors, ν_ℓ and $\nu_{\ell'}$, mix appreciably, since only one mixing angle and two neutrino masses m_i, m_j are then relevant,

$$P(\nu_\ell \to \nu_{\ell' \neq \ell}) = \sin^2 2\theta \sin^2 \left[1.27 |\Delta m^2_{ji}| (\mathrm{eV}^2) \frac{L(\mathrm{km})}{E_\nu(\mathrm{GeV})} \right] \ , \tag{3}$$

where the appropriate factors of $\hbar$ and c were included. Here $\Delta m^2_{ji} \equiv m_j^2 - m_i^2$ is the mass squared difference. Due to the large difference in the two observed Δm^2 values, this simple formula adequately describes most of the experiments as of now.

In general, the mixing matrix of 3 neutrinos is parametrized by three angles, conventionally denoted as $\theta_{12}, \theta_{13}, \theta_{23}$, one CP violating phase δ and two Majorana phases α_1, α_2 [8–10]. Using c for the cosine and s for the sine, the mixing matrix U is parametrized as

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2}\ \nu_1 \\ e^{i\alpha_2/2}\ \nu_2 \\ \nu_3 \end{pmatrix} . \quad (4)$$

The three neutrino masses m_i should be added to the parameter set that describes the matrix (4), representing therefore nine unknown parameters altogether.

The evidence for oscillations of solar (ν_e) and atmospheric (ν_μ and $\bar{\nu}_\mu$) neutrinos is compelling and generally accepted.

Evidence for oscillations of the solar ν_e have been reported first by the pioneering Davis et al. (Homestake) experiment [11]. It has been confirmed and reinforced later by Kamiokande, SAGE, GALLEX/GNO and Super-Kamiokande experiments [12, 13].

The SNO solar neutrino experiment [14, 15], in which it is possible to separately determine the flux of ν_e neutrinos reaching the detector (through the charged current reactions) and the flux of all active neutrinos (through the neutral current reactions), made the conclusion that solar neutrinos oscillate, inescapable.

Independently, KamLAND reactor antineutrino experiment has shown that $\bar{\nu}_e$ neutrinos oscillate as well [16, 17]. Moreover, the oscillation parameters extracted from that experiment agree perfectly with those from the solar ν_e experiments. This agreement, expected by the CPT-invariance, shows that the formalism of oscillations, including the matter effects, is well understood. Based on the combined analysis of these data the parameters Δm^2_{21} (including its positive sign) and $\theta_\odot \sim \theta_{12}$ have been determined with a remarkable accuracy.

Oscillations of the atmospheric ν_μ ($\bar{\nu}_\mu$) have been most clearly observed in the Super-Kamiokande experiment. In particular the observed zenith angle dependence of the multi-GeV and sub-GeV μ-like events [18, 19] represents a compelling evidence. (Indication for the atmospheric neutrino oscillations, based mostly on the μ/e ratio, existed for a long time.) As is well known, the SK atmospheric neutrino data is best described in terms of dominant two-neutrino $\nu_\mu \to \nu_\tau$ ($\bar{\nu}_\mu \to \bar{\nu}_\tau$) vacuum oscillations with maximal mixing. The analysis thus fixes the parameters $|\Delta m^2_{31}| \sim |\Delta m^2_{32}|$ and $\theta_{atm} = \theta_{23}$ (since $\cos\theta_{13} \sim 1$).

Finally, the remaining angle, θ_{13} remains unknown, but is constrained from above by the reactor neutrino CHOOZ and Palo Verde experiments [20, 21].

The Table I summarizes the present status of knowledge of the oscillation parameters (assuming three mass eigenstates, i.e. disregarding the possible existence of sterile neutrinos).

Thus, two of the three angles, and the two mass square differences have been determined reasonably well. The unknown quantities, accessible in future oscillation experiments (and discussed elsewhere in these reports) are the angle θ_{13} and the sign of the $\Delta m^2_{32} \sim \Delta m^2_{31}$. If that sign is positive, the neutrino mass pattern is called a *normal mass ordering* ($m_1 < m_2 < m_3$) and when it is negative it is called *inverted mass ordering* ($m_3 < m_1 < m_2$). The extreme mass orderings, $m_1 < m_2 \ll m_3$ and $m_3 \ll m_1 < m_2$, are called the *normal* and, respectively, *inverted* hierarchies. In addition, the phase δ governing CP violation in the flavor oscillation experiments remains unknown, and a topic of considerable interest. Determination of the CP phase δ is again extensively discussed elsewhere in this report.

The remaining unknown quantities, the absolute neutrino mass scale, and the two Majorana phases α_1 and α_2 are not accessible in oscillation experiments. Their determination is the ultimate goal of $0\nu\beta\beta$ and β decay experiments.

TABLE I: Neutrino oscillation parameters determined from various experiments (2004 status)

Parameter	Value $\pm 1\sigma$	Comment
Δm^2_{21}	$8.2^{+0.6}_{-0.5} \times 10^{-5}$ eV^2	
θ_{12}	$32.3^{\circ}{}^{+2.7}_{-2.4}$	For $\theta_{13} = 0$
$\lvert\Delta m^2_{32}\rvert$	$2.0^{+0.6}_{-0.4} \times 10^{-3}$ eV^2	
$\sin^2 2\theta_{23}$	> 0.94	For $\theta_{13} = 0$
$\sin^2 2\theta_{13}$	< 0.11	For $\Delta m^2_{atm} = 2 \times 10^{-3}$ eV^2

Oscillations and direct neutrino mass measurements

Direct neutrino mass measurements are based on the analysis of the kinematics of charged particles (leptons, pions) emitted together with neutrinos (flavor states) in various weak decays. The most sensitive neutrino mass measurement to date, involving electron type neutrinos, is based on fitting the shape of the beta spectrum (see section VI below). In such measurements the quantity

$$m_{\nu_e} = \sqrt{\sum_i |U_{ei}|^2 m_{\nu_i}^2} \tag{5}$$

is determined or constrained, where the sum is over all mass eigenvalues m_{ν_i} that are too close together to be resolved experimentally.

A limit on m_{ν_e} implies an *upper* limit on the *minimum* value $m_{\nu_{min}}$ of all m_{ν_i}, independent of the mixing parameters U_{ei}: $m_{\nu_{min}} \leq m_{\nu_e}$, i.e., the lightest neutrino cannot be heavier than m_{ν_e}. This is, in a sense, an almost trivial statement.

However, when the study of neutrino oscillations provides us with the values of *all* neutrino mass-squared differences Δm_{ij}^2 (including their signs) and the mixing parameters $|U_{ei}|^2$, and the value of $m_{\nu_e}^2$ has been determined in a future experiment, then the individual neutrino mass squares can be determined:

$$m_{\nu_j}^2 = m_{\nu_e}^2 - \sum_i |U_{ei}|^2 \Delta m_{ij}^2 \quad (\Delta m_{ij}^2 = m_{\nu_i}^2 - m_{\nu_j}^2) \ . \tag{6}$$

On the other hand, if only the absolute values $|\Delta m_{ij}^2|$ are known (but all of them), a limit on m_{ν_e} from beta decay may be used to define an *upper* limit on the *maximum* value $m_{\nu_{max}}$ of m_{ν_i}:

$$m_{\nu_{max}}^2 \leq m_{\nu_e}^2 + \sum_{i<j} |\Delta m_{ij}^2|. \tag{7}$$

In other words, knowing $|\Delta m_{ij}^2|$ one can use a limit on m_{ν_e} to constrain the heaviest active neutrino.

Oscillations, $0\nu\beta\beta$ decay, and neutrino mass

The neutrinoless double beta decay,

$$(Z, A) \rightarrow (Z+2, A) + e_1^- + e_2^- \tag{8}$$

violates lepton number conservation. It can be recognized by its electron sum energy spectrum. Since the nuclear masses are so much larger than the decay Q value, the nuclear recoil energy is negligible, and the electron sum energy of the $0\nu\beta\beta$ is simply a peak at $T_{e1} + T_{e2} = Q$ smeared only by the detector resolution.

The $0\nu\beta\beta$ decay involves a vertex changing two neutrons into two protons with the emission of two electrons and nothing else. One can visualize it by assuming that the process involves the exchange of various virtual particles, e.g. light or heavy Majorana neutrinos, right-handed weak interaction mediated by the W_R boson, SUSY particles, etc. No matter what the vertex is, the $0\nu\beta\beta$ decay can proceed only when neutrinos are massive Majorana particles [22].

Of primary interest is the process mediated by the exchange of light Majorana neutrinos interacting through the left-handed $V - A$ weak currents. The decay rate is then,

$$[T_{1/2}^{0\nu}(0^+ \rightarrow 0^+)]^{-1} \ = \ G^{0\nu}(E_0, Z) \left| M_{GT}^{0\nu} - \frac{g_V^2}{g_A^2} M_F^{0\nu} \right|^2 \langle m_{\beta\beta} \rangle^2 \ , \tag{9}$$

where $G^{0\nu}$ is the accurately calculable phase space integral, $\langle m_{\beta\beta} \rangle$ is the effective neutrino mass, and $M_{GT}^{0\nu}$, $M_F^{0\nu}$ are the nuclear matrix elements. The problems associated with the evaluation of the nuclear matrix elements are discussed in Section IV, where also corrections to the nuclear structure dependent part of the decay rate are discussed.

If the $0\nu\beta\beta$ decay is observed, and the nuclear matrix elements are known, one can deduce the corresponding $\langle m_{\beta\beta} \rangle$ value, which in turn is related to the oscillation parameters by

$$\langle m_{\beta\beta} \rangle = | \sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i} | \ , \tag{10}$$

where the sum is only over light neutrinos ($m_{\nu_i} < 10$ MeV). The Majorana phases α_i were defined earlier in Eq.(4). If the neutrinos ν_i are CP eigenstates, α_i is either 0 or π. Due to the presence of these unknown phases, cancellation of terms in the sum in Eq.(10) is possible, and $\langle m_{\beta\beta} \rangle$ could be smaller than any of the m_{ν_i} even if all neutrinos ν_i are Majorana particles.

We can use the values in Table I and express the $\langle m_{\beta\beta} \rangle$ in terms of the three unknown quantities: the mass scale, represented by the mass of the lightest neutrino $m_{\nu_{min}}$, and the two Majorana phases. In doing so, it is useful to distinguish three mass patterns: normal hierarchy (NH), $m_1 < m_2 \ll m_3$ (i.e. $m_{\nu_{min}} = m_1$), inverted hierarchy (IH), $m_3 \ll m_1 < m_2$ (i.e. $m_{\nu_{min}} = m_3$), and the quasi-degenerate spectrum (QD) where $m_{\nu_{min}} \gg \sqrt{|\Delta m^2_{32}|}$ as well as $m_{\nu_{min}} \gg \sqrt{|\Delta m^2_{21}|}$.

In the case of normal hierarchy, and assuming that $m_{\nu_{min}} \equiv m_1$ can be neglected, one obtains

$$\langle m_{\beta\beta} \rangle^{NH} \simeq |\sqrt{\Delta m^2_{21}} \sin^2\theta_{12} \cos^2\theta_{13} + \sqrt{|\Delta m^2_{31}|} \sin^2\theta_{13} e^{-i\alpha_2}| \ . \tag{11}$$

For $\theta_{13} = 0$ and the parameter values listed in Table I, $\langle m_{\beta\beta} \rangle^{NH} = 2.6 \pm 0.3$ meV. On the other hand, if $\tan\theta^2_{13} \geq \sin^2\theta_{12}\sqrt{|\Delta m^2_{21}/\Delta m^2_{31}} \sim 0.06$ a complete cancellation might occur and $\langle m_{\beta\beta} \rangle^{NH}$ might be vanishingly small. However, if $m_{\nu_{min}} > 0$ then $\langle m_{\beta\beta} \rangle^{NH}$ may vanish even for $\theta_{13} = 0$, see Fig. 1.

In the case of the inverted hierarchy, and again assuming that $m_{\nu_{min}} \equiv m_3$ can be neglected, one obtains

$$\langle m_{\beta\beta} \rangle^{IH} \simeq \sqrt{|\Delta m^2_{31}|} \cos^2\theta_{13} \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \frac{\alpha_2 - \alpha_1}{2}} \ . \tag{12}$$

Thus, if $\theta_{13} = 0$ and for the parameter values listed in Table I $\langle m_{\beta\beta} \rangle^{NH} \simeq 14 - 51$ meV, depending on the Majorana phases.

Finally, for the quasi-degenerate spectrum

$$\langle m_{\beta\beta} \rangle^{QD} \simeq m_0 |(\cos^2\theta_{12} e^{i\alpha_1} + \sin^2\theta_{12} e^{i\alpha_2}) \cos^2\theta_{13} + \sin^2\theta_{13}|. \tag{13}$$

If $\theta_{13} = 0$ and for the parameters listed in Table I, $\langle m_{\beta\beta} \rangle^{QD} \simeq (0.71 \pm 0.29) m_0$.

Detailed discussion of the relation between the $\langle m_{\beta\beta} \rangle$ and the absolute neutrino mass scale can be found in numerous papers (see, e.g. some of the more recent references [23–28]).

In Fig.1 we show the plot of $\langle m_{\beta\beta} \rangle$ versus $m_{\nu_{min}}$ using the oscillation parameters in Table I, and allowing for the maximum value of θ_{13} and one σ variations of them. One can clearly see the three regions (NH, IH, QD). Thus, determination of the $\langle m_{\beta\beta} \rangle$ value would allow, in general, to distinguish between these patterns, and to determine a range of $m_{\nu_{min}}$. One should keep in mind, however, that there are caveats to this statement for the situations where the corresponding bands merge (e.g. the IH and QD near $m_{\nu_{min}} \sim 0.05$ eV).

Despite this caveats, obviously, if one can experimentally establish that $\langle m_{\beta\beta} \rangle \geq 50$ meV, one can conclude that the QD pattern is the correct one, and one can read off an allowed range of $m_{\nu_{min}}$ values from the figure. (The sign of $\Delta m^2_{31} \sim \Delta m^2_{32}$ will remain undetermined in that case, however.)

On the other hand, if $\langle m_{\beta\beta} \rangle \sim$ 20-50 meV only an upper limit for the $m_{\nu_{min}}$ can be established, and the pattern is likely IH, even though exceptions exist. However, if (and that is unlikely in a foreseable future) the value of $m_{\nu_{min}}$ can be determined independently, the pattern can be resolved.

Finally, if one could determine that $\langle m_{\beta\beta} \rangle \leq 10$ meV but nonvanishing (which is again is unlikely in a foreseable future), one could conclude that the NH pattern is the correct one.

Altogether, observation of the $0\nu\beta\beta$ decay, and accurate determination of the $\langle m_{\beta\beta} \rangle$ value would not only establish that neutrinos are massive Majorana particles, but would contribute considerably to the determination of the absolute neutrino mass scale. Moreover, if the neutrino mass scale would be known from independent measurements, one could possibly obtain from the measured $\langle m_{\beta\beta} \rangle$ also some information about the CP violating Majorana phases.

Absolute neutrino mass scale

As shown above, $0\nu\beta\beta$ and β decays both depend on different combinations of the neutrino mass values and oscillation parameters. The $0\nu\beta\beta$ decay rate is proportional to the square of a coherent sum of the Majorana neutrino masses because $\langle m_{\beta\beta} \rangle$ arises from exchange of a virtual neutrino. On the other hand, in beta decay one can determine an incoherent sum because a real neutrino is emitted.

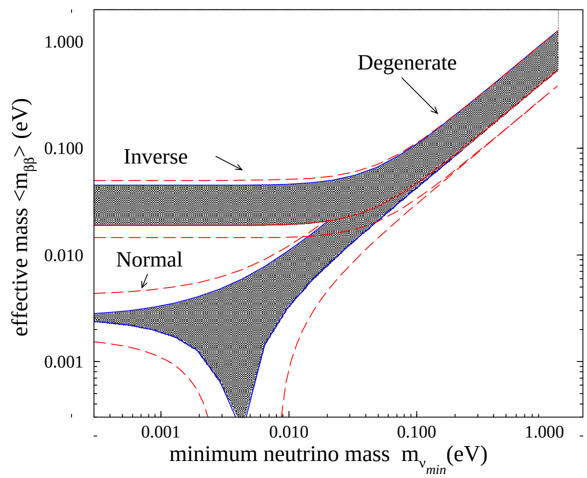

FIG. 1: Effective Majorana mass $\langle m_{\beta\beta}\rangle$ versus the minimum mass $m_{\nu_{min}}$. The different mass patterns are indicated. The shaded region corresponds to the best values of oscillation parameters, and $\theta_{13} = 0$. The dashed lines indicate the expanded range corresponding to the 1σ errors of the oscillation parameters and the maximum allowed θ_{13}. Note that the uppermost line is unchaged (within this scale) in that case.

Quite different source of information is based on cosmological and astrophysical observations where the density of the primordial neutrino sea is determined or constrained and thus a parameter proportional to the sum of the neutrino masses is determined.

Massive neutrinos would contribute to the cosmological matter density an amount,

$$\Omega_\nu h^2 = \Sigma m_{\nu_i}/92.5 \text{ eV} , \tag{14}$$

where Ω_ν is the neutrino mass density relative to the critical density and $100h$ is the Hubble constant in km/s/Mpc. From the requirement that the neutrinos left over from the Big Bang do not overclose the universe an upper limit, with a minimum assumptions (essentially just the requirement of stability), is obtained

$$m_\nu \leq \frac{46 \text{ eV}}{N_\nu} , \tag{15}$$

where N_ν is the number of neutrino species with standard weak interactions [29].

More restrictive limits are obtained from the requirement that excessive free streaming in the early universe would not suppress small scale power of the observed matter distribution. The relation between the damping scale d_{FS} caused by free streaming, and the neutrino mass is approximately

$$d_{FS} \text{ (Gpc)} \sim 1/m_\nu \text{ (eV)} . \tag{16}$$

The data on Cosmic Microwave Background (CMB) and large scale galaxy surveys can be used to constrain $N_\nu m_\nu$ for the quasi-degenerate neutrino mass spectrum, and thus also m_ν for various assumed number of neutrino flavors N_ν. The following Table II is based on [30]. Different analyses with different assumptions typically reach similar conclusions, suggesting that these limits are fairly robust (see more discussion further in this report).

For completeness, note that, in principle, neutrino mass can be also extracted from the time of flight determination of neutrinos from future galactic supernova. However, one does not expect to be able to reach sub-eV sensitivity with this method (see e.g.[31]).

It is worthwhile to stress that the various methods that depend on the neutrino absolute mass scale are complementary. If, ideally, a positive measurement is reached in all of them ($0\nu\beta\beta$ β decay, cosmology) one can test the results for consistency and perhaps determine the Majorana phases. We illustrate the idea [3] in Fig. 2 using a two-neutrino-species example of such a set of measurements. (A 3-species example is discussed in Ref. [3].) We took the mixing matrix and Δm^2 to be the best fit to the solar-neutrino data, with an arbitrary value for the Majorana phase α (of which there is only one) of 2.5 radians. We then made up values for Σ, $\langle m_{\beta\beta}\rangle$, and $\langle m_\beta\rangle$ assuming them to be the results of pretend measurements. Each curve in the m_2 vs. m_1 graph is defined by one of these measurements. We chose the value of Σ (from cosmology) to be 600 meV, corresponding to a quasidegenerate hierarchy, and let $\langle m_\beta\rangle$

TABLE II: Limits on $N_\nu m_\nu$ and on m_ν assuming quasi-degenerate mass spectrum. In the last column is the heaviest neutrino mass assuming that one neutrino dominates the sum.

N_ν	$N_\nu m_\nu$ (eV)	m_ν (eV)	$m_{\nu_{max}}$ (eV)
3	1.01	0.34	0.73
4	1.38	0.35	1.05
5	2.12	0.42	2.47
6	2.69	0.45	4.13

= 300 meV and $\langle m_{\beta\beta}\rangle$ = 171 meV. The m_2 versus m_1 curves from the "measurements" of the oscillation parameters, Σ, and β decay are:

$$
\begin{aligned}
m_2 &= \Sigma - m_1 \\
m_2 &= \sqrt{m_1^2 + \delta m_{12}^2} \\
m_2 &= \sqrt{(\langle m_\beta\rangle/U_{e2})^2 - (m_1 U_{e1}/U_{e2})^2}\,.
\end{aligned}
\tag{17}
$$

The $\beta\beta$ constraint is a little more complicated than that from β decay. The curve is also an ellipse but rotated with respect to the axes. All of the equations express m_2 in terms of m_1 and measured parameters and all should intersect at one (m_1,m_2) point. However, because the point is overdetermined, the $\beta\beta$ ellipse will intersect only for a correct choice of α. This provides a way to determine α. In Figure 2 we drew the $\beta\beta$ ellipse for $\alpha = 2.0$ radians and for the "true" value of 2.5 radians to show how the intersection does indeed depend on a correct choice of the phase.

Many authors have examined the potential to combine measurements from $\beta\beta$ decay, tritium β decay, and cosmology to determine the Majorana phases. (See e.g. [57–59].)

Leptogenesis

Leptogenesis is a natural possibility when the see-saw mechanism is realized by Nature. Since this mechanism predicts the light neutrinos to be of Majoarana type, $0\nu\beta\beta$ is also expected. Though the details of the connection of the high and low energy parameters remain to be investigated in a given model, leptogenesis always comes with $0\nu\beta\beta$. The only exception is when in the basis in which the charged leptons are diagonal the neutrino mass matrix has a zero entry in the ee element, resulting in no neutrinoless double beta decay. This implied texture will however have interesting physical implications by itself. In this section we discuss the relationship between neutrino mass and leptogenesis.

The origin of the matter-antimatter asymmetry is one of the most important questions in cosmology. The presently observed baryon asymmetry is [32]

$$
Y_B = \frac{n_B - n_{\bar{B}}}{s} \simeq 6.5 \times 10^{-10}\,. \tag{18}
$$

In 1967 A. Sakharov suggested that the baryon density can be explained in terms of microphysical laws [33]. Three conditions need to be fullfilled:

- Baryon number (or Lepton number, for the leptogenesis mechanism) violation. Assuming that the initial baryon asymmetry is negligible, as implied by inflationary models, baryon number violation is required to produce a net final baryon asymmetry.

- C and CP violation. The CP symmetry is the product of charge conjugation and parity. If CP is conserved, every reaction which produces a particle will be accompanied by a reaction which gives its antiparticle, with no creation of a net baryon number.

- Departure from thermal equilibrium.

Several mechanism have been proposed to understand the baryon asymmetry.

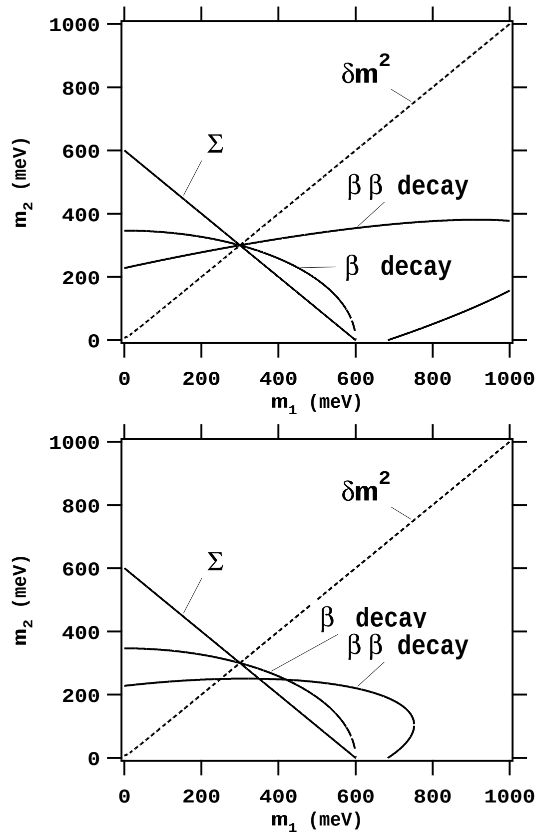

FIG. 2: A consistency plot for the neutrino mass eigenvalues m_1 and m_2, for various hypothetical measurements. This set of curves indicates how measured values of Σ, $\langle m_{\beta\beta}\rangle$, $\Delta m^2_{\rm sol}$, and $\langle m_\beta\rangle$ constrain the mass eigenvalues. The $0\nu\beta\beta$ curve has been drawn for an *incorrect* value of the phase in the bottom panel to indicate the sensitivity of this technique for extracting the CP-violating phase. See text for further description of the parameters used to draw the curves.

- Planck-scale baryogenesis. While we can expect a quantum theory of gravity not to preserve any quantum number, these effects would be relevant only at very early times and the baryon asymmetry generated in this way would be subsequently diluted in the inflationary epoch.

- GUT baryogenesis (see, e.g., ref. [34]). GUT theories assume the existence of an underlying theory at high scale with a simple gauge group which is then broken to the Standard Model gauge group at low energy scale. The unification scale is expected to be at $\sim 10^{16}$ GeV. In general these models have lepton and baryon number violation and have many new parameters with respect to the Standard Model which can provide new sources of CP-violation. However cosmological considerations, mainly overproduction of gravitinos, suggest that the reheating temperature after inflation should be not higher than $\sim 10^9$ GeV. If so, any baryon asymmetry produced at the GUT scale would be later diluted and negligible.

- Electroweak baryogenesis. The interactions of the Standard Model, even if preserving the lepton and baryon number at the perturbative level, do violate it non-perturbatively [35]. The ground states of a non-abelian gauge group are labeled by an integer n and are separated by energy barriers one from the other. At zero temperature, the instantons transitions between different vacua are exponentially suppressed, because they are due to quantum-tunneling effects. At high temperatures above the electroweak breaking scale, these transitions can proceed through sphaleron processes. This produces a net baryon number. It was pointed out the Standard Model can satisfy all the three Sakharov condition for baryogenesis [36]. The departure from equilibrium is realized at the electroweak symmetry breaking scale when the Higgs field acquires a vacuum expectation value different from zero and a phase transition takes place. However, the generated baryon asymmetry is by far too small to account for the observations. This is mainly due to the fact that the departure from equilibrium is not strong enough, as implied by a heavy Higgs, $m_h > 80$ GeV.

Supersymmetric extensions of the Standard Model contain new sources of CP-violation and an enlarged set of parameters which might produce a first order phase transition. The parameter space which allows for a sizable baryon number generation is rather small (it requires in particular a light stop) and it will be soon tested.

- Affleck-Dine baryogenesis [37]. Scalar fields carrying baryon and lepton number are naturally present in supersymmetric extension of the Standard Model (e.g. squarks and sleptons). A coherent scalar field, a field which has large vacuum expectation value, can in principle carry a large baryon number. This condensate can be produced in the Early Universe by the evolution of the scalar field along flat directions of its potential. The decay of the condensate into ordinary matter is then responsible for the baryon asymmetry of the Universe, as the baryon charge of the condensate is transferred to quarks. This is still a viable explanation for the baryon asymmetry of the Universe.

- Leptogenesis [38]. Let us notice that $B-L$ is conserved both at the perturbative and non-perturbative level. This implies that if one creates a net $B-L$, (e.g., a lepton number), the sphaleron processes would leave both baryon and lepton number comparable to the original $B-L$. This idea is implemented in the leptogenesis scenario [38]. Leptogenesis is particularly appealing because it takes place in the context of see-saw models [39], which naturally explain the smallness of neutrino masses. The see-saw mechanism requires the existence of heavy right-handed (RH) Majorana neutrinos, completely neutral under the Standard Theory gauge symmetry group. Consequently, they can acquire Majorana masses that are not related to the electroweak symmetry breaking mechanism, and can, in principle, be much heavier than any of the known particles. Introducing a Dirac neutrino mass term and a Majorana mass term for the right–handed neutrinos via the Lagrangian

$$-\mathcal{L} = \overline{\nu_{Li}}\,(m_D)_{ij}\,N_{Rj} + \frac{1}{2}\,\overline{(N_{Ri})^c}\,(M_R)_{ij}\,N_{Rj}\ , \tag{19}$$

leads, for sufficiently large M_R, to the well know see–saw [39] formula

$$m_\nu \simeq -m_D\, M_R^{-1}\, m_D^T\ , \tag{20}$$

$$= U_{\rm PMNS}\, D_m\, U_{\rm PMNS}^T \tag{21}$$

where terms of order $\mathcal{O}(M_R^{-2})$ are neglected. Here D_m is a diagonal matrix containing the masses $m_{1,2,3}$ of the three light massive Majorana neutrinos and $U_{\rm PMNS}$ is the unitary Pontecorvo–Maki–Nagakawa–Sakata lepton mixing matrix.

The CP-violating and out-of-equilibrium decays of RH neutrinos produce a lepton asymmetry [38] that can be converted into a baryon asymmetry through anomalous electroweak processes [36, 40]. The requisite CP violating decay asymmetry is caused by the interference of the tree level contribution and the one–loop corrections in the decay rate of the three heavy Majorana neutrinos, $N_i \to \Phi^-\,\ell^+$ and $N_i \to \Phi^+\,\ell^-$:

$$\begin{aligned} \varepsilon_i &= \frac{\Gamma(N_i \to \Phi^-\,\ell^+) - \Gamma(N_i \to \Phi^+\,\ell^-)}{\Gamma(N_i \to \Phi^-\,\ell^+) + \Gamma(N_i \to \Phi^+\,\ell^-)} \\ &\simeq \frac{1}{8\,\pi\,v^2} \sum_{j\neq i} \frac{{\rm Im}(m_D^\dagger m_D)^2_{ij}}{(m_D^\dagger m_D)_{ii}}\ (f(x_j)+g(x_j))\ , \end{aligned} \tag{22}$$

where Φ and ℓ indicate the Higgs field and the charged leptons, respectively. Here $v \simeq 174$ GeV is the electroweak symmetry breaking scale and $x_j \equiv M_j^2/M_i^2$. The functions f and g stem from vertex [38, 41] and from self–energy [42] contributions.

$$\begin{aligned} f(x) &= \sqrt{x}\left(1-(1+x)\,\ln\left(\frac{1+x}{x}\right)\right) \\ g(x) &= \frac{\sqrt{x}}{1-x} \end{aligned}\ . \tag{23}$$

For $x \gg 1$, i.e., for hierarchical heavy Majorana neutrinos, one has $f(x)+g(x) \simeq -\frac{3}{2\sqrt{x}}$. Then, the baryon asymmetry is obtained via $Y_B = a\,(\kappa/g^*)\,\varepsilon_1$, where $a \simeq -1/2$ is the fraction of the lepton asymmetry converted into a baryon asymmetry [36, 40], $g^* \simeq 100$ is the number of massless degrees of freedom at the time of the decay, and κ is an efficiency factor that is obtained by solving the Boltzmann equations [43]. Typically, one gets $Y_B \sim 6\times10^{-10}$ when $\varepsilon_1 \sim (10^{-6}-10^{-7})$ and $\kappa \sim (10^{-3}-10^{-2})$. A similar estimate of Y_B is obtained in the supersymmetric (SUSY) theories as well [42].

In non-supersyymetric models which embedd the see-saw mechanism, lepton flavour violating (LFV) charged lepton decays such as $\mu \to e+\gamma$, $\tau \to \mu+\gamma$, $\tau \to e+\gamma$, are predicted to take place with branching ratios which are strongly suppressed [44]. SUSY theories have additional sources of lepton charge non-conservation. If SUSY is broken above the RH Majorana mass scale, as, e.g, in gravity-mediated breaking scenarios, there are renormalization group effects that generate new lepton charge non-conserving couplings at low energy even if such couplings are absent at the GUT scale [45, 46]. In contrast to the non-supersymmetric case, the LVF processes can proceed with rates and cross-sections which are within the sensitivity of presently operating and proposed experiments. Under the assumption of flavour universality of the SUSY breaking sector (scalar masses and trilinear couplings) at the GUT scale M_X, using the leading–log approximation, one can estimate [45–47] the branching ratio of the charged lepton decays $\ell_i \to \ell_j + \gamma$, $\ell_i(\ell_j) = \tau, \mu, e$ for $i(j) = 3, 2, 1$, $i > j$,

$$\begin{aligned} BR(\ell_i \to \ell_j + \gamma) \simeq \alpha^3 \left(\frac{(3 + a_0)\, m_0^2}{8\, \pi^2\, m_S^4\, G_F\, v^2} \right)^2 \\ \left| (m_D \; \text{diag}(\log \tfrac{M_X}{M_1}, \tfrac{M_X}{M_2}, \tfrac{M_X}{M_3})\; m_D^\dagger)_{ij} \right|^2 \tan^2 \beta \;, \end{aligned} \tag{24}$$

where m_S denotes a slepton mass, m_0 is the universal mass scale of the sparticles and a_0 is a trilinear coupling (all at M_X) (for details, see, e.g., ref. [47]).

Establishing a connection between the parameters at low energy (neutrino masses, mixing angles and CP-violating phases), measurable in principle in present and future experiments, and at high energy (relevant in leptogenesis) has gathered a great interest in the last few years. The number of parameters in the full Lagrangian of models which implement the see-saw mechanism is larger than the ones in the low-energy sector: in the case of 3 light neutrinos and three heavy ones, at high energy the theory contains in the neutrino sector 18 parameters of which 12 real ones and 6 phases, while at low energy only 9 are accessible - 3 angles, 3 masses and 3 phases. The decoupling of the heavy right-handed neutrinos implies the loss of information on 9 parameters. This implies that reconstructing the high energy parameters entering in the see-saw models from the measurement of the masses, angles and CP-violating phases of m_ν is in general difficult, if not impossible, and depends on the specific model considered.

Using the weak basis in which both M_R and the charged lepton mass matrix are real and diagonal, we find useful to parametrize the Dirac mass by the biunitary or the orthogonal parametrizations.

Biunitary parametrization. We can write the complex 3×3 Dirac mass as (see, e.g., ref [48]):

$$m_D = U_L^\dagger \, m_D^{\text{diag}} \, U_R \;, \tag{25}$$

where U_L and U_R are unitary 3×3 matrices and m_D^{diag} is a real diagonal matrix. All the CP-violating phases are contained in U_L and U_R.

Orthogonal parametrization.

By using the see-saw formula, eq. (20), we can express m_D as [46, 49]:

$$m_D = i \, U_{\text{PMNS}} \, D_m^{1/2} \, R \, M_R^{1/2} \;, \tag{26}$$

where D_m is the diagonal real matrix which containes the low-energy light neutrino masses, and R is a complex orthogonal matrix. R contains 3 real parameters and 3 phases.

The use of the two indicated parametrization clarifies the dependence of the processes we are interested in, e.g. leptogenesis and LFV charged lepton decays, on the different parameters entering in m_D. In particular we have that:
- for leptogenesis, the decay asymmetry ε_1 depends on the hermitian matrix $m_D^\dagger m_D$:

$$m_D^\dagger m_D = \begin{cases} U_R^\dagger \, (m_D^{\text{diag}})^2 \, U_R \;, & \text{bi–unitary;} \\ M_R^{1/2} \, R^\dagger \, D_m \, R \, M_R^{1/2} \;, & \text{orthogonal.} \end{cases} \tag{27}$$

We can notice that the PMNS unitary mixing matrix U does not enter esplicitly into the expression for the lepton asymmetry.

- Concerning LFV decays, in supersymmetric versions of the see–saw mechanism, their rates depend approximately on [45, 46]

$$m_D m_D^\dagger = \begin{cases} U_L^\dagger \, (m_D^{\text{diag}})^2 \, U_L \;, \\ U_{\text{PMNS}} \, D_m^{1/2} \, R \, M_R \, R^\dagger \, D_m^{1/2} \, U_{\text{PMNS}}^\dagger \;, \end{cases} \tag{28}$$

by using the biunitary (upper expression) or the orthogonal parametrization (lower expression).

- finally, in the biunitary parametrization, the neutrino mass matrix m_ν can be written as:

$$m_\nu = -U_L^\dagger\, m_D^{\rm diag}\, U_R\, M_R^{-1}\, U_R^T\, m_D^{\rm diag}\, U_L^* \ . \tag{29}$$

This shows that the phases in $U_{\rm PMNS}$ receive contribution from CP-violation both in the right-handed sector, responsible for leptogenesis, and in the left-handed one, which enters in lepton flavour violating processes. Due to the complicated way in which the high energy phases and real parameters enter in m_ν, eq. (29), if there is CP-violation at high energy, as required by the leptogenesis mechanism, we can expect in general to have CP-violation at low-energy, as a complete cancellation would require some fine-tuning or special forms of m_D and M_R. Let us mention that an observation of CP-violation at low energy, however, does not imply necessarily CP-violation in U_R as it might receive all its contributions from U_L.

More specifically, from eq. (29), we see that, in general, there is no one-to-one link between low energy CP-violation in the lepton sector and the baryon asymmetry: a measurement of the low energy CP-violating phases does not allow to reconstruct the leptogenesis phases [50]. However most specific models allow for such a connection. In particular if the number of parameter is reduced in m_D, then a one-to-one correspondence between high energy and low energy parameters might be established. This can be achieved in models which allow for CP-violation only in the right-handed sector, that is in U_R, or which reduce the number of independent parameters at high energy, for example by requiring only two right-handed neutrinos [51]. Each model of neutrino mass generation should be studied in detail separately to establish the feasibility of the leptogenesis mechanism [52].

Furthermore the amount of baryon asymmetry depends on the type of light and heavy neutrino mass spectra and succesful leptogenesis imposes some constrains on the allowed mass scales [48, 53, 54]. For example in ref. [48] the case of strongly hierarchical see-saw models was analyzed, assuming a hierarchical structure of the heavy Majorana neutrino masses and of the neutrino Dirac mass matrix m_D. In order to produce a sufficient amount of baryon asymmetry via the leptogenesis mechanism, the scale of m_D should be given by the up–quark masses. In this case the CP violation effects in neutrino oscillations can be observable, but, in general, there is no direct connection between the latter and the CP violation in leptogenesis. In ref. [54] it is also shown that, in the case of thermal leptogenesis with a hierarchical structure of the heavy Majorana masses, a strong bound on the light neutrino masses can be put of order 0.1 eV. This bound can be weakened if one assumes non-thermal right-handed neutrino production and/or an enhancement of the decay asymmetry due to quasi-degenerate right-handed neutrinos (resonant leptogenesis). For example, in ref. [49], the case of quasi-degenerate spectrum of light neutrinos, $m_{1,2,3} \cong m_\nu > 0.2$ eV, was considered. It was shown that leptogenesis is feasible and can provide the observationally required baryon asymmetry of the Universe. Furthermore it was pointed out that the branching ratios for the lepton flavour processes, $\mu \to e + \gamma$, $\tau \to \mu + \gamma$ and $\tau \to e + \gamma$ decay, might be close to the present bounds and that they depend on the Majorana CP-violating phases which enter in $\langle m \rangle$.

The possible observation of $0\nu\beta\beta$ decay would play an important role in understanding the origin of the baryon asymmetry as it would imply that lepton number (one of the main conditions for leptogenesis) indeed is not conserved. Furthermore the Majorana nature of neutrinos would be established: the see-saw mechanism would be regarded as a reasonable explanation of neutrino mass generation. Leptogenesis naturally takes place in this scenario. Finally the observation of CP-violation in the lepton sector, in neutrino oscillation experiments and/or $0\nu\beta\beta$ decay, would suggest the existence of CP-violation at high energy, which might be related to the one responsible for leptogenesis.

In conclusion, the observation of lepton number violation in $0\nu\beta\beta$ decay and, in addition, possibly of CP-violation in the lepton sector, would be a strong indication, even if not a proof (as it is not possible to reconstruct in a model indipendent way the high energy parameters from m_ν), of leptogenesis as the explanation for the observed baryon asymmetry of the Universe.

Alternative tests of lepton number conservation

Our main emphasis is on the study of the $0\nu\beta\beta$ decay,

$$(A,Z) \longrightarrow (A,Z+2)\ +\ e^-\ +\ e^- \ . \tag{30}$$

However, alternatively, similar physics could be tested in other processes, e.g. in

$$\mu^-\ +\ (A,Z)\ \longrightarrow\ e^+\ +\ (A,Z-2) \tag{31}$$

$$K^+\ \longrightarrow\ \mu^+\ +\ \mu^+\ +\ \pi^- \tag{32}$$

which can be mediated by the exchange of virtual massive Majorana neutrinos [55, 56] and where rather restrictive limits on the corresponding branching ratios exist. These Lepton number violating decay rates are typically proportional to an average Majorana neutrino mass of the form: $\langle m_{\ell\ell'}\rangle^2 = |\sum_i U_{\ell i}U_{\ell' i}e^{\alpha_i}m_i|^2$, where $\alpha_i/2$ denotes the Majorana phases (which can lead to destructive interference).

Searches for muon-positron conversion (31) and rare kaon decays (32) yield: $\langle m_{\mu e}\rangle < 17(82)$ MeV, and $\langle m_{\mu\mu}\rangle < 4\times10^4$ MeV, respectively (see [1] and references therein). These bounds therefore do not constitute a useful constraint for the mass pattern of the three light neutrinos. Similarly to the kinematic tests, new Majorana mass experiments are focusing on process $0\nu\beta\beta$ offering by far the best sensitivity.

Note that other lepton number violating processes might also exist, causing for example the emission of the $\bar{\nu}_e$ antineutrinos by the Sun. Even though the existence of such processes would again signal that neutrinos are massive Majorana particles, the interpretation of the rate in terms of neutrino masses is not straigthforward. Instead, other mechanisms might be at play, like the spin-flavor precession combined with neutrino oscillations (relevant parameter is then $\mu_\nu B_T$, where μ_ν is the transition magnetic moment and B_T is the magnetic field in the Sun [60]) or neutrino decay (the relevant parameter is then τ/m of the heavier neutrino [61]).

Mechanism of $0\nu\beta\beta$ decay

Although the occurrence of $0\nu\beta\beta$ decay implies the existence of massive Majorana neutrinos [22], their exchange need not be the only and even dominant contribution to the decay rate. Almost any physics that violates the total lepton number can cause $0\nu\beta\beta$ decay. A heavy Majorana neutrino can be exchanged, or supersymmetric particles, or a leptoquark. Right-handed weak currents, either leptonic or hadronic, can cause the absorption of an emitted virtual neutrino without the helicity flip that depends on the neutrino mass. Moreover, heavy particle exchange, heavy neutrinos, supersymmetric particles (see, e.g., [62]), resulting from lepton number violation dynamics at some scale above the electroweak one can lead to $0\nu\beta\beta$ decay with the same single electron spectra as in the favored case of the light Majorana neutrino exchange. These alternative mechanisms, if dominant, would not allow (or would make it very difficult) to extract the effective Majorana mass $\langle m_{\beta\beta}\rangle$ from the measured $0\nu\beta\beta$ decay rate.

The relative size of heavy (A_H) versus light particle (A_L) exchange contributions to the decay amplitude can be crudely estimated as follows [63]:

$$A_L \sim G_F^2 \frac{m_{\beta\beta}}{\langle\bar{k}^2\rangle},\ A_H \sim G_F^2 \frac{M_W^4}{\Lambda^5},\ \frac{A_H}{A_L} \sim \frac{M_W^4\langle\bar{k}^2\rangle}{\Lambda^5 m_{\beta\beta}}\ , \tag{33}$$

where $\bar{k} \sim$ (50 MeV) is the typical light neutrino virtual momentum, and Λ is the heavy mass scale relevant to the lepton number violation dynamics. Therefore, $A_H/A_L \sim O(1)$ for $m_{\beta\beta} \sim 0.1 - 0.5$ eV and $\Lambda \sim 1$ TeV, and thus the TeV scale leads to similar $0\nu\beta\beta$ decay rate as the exchange of light Majorana neutrinos with the effective mass $m_{\beta\beta} \sim 0.1 - 0.5$ eV. (Note that if this heavy mass scale Λ is larger than 3 - 5 TeV the A_L will clearly dominate.)

The exchange of heavy particles involves short-range propagators that give rise to decay rates of the same form as in the mass-driven mode: simple two-s-wave-electron phase space multiplied by the square of an amplitude. Two-nucleon correlations do not suppress the effects of heavy particles, which can be transmitted between nucleons by pions [62]. The angular distributions and single-electrons spectra will therefore be the same in all these processes. One way to distinguish one from another is to take advantage of the different nuclear matrix elements that enter the amplitudes (leading to different total decay rates). Unknown parameters such as the effective neutrino mass or the trilinear R-parity-violating supersymmetric coupling (violation of R parity naturally accompanies Majorana neutrino-mass terms) also enter the rates, so several transitions would have to be measured. This might be best accomplished [66] by measuring transitions to several final states in the same nucleus, but if the matrix elements can be calculated accurately enough one could also measure the rates to the ground states of several different nuclei. The problems in determining the source of $0\nu\beta\beta$ decay are mitigated by constraints from other experiments on many extra-Standard models. Some of these constraints will be much stronger once the Large Hadron Collider comes on line.

Alternatively, it has been argued in [67] that the study of the lepton flavor violating processes $\mu \to e$ conversion, and $\mu \to e + \gamma$ will provide important insight about the mechanism of the $0\nu\beta\beta$ decay. In particular, the ratio of the branching fractions of these processes provides a diagnostic tool for establishing whether the exchange of light Majorana neutrinos is the dominant mechanism (and hence determination of $\langle m_{\beta\beta}\rangle$ is possible) or whether further more involved analysis is needed.

III. NUCLEAR STRUCTURE ISSUES

The observation of $0\nu\beta\beta$ decay would immediately tell us that neutrinos are Majorana particles and give us an estimate of their overall mass scale. But without accurate calculations of the nuclear matrix elements that determine the decay rate it will be difficult to reach quantitative conclusions about masses and hierarchies.

Theorists have tried hard to develop many-body techniques that will allow such calculations. In order to test the calculations they have tried to calibrate them against related observables: $2\nu\beta\beta$ decay, ordinary β^+ and β^- decay, Gamow-Teller strength distributions, odd-even mass differences and single-particle spectra. They have tried to exploit approximate isospin and $SU(4)$ symmetries in the nuclear Hamiltonian and to extend well-known many-body methods in novel ways. In spite of all this effort, we know the matrix elements with only limited accuracy. In this section we review the state of the nuclear-structure calculations and discuss ways to improve them.

Most recent attempts to calculate the nuclear matrix elements have been based on the neutron-proton Quasiparticle Random Phase Approximation (QRPA) or extensions to it. Of those that haven't, the most prominent are based on the shell model (SM). While the two methods have much in common — their starting point is a Slater determinant of independent nucleons — the kinds of correlations they include are complementary. The QRPA treats a large fraction of the nucleons as "active" and allows these nucleons a large single-particle space to move in. But RPA correlations are of a specific and simple type best suited for collective motion. The shell model, by contrast, treats a small fraction of the nucleons in a limited single-particle space, but allows the nucleons there to correlate in arbitrary ways. That these very different approaches yield similar results indicates that both capture most of the important physics. That, by itself, is encouraging and restricts the possible values of nuclear matrix elements considerably.

QRPA

The application of QRPA to $\beta\beta$ decay began with the realization by [68] that in the QRPA the neutron-proton (np) particle-particle (i.e. pairing-like) interaction, which has little effect on the collective Gamow-Teller resonance, suppresses $2\nu\beta\beta$ rates considerably. Soon afterward, [69] and [70] demonstrated a similar though smaller effect on $0\nu\beta\beta$ decay. It was quickly realized, however, that the QRPA was not designed to handle realistic np pairing; the calculated half-lives were unnaturally sensitive to the strength of the pairing interaction. As a result, the rates of $\beta\beta$ decay, particularly $2\nu\beta\beta$ decay, were hard to predict precisely because a small change in a phenomenological parameter (the strength of np isoscalar pairing) caused a large change in the lifetimes and eventually the breakdown (called a "collapse") of the entire method when the parameter exceeds some critical value. Most recent work in the QRPA has aimed at modifying the undesirable aspects of the method so that its sensitivity to np pairing becomes more realistic.

There has been a large number of attempts to extend the validity of QRPA. We will not list them here, or discuss them in detail. Comprehensive discussion can be found in [3]. Earlier and even more complete discussion of the issues involved can be found in [71].

Unfortunately, it's not clear which of the extensions of the standard QRPA is best. Some of them violate an important sum rule for single β strength, and studies in solvable models suggest that the reduced dependence (at least of the 'renormailzed QRPA (RQRPA)) on neutron-proton pairing may be spurious resulting from an artificial reduction of isoscalar pairing correlations. There are not many obvious reasons to prefer one of these QRPA extensions or the other.

Recently, one of the methods, RQRPA, was modified even further, so that the single β sum rule was restored. The resulting method, called the "Fully Renormalized QRPA" has yet to be applied to $0\nu\beta\beta$ decay. Even more recently, Ref. [72] raised the issue of nuclear deformation, which has usually been ignored in QRPA-like treatments of nearly spherical nuclei. (Psuedo-SU(3)-based truncations have been used to treat it in well-deformed nuclei [73]). The authors of [72] argued that differences in deformation between the initial and final nuclei can have large effects on the $2\nu\beta\beta$ half-life. These ideas, too, have not yet been applied to $0\nu\beta\beta$ decay.

The profusion of RPA-based extensions is both good and bad. The sheer number of methods applied gives us a kind of statistical sample of calculations, which could give an idea of the theoretical uncertainty in the matrix elements. But the sample may be biased by the omission of non-RPA correlations in all but a few calculations. Also, different calculations are done with different ways of fixing the parameters, e.g. some insist to reproduce the $2\nu\beta\beta$ rate, other are unable to do that (or do not insist on it), etc. It is not clear, therefore, that the spread of the calculated values indeed corresponds to the spread of the possible matrix elements within even just QRPA and its extensions.

Shell Model

The obvious alternative to QRPA, and the current method of choice for nuclear structure calculations in heavy nuclei where applicable, is the shell model. It has ability to represent the nuclear wave function to arbitrary accuracy, provided a large enough model space is used. This caveat is a huge one, however. Current computers allow very large bases (millions of states), but in heavy nuclei this is still not nearly enough. Techniques for constructing "effective" interactions and operators that give exact results in truncated model spaces exist but are hard to implement. Even in its crude form with relatively small model spaces and bare operators, however, the shell model seems to offer some advantages over the QRPA. Its complicated valence-shell correlations, which the QRPA omits (though it tries to compensate for them by renormalizating parameters) apparently affect the $\beta\beta$ matrix elements [74].

The first modern shell-model calculations of $\beta\beta$ decay date from the work Haxton and Stephenson [75] and references therein. Only a few truly large-scale shell model calculations have been performed. The heavy deformed $\beta\beta$ nuclei, ^{238}U, and ^{150}Nd, for example, require bases that are too large to expect real accuracy. Realistic work has thus been restricted to few nuclei, in particular to ^{48}Ca, ^{76}Ge, and ^{136}Xe, though less comprehensive calculations have been carried out in several other nuclei [71].

Large spaces challenge us not only through the problem of diagonalizing large matrices, but also by requiring us to construct a good effective interaction. The bare nucleon-nucleon interaction needs to be modified in truncated spaces (this is an issue in the QRPA as well, though a less serious one). Currently, effective interactions are built through a combination of perturbation theory, phenomenology, and painstaking fitting. The last of these, in particular, becomes increasingly difficult when millions of matrix elements are required.

Related to the problem of the effective interaction is the renormalization of transition operators. Though the problem of the effective Gamow-Teller operator which enters directly into $2\nu\beta\beta$ decay, has drawn some attention, very little work has been done on the renormalization of the two-body operators that govern $0\nu\beta\beta$ decay. Shell model calculations won't be truly reliable until they address this issue, which is connected with deficiencies in the wave function caused by neglect of single-particle levels far from the Fermi surface. Ref. [76] suggests that significant improvement on the state of the art will be difficult but not impossible in the coming years.

Constraining Matrix Elements with Other Observables

The more observables a calculation can reproduce, the more trustworthy it becomes. And if the underlying model contains some free parameters, these observables can fix them. The renormalization of free parameters can make up for deficiencies in the model, reducing differences between, e.g., the QRPA and RQRPA once the parameters of both have been fit to relevant data. The more closely an observable resembles $0\nu\beta\beta$ decay, the more relevant it is.

Gamow-Teller distributions, both in the β^- and β^+ directions, enter indirectly into both kinds of $\beta\beta$ decay, and are measurable through (p,n) and analogous nucleon exchange reactions. Ref.[77] is particularly careful to reproduce those transitions as well as possible. Pion double charge exchange, in which a π^+ enters and a π^- leaves, involves the transformation of two neutrons into two protons, like $\beta\beta$ decay, but the nuclear operators responsible aren't the same in the two cases. Perhaps the most relevant quantity for calibrating calculations of $0\nu\beta\beta$ decay is $2\nu\beta\beta$ decay, which has now been measured in 10 different nuclei.

Two recent papers have tried to use $2\nu\beta\beta$ decay to fix the strength of np pairing in QRPA-based calculations. Ref. [78] used it only for the $J^\pi = 1^+$ channel relevant for $2\nu\beta\beta$ decay, leaving the np pairing strength unrenormalized in other channels. By contrast, Ref [79] renormalized the strength in all channels by the same amount. The results of the two procedures were different; the former reference found that the $0\nu\beta\beta$ matrix elements depended significantly on the theoretical approach, while the later one found almost no dependence on model-space size, on the form of the nucleon-nucleon interaction, or on whether the QRPA or RQRPA was used. The authors argued that fixing the np pairing strength to $2\nu\beta\beta$ rates essentially eliminates uncertainty associated with variations in QRPA calculations of $0\nu\beta\beta$ rates, though they left open the question of how close to reality the calculated rates were.

The conclusion of [79] is supported by the work [80] where the $2\nu\beta\beta$ was also used to fix the relevant parameter and essentially no difference between QRPA, RQRPA, and the new variant developed there was found. Moreover, when the fact that higher order terms are not included in [80], but are included in [79] (a reduction by $\sim 30\%$) are taken into account, these two calculations agree quite well. Another case is the work [81] which uses yet another variant of the theory and seemingly disagrees drastically with other calculations for the case of ^{76}Ge $0\nu\beta\beta$ decay. However, in an earlier work using the same method and parameters [82], it is clear that the rate of the $2\nu\beta\beta$ decay is incorrect by a large factor. When the relevant parameters are adjusted to give the correct $2\nu\beta\beta$ rate, the result again agrees quite well with [79].

While this question remains open, it is clear that only calculations of the $0\nu\beta\beta$ nuclear matrix elements that also describe other relevant nuclear properties should be included in the estimate of the uncertainty.

Reducing the Uncertainty

What can be done to improve the situation? In the near term, improvements can be made in both QRPA-based and shell-model calculations. First, existing calculations should be reexamined to check for consistency. One important issue is the proper value of the axial-vector coupling constant g_A, which is often set to 1 (versus its real value of 1.26) in calculations of β decay and $2\nu\beta\beta$ decay to account for the observed quenching of low-energy Gamow-Teller strength. What value should one use for $0\nu\beta\beta$ decay, which goes through intermediate states of all multipolarity, not just 1^+? Some authors use $g_A = 1$, some $g_A = 1.26$, and some $g_A = 1$ for the 1^+ multipole and 1.26 for the others. (Often authors don't reveal their prescriptions.) The second of these choices appears inconsistent with the treatment of $2\nu\beta\beta$ decay. Since the square of g_A enters the matrix element, this issue is not totally trivial. The striking results of Ref. [79] suggest that an inconsistent treatment is responsible for some of the spread in the calculated nuclear matrix elements. More and better charge-exchange experiments would help teach us whether higher-multipole strength is also quenched.

Next, the various versions of the QRPA should be tested against exact solutions in a solvable model that is as realistic as possible. The most realistic used so far are the $SO(5)$-based model used to study the QRPA and RQRPA for Fermi $2\nu\beta\beta$ decay [83], a two-level version of that model used in [76] for the QRPA in Fermi $2\nu\beta\beta$ and $0\nu\beta\beta$ decay, and an $SO(8)$-based model used to test the QRPA and RQRPA for both Fermi and Gamow-Teller $2\nu\beta\beta$ decay in Ref. [84]. It should be possible to extend the $SO(8)$ model to several sets of levels and develop techniques for evaluating $0\nu\beta\beta$ matrix elements in it. All these models, however, leave out spin-orbit splitting, which weakens the collectivity of np pairing. Using these models should help to understand the virtues and deficiencies of various QRPA extensions.

Along the same lines, we will need to understand the extent to which such methods can reproduce other observables, and their sensitivity to remaining uncertainties in their parameters. A careful study of the first issue was made in [77]. These efforts must be extended. The work is painstaking, and perhaps not as much fun as concocting still more variations of the QRPA, but it is crucial if we are to reduce theoretical uncertainty. Self-consistent Skyrme HFB+QRPA, applied to single-β decay in [85] and Gamow-Teller resonances in [86], may be helpful here; it offers a more general framework, in principal anyway, for addressing the variability of calculated matrix elements. Solvable models can be useful here too, because they can sometimes supply synthetic data to which parameters can be adjusted (as in [76]).

The best existing shell-model calculation produces smaller matrix elements than most QRPA calculations. Computer speed and memory is now at the point where the state of the shell-model art can be improved. The calculation of the $\beta\beta$ decay of ^{76}Ge in [74]used the $f_{5/2}p_{3/2}p_{1/2}g_{9/2}$ model space, allowing up to 8 particles (out of a maximum of 14) into the $g_{9/2}$ level. Nowadays, with the help of the factorization method (see [87, 88]), an accurate approximation to full shell-model calculations, we should be able to fully occupy the $g_{9/2}$ level, and perhaps include the $g_{7/2}$ and $f_{7/2}$ levels (though those complicate things by introducing spurious center-of-mass motion). In addition, one can try through diagrammatic perturbation theory to construct effective $0\nu\beta\beta$ operators for the model space that are consistent with the effective interaction. Though perturbation theory has convergence problems, the procedure should at least give us an idea of the uncertainty in the final answers, perhaps also indicating whether result obtained from the "bare" operators is too large or too small. Research into effective operators has been revived in recent years [89] and we can hope to improve on diagrammatic perturbation theory. One minor source of uncertainty connected with renormalization (which also affects the QRPA) is short-range two-nucleon correlations, currently treated phenomenologically, following [90].

In short, much can be done and we would be well served by coordinated attacks on these problems. There are relatively few theorists working in $\beta\beta$ decay, and their efforts have been fragmented. More collaborations, postdoctoral and Ph.D projects, meetings, etc., would make progress faster. *There is reason to be hopeful that the uncertainty will be reduced.* The shell-model matrix element may be too small because it does not include any particles outside the $fp + g_{9/2}$-shell. These particles, as shown by QRPA calculations, make the matrix element larger. We suspect that the results of a better shell-model calculation will be closer than the best current one to the QRPA results and that, as noted above, the spread in those results can be reduced. Finally, other nuclei may be more amenable to a good shell-model calculation than Ge. ^{136}Xe has 82 neutrons (a magic number) making it a particularly good candidate.

IV. COSMOLOGY AND NEUTRINO MASS

Neutrinos play an important role in astrophysics and cosmology (see also section IIID). In cosmology, relic neutrinos may constitute an important fraction of the hot dark matter (HDM) influencing the evolution of large scale structures (LSS)[92]. The imprint of neutrino HDM on LSS evolution is quite distinct from other dark matter candidates such as supersymmetric particles, which act as non-relativistic or Cold Dark Matter (CDM). Cosmological models of structure formation strongly depend on the relative amounts of CDM and HDM in the universe, hence a determination of the neutrino contribution Ω_ν to the total dark matter content Ω of the universe is important for our understanding of structure formation [92]. Such an investigation is a strong motivation for the next-generation terrestrial neutrino mass experiments. For example, a single β-decay experiment with a neutrino mass sensitivity of 0.2 eV (90 %CL.) will be sensitive to a neutrino contribution $\Omega_\nu = 0.015$. Such measurements would either significantly constrain or fix the role of HDM in structure formation by a model independent method.

Two areas of astrophysics where an understanding of neutrino mass is important are supernova dynamics and cosmic ray physics. In the area of cosmic rays, a new model has been proposed which aims at explaining the origin of ultra high energy (UHE) cosmic rays. This so-called Z-burst model would require relic neutrino masses within the sensitivity range of next generation neutrino mass experimments.

Cosmological studies and neutrinos

The contribution Ω_ν of relic neutrinos to the total density Ω can be probed by a combination of precise measurements of the temperature fluctuations of the cosmic microwave background radiation and with measurements of the matter fluctuation at large scales by high statistics galaxy redshift surveys. The results for the mass density of neutrinos can then be transformed into neutrino mass results based on the calculated relic neutrino density of $112\,\nu$'s/cm^3 in the framework of the canonical standard cosmological model. (Detailed information on these neutrinos and cosmology can be found in the Astrophysics and Cosmology working group report.)

Results from cosmological studies

Early cosmological bounds on Σm_ν, based on pre-WMAP/SDSS/ 2dFGRS data, gave upper limits in the range of 3 – 6 eV, comparable to the present laboratory limit from tritium β-decay. Recent cosmological studies are based on different combinations of the high quality data from WMAP, small scale high resolution CMBR experiments, and the two large galaxy redhift surveys 2dFGRS and SDSS. In some cases additional structure information from Lyman-α data or X-ray luminosities from clusters have been added.

Table III presents a summary of either upper limits or best values for neutrino masses derived from recent cosmological studies. The table shows the considerable spread in the results published recently. This is due to several generic difficulties associated with cosmological studies. First, these studies suffer from the problem of parameter degeneracy [97]. Different combinations of cosmological parameter can describe the LSS and CMBR data equally well, so additional information is required to break the degeneracy. The errors associated with these input parameters also imply that the ν-mass results crucially depend on the *priors* for these parameters. Different priors for cosmological parameters result in limits for the sum of neutrino masses Σm_ν which differ by factors of 2 or more.

The strong dependence of cosmological neutrino mass results can be illustrated by comparing the strongest upper limit on m_ν reported in the literature, the WMAP upper limit [32] of $m_\nu < 0.27\,eV$ (95 % CL.), with tentative evidence for non-zero neutrino masses reported by Allan *et al.* [95]. Both analyses use substantially identical sets of input parameters, most notably the WMAP and 2dFGRS data. However, while the WMAP authors[32] use additional Lyman-α data for their analysis, Allan *et al.* [95] use X-ray luminosity functions (XLF) of galaxy clusters obtained with the orbiting Chandra X-ray telescope. This small change of input data transforms an upper limit into evidence for non-zero masses with Σm_ν=0.56 eV as best fit value. It is interesting to note that both the use of Lyman-α data as well as the use of the measured XLF have been criticized in the literature. This clearly underlines that cosmological studies, as impressive as they are with regard to the determination of cosmological parameters, still yield *model-dependent* results for neutrino masses.

Further concerns with cosmological neutrino mass studies are associated with systematic errors. LSS data from galaxy surveys suffer from the problem of biasing (i.e. to what extent does the galaxy distributing trace the distribution of cold dark matter and dark baryons), possible redshift-space distortions and selection effects. A model-independent input of the value of the neutrino mass to cosmological studies would thus be especially important for future high

author	WMAP	CMB_{hi-l}	SDSS	2dF	other data	$\Sigma\, m_\nu$ [eV]
Bar'03 [93]	x	x	x	x	h (HST)	<0.75
Teg'03 [94]	x	x	x		SNIa	<1.7
ASB'03 [95]	x	x		x	XLF	$=0.36$-1.03
WMAP [32]	x	x		x	Lyα , h (HST)	<0.7
Bla'03 [96]	x			x	$\Omega_m=1$	$=2.4$
Han'03 [97]	x	x		x	h (HST), SNIa	<1.01
Han'03 [97]	x	x		x		<1.2
Han'03 [97]	x			x		<2.12

TABLE III: Survey of neutrino mass results obtained from the most recent cosmological studies. For each study the specific set of input data is listed: WMAP angular and/or polarisation data, high resolution CMBR experiments like CBI etc, LSS data from the SDSS and the 2dFGRS galaxy surveys, and other data.

precision cosmological studies. A laboratory measurement of m_ν could break the existing degeneracies between Ω_ν and other cosmological parameters, and thus help to provide a better picture of large scale structure evolution.

Beyond the 'concordance' model

The results of the cosmological studies presented above in table III have been obtained within the 'canonical standard cosmological model'. In the following we briefly list studies which are outside the present so-called 'concordance' flat ΛCDM models.

In [96] the authors argue that cosmological data can be fitted equally well in the framework of an Einstein-de Sitter universe with with *zero* cosmological constant Λ, albeit at the expense of requiring a very low value for the Hubble constant of $H_0 \simeq 46$ km/s/Mpc. The authors claim that CMB and LSS data seem to imply the existence of non-cold dark matter component.

I n addition,several authors [98] have speculated about the interesting coincidence between the smallness of neutrino masses ($m_\nu < 1$ eV) and the deduced vacuum density $\rho_V \approx (\,10^{-3}$ eV $)^4$ responsible for the cosmological dark energy Λ. In this framework, the masses of the active ν-species vary like the inverse of the ν-density. Accordingly, the neutrino mass could be of order of 1 eV today.

Another 'coincidence' problem ($\Omega_\Lambda = \Omega_m$) has been used by M Tegmark et al. [99] to investigate the possibility that m_ν is a stochastic variable, which is randomized during inflation.

Yet another possible modification to the neutrino sector of the 'concordance' model has been brought up by the authors of [100]. They assume that neutrinos have small extra scalar or pseudoscalar interactions. Should neutrinos possess even only tiny couplings of the order of 10^{-5} to hypothetical scalar ϕ bosons, the neutrino density Ω_ν could be affected strongly by annihilation processes of the type $\nu\,\nu \leftrightarrow \phi\;\phi$. In this scenario neutrinos would not decouple from matter at $T = 1$ MeV, but would stay in thermal equilibrium until much later times ($T = 1$eV), which would inhibit free streaming.

Relic neutrinos have not been detected at present, and will likely not be detected in the nearer future due to their very low energy in the μeV range. For this reason, the 'neutrinoless universe' scenario can only be tested by comparing the model-independent neutrino mass result from single and double beta decay experiments along with cosmological data.

Future Perspectives

At present, the cosmological studies of m_ν are still model-dependent due to systematic effects such as biasing, parameter degeneracy, possible selection effects, possible contributions from non-linear effects and the strong influence of priors on the neutrino mass results. Future high precision studies aim at strongly reducing these systematic effects.

In the field of CMBR experiments, the new promising technique of studying distortions of the CMBR temperature and polarization maps induced by gravitational lensing has been proposed [101]. This technique is sensitive to changes of structure evolution at late times due to massive neutrinos and thus could break the degeneracy between neutrino mass, equation-of-state of the dark energy and the primordial power spectrum amplitude. In [101] the sensitivity of this method is estimated to come down to Σm_ν=0.3 eV. This is of the same order as what is expected in [102] for the ν-mass sensitivity (m_ν=0.14 eV) from the Planck satellite scheduled to start operations in 2008.

These investigations will be complemented by future deep galaxy surveys extending out to redshift parameters z=2 (DEEP2, VLT-Virmos) as well as dedicated studies of lensing effects on galaxy clusters (LSST, Large Synoptic Survey Telescope).

V. EXPERIMENTAL PROSPECTS FOR β DECAY

Motivation for absolute measurements

The SM of particle physics describes present experimental data up to the electroweak scale, but does not explain the observed pattern of the fermion masses or the mixing among the fermion generations. In addition it explicitly assumes neutrinos are massless and offers no explanation for the observed ν-masses and ν-mixing.

There are many theories beyond the Standard Model, which explore the origins of neutrino masses and mixing. In these theories, which often work within the framework of Supersymmetry, neutrinos naturally acquire mass. A large group of models makes use of the so-called see-saw effect to generate neutrino masses. Other classes of theories are based on completely different possible origins of neutrino masses, such as radiative corrections arising from an extended Higgs sector. As neutrino masses are much smaller than the masses of the other fermions, the knowledge of the absolute values of neutrino masses is crucial for our understanding of the fermion masses in general. Recently it has been pointed out that the *absolute mass scale of neutrinos* may be even more significant and straightforward for the fundamental theory of fermion masses than the determination of the neutrino mixing angles and CP-violating phases [91]. It will likely be the absolute mass scale of neutrinos which will determine the scale of new physics.

Introduction (related to kinematical experimental techniques)

Two kinematical experimental techniques that probe neutrino mass directly, are precise observations of decay kinematics in nuclear or particle decay processes and the utilization of time of flight measurements in the detection of supernova neutrinos incident on terrestrial neutrino detectors. The decay measurements, which are based on purely kinematical observables, have essentially no reliance on theoretical assumptions about neutrino properties and hence offer a completely model independent probe of absolute neutrino mass.

Examples of decay measurements include studies of β -decay spectra shapes, measurements of muon momentum in pion decay, and invariant mass studies of multi-particle semileptonic decays of the τ. However, the recent measurement of large mixing angles in the lepton sector gives a clear advantage to β -decay spectra shape measurements, since these experiments probe all three neutrino mass eigenstates and are approaching the sub-eV range os sensitivity. These next generation β -decay measurements will complement other laboratory and cosmological methods to investigate neutrino masses. The combination and comparison of results from β-decay, $0\nu\beta\beta$ and cosmological studies will be essential for our understanding of the role of neutrinos in our physical world, both at the Micro- and Macro world.

In contrast to $0\nu\beta\beta$ experiments, kinematic investigations of the neutrino mass do not rely on further assumptions on the neutrino mass type, Majorana or Dirac. Such kinematic experiments can be classified into two categories both making use of the relativistic energy momentum relation $E^2 = p^2c^2 + m^2c^4$ as well as of energy and momentum conservation.

Neutrino time-of-flight studies

The narrow time signal of a supernova (SN) neutrino burst of less than 10 s in combination with the very long-baseline between source and detector of several kpc would allow the investigation of small ToF effects resulting from small ν-masses. Supernova ToF studies are based on the observation of the energy-dependent time delay of massive neutrinos relative to massless neutrinos. This method provides an experimental sensitivity for the rest masses of ν_e, $\nu_\mu$and $\nu_\tau$of a few tens of eV. This sensitivity can be pushed into the few-eV range, if additional assumptions on the time evolution of the ν-burst are being made. In this case the ν-mass sensitivity becomes model-dependent, however.

Recently, new methods have been proposed which do not rely on details of the ν-burst timing which might yield sensitivity in the few-eV range for ν_μ and ν_τ. The two most promising techniques are: a) the measurement of the abrupt termination of the SN-ν signal due to the early formation of a black hole [161, 162] and b) the correlation of SN ν-signals with independent signals from gravitational wave experiments [163]. Except for exceedingly close by supernova, $< 1\,\mathrm{kpc}$, the sensitivity from the first technique to neutrino mass would still only be at the level of a few eV. Estimates for the sensitivity to the second method are also expected to also be only at the eV level.

If future measurements were to reveal a SN ν-pulse which is terminated abruptly after a few seconds, the information on the ν-mass provided by next-generation terrestrial experiments would likely be used to help further our understanding of supernovae dynamics.

Weak particle decay processes

The investigation of the kinematics of weak decays is based on the measurement of the charged decay products of weak decays. For the masses of ν_μ and ν_τ the measurement of pion decays into muons and ν_μ at PSI and the investigation of τ-decays into 5 pions and ν_τ at LEP have yielded the upper limits:

$$\begin{array}{lllll} m(\nu_\mu) & < & 190 \;\; \mathrm{keV} & \text{at } 90 \text{ \% confidence} & [164] \\ m(\nu_\tau) & < & 18.2 \;\; \mathrm{MeV} & \text{at } 95 \text{ \% confidence} & [164] \end{array}$$

Both limits are much larger than those attainable in beta decay spectra studies.

β decay

The technique for detecting neutrino mass in beta decay is essentially to search for a distortion in the shape of the beta spectrum in the endpoint energy region. The most sensitive searches for the electron neutrino mass up to now are based on the investigation of the electron spectrum of tritium β decay

$$^3\mathrm{H} \rightarrow ^3\mathrm{He}^+ + \mathrm{e}^- + \bar{\nu}_e \quad . \tag{34}$$

The electron energy spectrum of tritium β decay for a neutrino with mass m_ν is given by

$$\frac{dN}{dE} = C \times F(Z,E)pE(E_0 - E)[(E_0 - E)^2 - m_\nu^2]^{\frac{1}{2}}\Theta(E_0 - E - m_\nu), \tag{35}$$

where E denotes the electron energy, p is the electron momentum, E_0 corresponds to the total decay energy, $F(Z,E)$ is the Fermi function, taking into account the Coulomb interaction of the outgoing electron in the final state, the stepfunction $\Theta(E_0 - E - m_\nu)$ ensures energy conservation, and C is given by

$$C = G_F^2 \frac{m_e^5}{2\pi^3} \cos^2\theta_C |M|^2 \; . \tag{36}$$

Here G_F is the Fermi constant, θ_C is the Cabibbo angle, m_e the mass of the electron and M is the nuclear matrix element. As both M and $F(Z,E)$ are independent of m_ν, the dependence of the spectral shape on m_ν is given by the phase space factor only. In addition, the bound on the neutrino mass from tritium β decay is independent of whether the electron neutrino is a Majorana or a Dirac particle.

The signature of an electron neutrino with a mass of $\mathrm{m}(\nu_e)$=1 eV is shown in Fig. 3, in comparison with the undistorted β spectrum of a massless ν_e . The spectral distortion is statistically significant only in a region close to the β endpoint. This is due to the rapidly rising count rate below the endpoint $\mathrm{dN/dE} \propto (E_0 - E)^2$. Therefore, only a very narrow region close to the endpoint E_0 is analyzed. Note that in fitting the measured shape to a calculated shape the functional form depends on m_ν^2 and is not defined for $m_\nu^2 < 0$.

One immediate difficulty apparent in the figure is that there are very few decays in the region of interest, only $2 \cdot 10^{-13}$ of the total rate is in the last eV. A related problem is that one must carefully eliminate or minimize backgrounds. In addition subtle effects such as instrumental resolution, energy loss of the electrons, and atomic or molecular physics excitations during the decay can cause shape distortions that are of similar size to the effect of nonzero neutrino mass but of opposite sign. Hence tritium β decay experiments with high neutrino mass sensitivity require a huge luminosity combined with very high energy resolution. Furthermore, a precise determination of a value or limit for m_ν requires complete and accurate understanding of all systematic effects that can alter the shape of the spectrum.

Apart from offering a low endpoint energy E_0 and a moderate half life of 12.3 y, tritium has further advantages as β emitter in ν mass investigations:

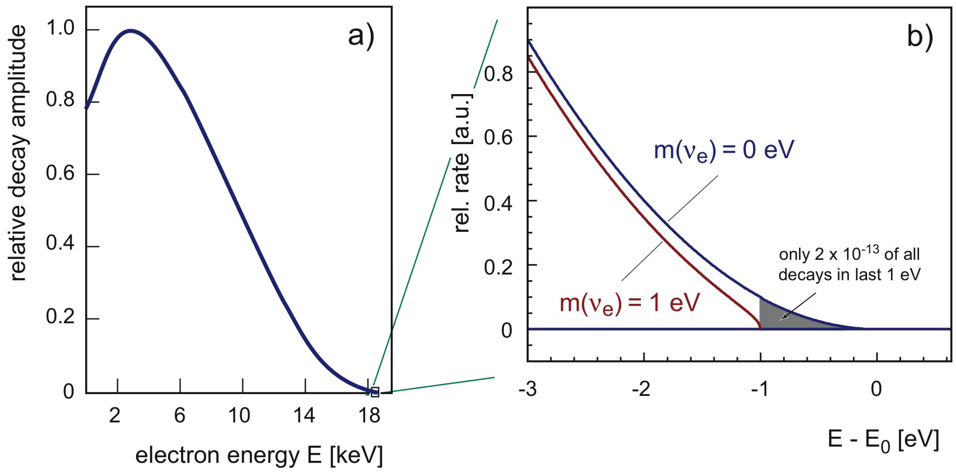

FIG. 3: The electron energy spectrum of tritium β decay: (a) complete and (b) narrow region around endpoint E_0. The β spectrum is shown for neutrino masses of 0 and 1 eV.

1. the hydrogen isotope tritium and its daughter, the $^3He^+$ ion, have a simple electron shell configuration. Atomic corrections for the β decaying atom -or molecule- and corrections due to the interaction of the outgoing β-electron with the tritium source can be calculated in a simple and straightforward manner

2. The tritium β decay is a super-allowed nuclear transition. Therefore, no corrections from the nuclear transition matrix elements M have to be taken into account.

The combination of all these features makes tritium an almost ideal β emitter for neutrino mass investigations.

Current tritium β-decay results

The Mainz and Troitsk groups have set the most precise limits on the electron antineutrino mass. Both experiments utilize novel magnetic solenoidal retarding electrostatic spectrometers which measure an integral beta spectrum, integrating all energies above the acceptance energy of the spectrometer. In their measurements, the Mainz group utilized a frozen molecular tritium source. Their result [165] is:

$$m^2_{\nu_e} = -1.2 \pm 2.2 \pm 2.1 \ eV^2, \tag{37}$$

which yields a limit of:

$$m_{\nu_e} < 2.2 \ eV \quad (95\% CL). \tag{38}$$

This result is based on data that has passed several systematic and consistency checks. The Troitsk group[166, 167] developed a gaseous molecular tritium source and has also published a limit similar to that of the Mainz group of

$$m^2_{\nu_e} = -2.3 \pm 2.5 \pm 2.0 \ eV^2, \tag{39}$$

with a limit of:

$$m_{\nu_e} < 2.1 \ eV \quad (95\% CL). \tag{40}$$

However, they must include a not well understood step function near the endpoint in order to produce such a limit.

Next generation experiments

*The **KA**rlsruhe **TRI**tium **N**eutrino project (KATRIN) experiment*

The **KA**rlsruhe **TRI**tium **N**eutrino project (KATRIN) experiment is a next-generation tritium β-decay experiment designed to measure the mass of the neutrino with sub-eV sensitivity[168]. KATRIN utilizes a windowless gaseous molecular tritium source and a 10 m diameter magnetic solenoidial retarding electrostatic type spectrometer. The experiment will be constructed adjacent to the Tritium Laboratory Karlsruhue at the Forschungszentrum Karlsruhe (FZK). The collaboration membership includes a significant number of collaborators from the most recent successful tritium β-decay experiments, including Mainz and Troitsk, as well as the Washington group which developed the original LANL gaseous based tritium source. The current schedule calls for for KATRIN to become operational during 2008. The experiment expects to achieve an order of magnitude more sensitivity than the best β-decay measurements carried out to date. (Note, since the shape effects are proportional to m_ν^2 this implies a factor of 100 increase in sensitivity.) Based on the current design, KATRIN expects after three years of running to reach a sensitivity to neutrino mass of 0.20 eV (90% CL) and would hence be able to observe a neutrino mass with a mass of 0.35eV at the 5 sigma significance level. The experiment has recently received a firm funding commitment from the German funding ministry.

NEXTEX (Neutrino Experiment at Texas)

The **N**eutrino **EX**periment at **TEX**as is an experiment that has been under construction for more than 10 years with the goal of measuring the electron antineutrino mass to 0.5 eV (lower limit at 3σ). Collaborating institutions are The University of Texas at Austin, Nebraska, Brandeis, Michigan Technological Institute, Pomona College, and Southwestern University. The experiment uses the end point method for gaseous tritium decay, and the apparatus consists of three serial electrostatic differential analyzers. Presently the experiment is funded by the NSF to demonstrate proof of principle. Construction completion and final approval by the site committee is expected by the collaborators within 1 year. The experiment will run for 3 years and the anticipated funding request would be $3.9M.

Other approaches to β decay

A different approach to directly measure the electron neutrino mass is the use of cryogenic bolometers. In this case, the β source can be identical to the β-electron spectrometer. This new technique has been applied to the isotope ^{187}Re, which has a 7 times lower endpoint energy than tritium[169, 170]. Current microcalorimeters reach an energy resolution of $\Delta E \sim 5\,\mathrm{eV}$ for short-term measurements and yield an upper limit of $m(\nu_e) < 15\,\mathrm{eV}$ [169, 170]. To further improve the statistical accuracy, the principle of integration of active source and detector requires the operation of large arrays of microcalorimeters. The sensitivity on the neutrino mass in the next 5-7 years is expected to reach below the few eV level[169].

VI. EXPERIMENTAL PROSPECTS FOR $\beta\beta$

If an experiment observes $0\nu\beta\beta$ it will have profound physics implications. Such an extraordinary claim will require extraordinary evidence. The recent claim[103] for an observation of $0\nu\beta\beta$ has been controversial (See discussion below). Also previous "false peaks" in $\beta\beta$ spectra have appeared near a $0\nu\beta\beta$ endpoint energy (see discussion in [104], page 273). One must ask the question: What evidence is required to convincingly demonstrate that $0\nu\beta\beta$ has been observed? Low-statistical-significance peaks ($\approx 2\sigma$) have faded with additional data, so one must require strong statistical significance (perhaps 5σ). (See Fig. 4.) This will require a large signal-to-noise ratio that will most likely be accomplished by an ultra-low-background experiment whose source is its detector. Such experiments are usually calorimetric and provide little information beyond just the energy measurement.

How does an experiment demonstrate that an observed peak is actually due to $\beta\beta$ decay and not some unknown radioactivity? Additional information beyond just an energy measurement may be required. For example, although there is some uncertainty associated with the matrix elements, it is not so large that a comparison of measured rates in two different isotopes could not be used to demonstrate consistency with the Majorana-neutrino hypothesis. Alternatively, experiments that provide an additional handle on the signal, for example by measuring a variety of kinematical variables, demonstrating that 2 electrons are present in the final state, observing the γ rays associated with an excited state, or identifying the daughter nucleus, may lend further credibility to a claim. Experiments that provide this extra handle may require a significantly more complicated apparatus and therefore face additional challenges.

The exciting aspect of $\beta\beta$ research today is that many proposed experiments intend to reach a Majorana mass sensitivity of $\sqrt{\delta m^2_{\mathrm{atm}}}$. Several different isotopes and experimental techniques are being pursued actively and many

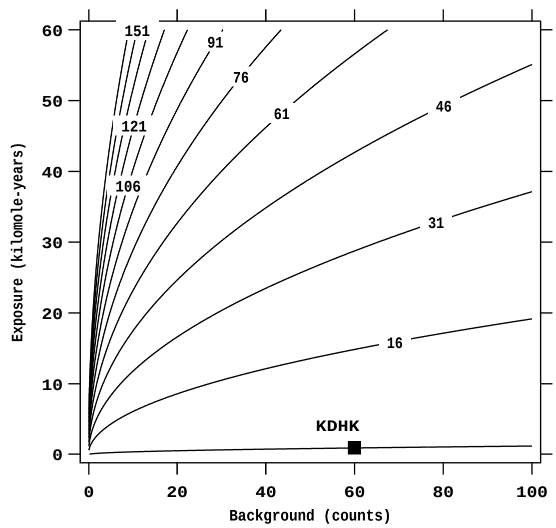

FIG. 4: This contour plot shows the half life, in units of 10^{25} y, for a peak of 5σ significance for a given exposure and background. The KDHK point is shown.

TABLE IV: A summary of the recent $0\nu\beta\beta$ results. The $\langle m_{\beta\beta}\rangle$ limits are those deduced by the authors. All limits are at 90% confidence level unless otherwise indicated. The columns providing the exposure and background are based on arithmetic done by the authors of this paper, who take responsibility for any errors in interpreting data from the original sources.

Isotope	Exposure (kmole-y)	Background (counts)	Half-Life Limit (y)	$\langle m_{\beta\beta}\rangle$ (meV)
^{48}Ca	5×10^{-5}	0	$> 1.4 \times 10^{22}$	$< 7200 - 44700$[105]
^{76}Ge	0.467	21	$> 1.9 \times 10^{25}$	< 350[106]
^{76}Ge	0.117	3.5	$> 1.6 \times 10^{25}$	$< 330 - 1350$[107]
^{76}Ge	0.943	61	$= 1.2 \times 10^{25}$	$= 440$[103]
^{82}Se	7×10^{-5}	0	$> 2.7 \times 10^{22}$(68%)	< 5000[108]
^{100}Mo	5×10^{-4}	4	$> 5.5 \times 10^{22}$	< 2100[109]
^{116}Cd	1×10^{-3}	14	$> 1.7 \times 10^{23}$	< 1700[110]
^{128}Te	Geochem.	NA	$> 7.7 \times 10^{24}$	$< 1100 - 1500$[111]
^{130}Te	0.025	5	$> 5.5 \times 10^{23}$	$< 370 - 1900$[112]
^{136}Xe	7×10^{-3}	16	$> 4.4 \times 10^{23}$	$< 1800 - 5200$[113]
^{150}Nd	6×10^{-5}	0	$> 1.2 \times 10^{21}$	< 3000[114]

of the programs look viable. In this section we describe the current situation in experimental $\beta\beta$ decay .

Results to date

Table IV lists the recent $0\nu\beta\beta$ results. The best limits to date come from the enriched Ge experiments. The two experiments had comparable results although the Heidelberg-Moscow result was marginally better. The $T^{0\nu}_{1/2}$ limits near 2×10^{25} y results in a $\langle m_{\beta\beta}\rangle$ limit near 300 meV, with an uncertainty of about a factor of 3 because of the uncertainty in $|M_{0\nu}|$. One recent paper[115] performed a joint analysis of the two experiments and found $T^{0\nu}_{1/2} > 2.5 \times 10^{25}$ y.

Most of the results listed in Table IV are at least a few years old. The obvious exceptions to this are the Te and Cd results. CUORICINO continues to collect data.

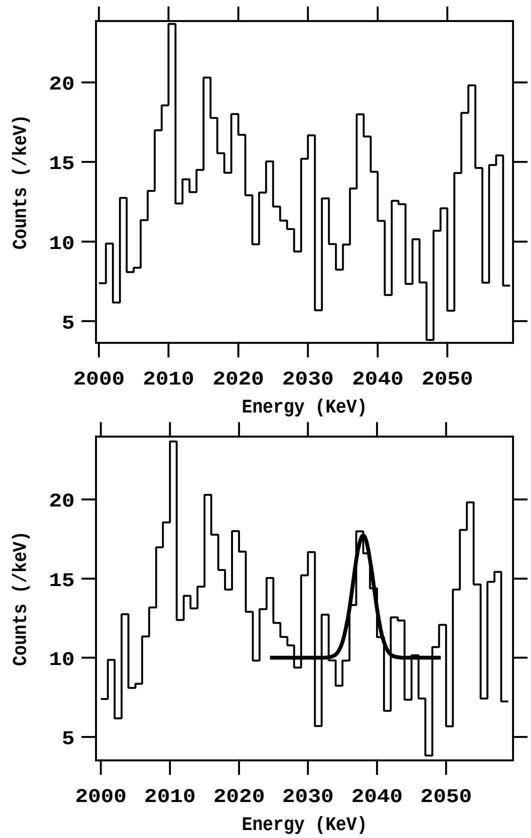

FIG. 5: The spectrum from the Heidelberg-Moscow experiment upon which the claim for $0\nu\beta\beta$ is based. The data in the two panels are identical. The lower panel has a Gaussian curve to indicate the strength of the claimed $0\nu\beta\beta$ peak.

A claim for the observation of $0\nu\beta\beta$

In early 2002, a claim for the observation of $0\nu\beta\beta$ was published (Klapdor-Kleingrothaus *et al.*2002a). The paper made a poor case for the claim and drew strong criticism[115, 117, 118]. The initial response to the criticism was emotional[119]. In addition, one of the original co-authors wrote a separate reply[120] that mostly defended the claim yet acknowledged some significant difficulty with the analysis. This author's name doesn't appear on later papers. More recently, however, supporting evidence for the claim has been presented and we recommend the reader study Ref. [121] for a good discussion of the initial evidence and Ref. [103] for the most recent data analysis. Importantly, this later paper includes additional data and therefore an increase in the statistics of the claim. In this subsection we summarize the current situation. (We use the shorthand KDHK to refer to the collection of papers supporting the claim.)

Figure 5 shows the spectrum corresponding to 71.7 kg-y of data from the Heidelberg-Moscow experiment between 2000 and 2060 keV[103]. This spectrum is shown here to assist the casual reader in understanding the issues. However, the critical reader is encouraged to read the papers listed in the references as the authors analyze several variations of this data using different techniques. The fit about the expected $0\nu\beta\beta$ peak energy yields 28.75 $\pm$ 6.86 counts assigned to $0\nu\beta\beta$. The paper claims a significance of approxmately 4σ for the peak, where the precise significance value depends on the details of the analysis. The corresponding best-fit lifetime, $T^{0\nu}_{1/2} = 1.19 \times 10^{25}$ years[103], leads to a $\langle m_{\beta\beta}\rangle$ of 440 meV with the matrix element calculation of Ref. [122] chosen by the authors.

In the region between 2000 and 2100 keV, the KDHK analysis of 2002 found a total of 7 peaks. Four of these were attributed to ^{214}Bi (2011, 2017, 2022, 2053 keV), one was attributed to $0\nu\beta\beta$ decay (2039 keV), and two were unidentified (2066 and 2075 keV). The KDHK analysis of 2004 does not discuss the spectrum above 2060 in detail. An additional possible feature may also be present near 2030 keV. A study[146] comparing simulation to calibration with ^{214}Bi demonstrates that if the location of the Bi is known, the spectrum can be calculated. Furthermore, the relative strengths of the strong Bi lines at 609, 1764 and 2204 keV can be used to determine the location of the activity. Because the results of summing effects depend on the proximity of the activity, its location is critical for the simulation of the weak peaks near the $0\nu\beta\beta$ endpoint. The study also shows that the spectrum can't be naively estimated, as was done in Ref. [117]. In fact, Table VII in Klapdor-Kleingrothaus (2002c) finds, even with a careful simulation, that the expected strengths of the ^{214}Bi peaks in the 2000-2100 keV region are not predicted well by scaling to the strong peaks. That is, the measured intensities of the weak peaks are difficult to simulate without knowing the exact location of the activity. Furthermore, the deduced strengths of the weak lines are more intense than expected by scaling from the strong peaks, even though the activity location is chosen to best describe the relative intensities of the strong peaks.

Double-beta decay produces two electrons that have a short range in solid Ge. Therefore, the energy deposit is inherently localized. Background process, such as the γ rays from ^{214}Bi, tend to produce multiple energy deposits. The pulse waveform can be analyzed to distinguish single site events (SSE) from multiple site events. Such an analysis by KDHK[103, 123] tends to indicate that the Bi lines and the unidentified lines behave as multiple site events, whereas the $0\nu\beta\beta$ candidate events behave as SSE. Note, however, that the statistics are still poor for the experimental lines and this conclusion has a large uncertainty. Nonetheless, this feature of the data is very intriguing and clearly a strength of the KDHK analysis.

An analysis by Zdesenko *et al.*[115] points out the strong dependence of the result on the choice of the window width of the earlier 2002 analysis. The KDHK analysis argues that a small window is required because of the neighboring background lines. Even so, their Monte Carlo analysis shows that the result becomes less stable for small windows (see Fig. 9 in Ref. [121]). Zdesenko *et al.*[115] also remind us that the significance of a signal is overestimated when the regions used to estimate the background are comparable to the region used to determine the signal[124]. The report of Ref. [103] fits a wide region containing several peaks simultaneously after using a Bayesian procedure to identify the location of the peaks.

The claim for $0\nu\beta\beta$ decay was made by a fraction of the Heidelberg-Moscow collaboration. A separate group of the original collaboration presented their analysis of the data at the IV International Conference on Non-Accelerator New Physics[125]. They indicate that the data can be separated into two distinct sets with different experimental conditions. One set includes events that are described as "underthreshold pulses" and one set that does not. Analysis of the two sets produce very different conclusions about the presence of the claimed peak. They conclude that the evidence is an experimental artifact and not a result of $0\nu\beta\beta$decay. KDHK responds[103] that these corrupt data were not included in their analysis.

Traditionally, $\beta\beta$ experiments have ignored systematic uncertainties in their analysis. Only recently with the start-up of high-statistics $2\nu\beta\beta$ results has this situation begun to change. Historically, $0\nu\beta\beta$ results have always been quoted as upper limits based on low count rates. As a result, systematic uncertainties tended to be negligible in the final quoted values. With a claim of a positive result, however, the stakes are dramatically raised. It is clear that it is difficult to produce a convincing result when the signal counts are comparable to expected statistical fluctuations in the background. The further presence of nearby unidentified peaks makes the case even harder to prove. Although KDHK does discuss some systematic uncertainties qualitatively and indicates they are small (in the position of the $0\nu\beta\beta$ peak, and the expected peak width, for example), there is no consideration of an uncertainty associated with the background model.

The next round of proposed $0\nu\beta\beta$ experiments are designed to reach $\sqrt{\delta m^2_{\rm atm}}$ and therefore will quickly confirm or repudiate this claim. This is fortunate since the feature near 2039 keV in the KDHK claim will likely require an experimental test. These experiments should provide a detailed listing of all identified systematic uncertainties and a quantified estimate of their size. Furthermore, because the stakes are very high and there will be many people who are biased, either for or against the KDHK claim, blind analyses should also become part of the experimental design.

The Search for Decays to Excited States

Searches for $\beta\beta$ to excited states in the daughter atom have been performed in a number of isotopes but only observed in ^{100}Mo (The experimental situation is reviewed by Barabash[126].) and ^{150}Nd[127]. These experiments typically search for the γ rays that characterize the excited states and therefore are not mode-specific searches. The interpretation therefore is that the measured rate (or limit) is for the $2\nu\beta\beta$ mode. These data may be very useful to QRPA nuclear theory because the behavior of the nuclear matrix elements with respect to g_{pp} for the excited state decays is different than for transitions to the ground state[128–130]. Thus, the excited state transitions probe different aspects of the theory and may provide insight into the physics of the matrix elements.

A further reason for interest in decays to the excited state, as mentioned earlier, is the potential ability to discover the process mediating the decay[131, 132]. However, the decay rate to an excited state is 10-100 times smaller than rate to the ground state[133, 134]. Furthermore the structure of the excited state in the daughter nucleus is not as well understood as the ground state, and this increases the relative uncertainty in the nuclear matrix element.

The Search for $\beta^+\beta^+$ Modes of Decay

The β^+ modes of decay have not received the attention of the β^- modes because of the greatly reduced phase space and corresponding long half-lives. However, the rate is proportional to $\langle m_{\beta\beta}\rangle^2$ and its detection would provide additional matrix-element data. Furthermore, if the zero-neutrino mode were detected, it might provide a handle on whether the decay is predominantly mediated by a light neutrino or by right-handed currents[135].

Radiative neutrinoless double electron capture is a possible alternative to traditional neutrinoless double beta decay[136]. In this process, two electrons are captured from the atomic electron cloud and a radiated photon carries the full Q-value for the decay. A resonance condition can enhance the rate when the energy release is close to the 2P-1S energy difference. In this case, high-Z, low-energy-release isotopes are favored (e.g. ^{112}Sn). Unfortunately the mass differences for the candidate isotopes are not known precisely enough to accurately predict the overlap between the two energies. If a favorable overlap does exist, however, the sensitivity to $\langle m_{\beta\beta}\rangle$ might rival that of $0\nu\beta\beta$decay.

Towards a 100-kg experiment

The KDHK spectrum shows a feature very close to the $0\nu\beta\beta$ endpoint. This intriguing result will need to be confirmed or refuted experimentally. One can see the required operation parameters for a confirmation experiment from the KDHK result. One needs about 75 kg-y of exposure, and a background lower than about 0.5 counts/(kg y). Note that most of the proposals described above will all accomplish this very early on in their program if they meet their design goals. If instead one designs an experiment only to test the claim (not to provide a precise measurement of the $T^{0\nu}_{1/2}$) then a 100-kg experiment could provide the answer after a modest run time.

If the KDHK result holds up, it will be a very exciting time for neutrino-mass research. A $\langle m_{\beta\beta}\rangle$ near 400 meV means that β-decay experiments and cosmology will be sensitive to the mass. As a result, one can certainly imagine a not-too-distant future in which we know the neutrino mass and its Majorana-Dirac character. Towards this goal, a precision measurement of $\langle m_{\beta\beta}\rangle$ will be required. To accomplish this, we will need more than one $\beta\beta$ experiment, each with a half-life measurement accurate to 10-20%. At this level the uncertainty will be dominated by the matrix element uncertainty even if future calculations can be trusted to 50%. With two experiments utilizing different isotopes, one might disentangle the uncertainty in $|M_{0\nu}|$.

Towards a 100-ton experiment

The next generation of experiments hopes to be sensitive to $\sqrt{\delta m^2_{\rm atm}}$. If they fail to see $0\nu\beta\beta$ at that level, the target for the succeeding generation of efforts will be $\sqrt{\delta m^2_{\rm sol}}$. This scale is an order of magnitude lower and hence will require two orders of magnitude more isotopic mass, approximately 100 tons of isotope.

Proposed Experiments for $\beta\beta$ Decay

The recent reviews by Elliott and Vogel[1] and Elliott and Engel[3] describe the basics of experimental $0\nu\beta\beta$ decay in some detail. Therefore, we refer the reader to those articles and only summarize the status of the various projects. Table V lists the proposals.

CANDLES

The CANDLES collaboration has recently published the best limit on $0\nu\beta\beta$ decay of 1.4×10^{22} y in ^{48}Ca[105]. Using the ELEGANTS VI detector, this experiment consisted of 6.66 kg of CaF_2(Eu) crystals surrounded by CsI crystals, a layer of Cd, a layer of Pb, a layer of Cu, and a layer of LiH-loaded paraffin, all enclosed within an air-tight box.

TABLE V: A summary of the $0\nu\beta\beta$ proposals. Background estimates were not available for all projects. The quantity of isotope includes the estimated efficiency for $0\nu\beta\beta$.

Collaboration	Isotope (kmol)	Anticipated Background (counts/y)	Detector Description
CAMEO[137]	^{116}Cd (2)	few/year	$CdWO_4$ crystals in liq. scint.
CANDLES[139]	^{48}Ca (0.04)		CaF_2 crystals in liq. scint.
COBRA[140]			CdTe semiconductors
CUORE[141]	^{130}Te (1.4)	≈ 60/y	TeO_2 bolometers
DCBA[142]	^{82}Se (2)	≈ 40/y	Nd foils and tracking chambers
EXO[143]	^{136}Xe (4.2)	< 1/y	Xe TPC,
GEM[144]	^{76}Ge (11)	≈ 0.8/y	Ge detectors in LN
GENIUS[145]	^{76}Ge (8.8)	≈ 0.6/y	Ge detectors in LN
GSO[147, 148]	^{160}Gd (1.7)		Gd_2SiO_5 crystals in liq. scint.
Majorana[149]	^{76}Ge (3.5)	≈ 1/y	Segmented Ge detectors
MOON[150]	^{100}Mo (2.5)	≈ 8/y	Mo foils and plastic scint.
MPI bare Ge[151]	^{76}Ge (8.8)		Ge detectors in LN
Nano-crystals[152]	≈ 100 kmol		suspended nanoparticles
Super-NEMO[153]	^{82}Se (0.6)	≈ 1/y	foils with tracking
Xe[154]	^{136}Xe (6.3)	≈ 118/y	Xe dissolved in liq. scint.
XMASS[155]	^{136}Xe (6.1)		liquid Xe

This box was then surrounded by boron-loaded water tanks and situated underground at the Oto Cosmo Observatory. This measurement successfully demonstrated the use of these crystals for $\beta\beta$ studies.

An improved version of this crystal technology, the CANDLES-III detector[139], is presently being constructed with 200 kg of CaF_2 crystals. These crystals have better light transmission than the CaF_2(Eu) crystals. This design uses sixty 10-cm^3 CaF_2 crystals, which are immersed in liquid scintillator. The collaboration has also proposed a 3.2-t experiment that hopes to reach 100 meV for $\langle m_{\beta\beta} \rangle$.

COBRA

The COBRA experiment[140] uses CdZnTe or CdTe semiconductor crystals. These crystals have many of the advantages of Ge detectors but, in addition, operate at room temperature. Because the crystals contain Cd and Te, there are 7 $\beta\beta$ and $\beta^+\beta^+$ isotopes contained. The final proposed configuration is for 64000 1-cm^3 crystals for a total mass of 370 kg. The collaboration has already obtained 30-keV resolution at 2.6 MeV with these detectors and has published initial $\beta\beta$-decay studies[156]. Background studies are the current focus of the efforts. Although it is tempting to focus on the naturally isotopic abundant ^{130}Te for $0\nu\beta\beta$ decay, the presence of the higher Q-value ^{116}Cd creates a serious background from its $2\nu\beta\beta$ decay. Detectors enriched in ^{116}Cd are probably required to reach 45 meV.

CUORE

CUORE and CUORICINO are based on the technique of cryogenic detectors. When operated at low temperature, the absorbers of these detectors have a heat capacity so low that even the small energy released by a single radioactive decay event can be observed and measured by means of a suitable thermal sensor. With crystals of mass near to a kilogram, with NTD Ge (Neutron Transmutation Doped germanium) thermistors, an energy resolution similar to that of germanium diodes has been achieved. In addition, thermal detectors allow a wide choice of nuclei to be used for double beta decay searches. The experiment CUORICINO is located in the Gran Sasso underground laboratory and it is a prototype for CUORE (Cryogenic Underground Observatory for Rare Events). CUORICINO is an array of 44 crystals of TeO_2 each 5x5x5 cm and 18 crystals each 3x3x6 cm. With its mass of approximately 40 kg, CUORICINO is by far the most massive cryogenic set-up in operation. Due the large isotopic abundance (34%) of the double beta decay candidate ^{130}Te, no isotopic enrichment is required, but two of the 3x3x6 cm crystals are enriched in ^{130}Te and two other in ^{128}Te to investigate $2\nu\beta\beta$. In only three months of operation, CUORICINO has obtained a 90% c.l. limit on the lifetime against neutrinoless double beta decay of 7.5×10^{23} yr[112], corresponding to an upper limit on the average neutrino mass ranging from 0.3 to 1.7 eV. This result rivals the best limits obtained from many years of searches for the double beta decay of ^{76}Ge. CUORE will consist of an array consisting of 25 columns of 10 planes of 4 TeO_2 crystals each 5x5x5 cm of for a total of 1000 crystals with a mass around 760 kg. Each tower will therefore be similar to the single tower of CUORICINO, which consists of 13 planes. As far as time is concerned, CUORICINO is now running and its larger brother CUORE will be available in four years from the start of construction (likely summer of 2004).

The present background of CUORICINO in the region of neutrinoless double beta decay (0.20+0.02 counts/keV/kg/year) is in excellent agreement with the previously predicted value (0.22 counts/keV/kg/year). In the present measurement this background is mainly due to the surface contamination of copper and crystals and recently it has become understood how to reduce it by an order of magnitude by surface treatment. Taking into account that the structure of CUORE allows a large suppression of background by applying the anticoincidence method we can guarantee a conservative value of background of 0.01 counts/keV/kg/year. We believe that in the next four years we can achieve a further improvement in the energy resolution, in the radioactive contamination, and in the neutron and cosmic ray background. Thus, it is reasonable to predict a background of 0.001 counts/keV/kg/year for CUORE. As a consequence we believe that the CUORE sensitivity can be in the few tens of millielectronvolts for the average neutrino mass[141].

DCBA

As demonstrated by the history of discoveries of extremely rare events, magnetic tracking detectors have played important roles. Thus this collaboration bases its search for $0\nu\beta\beta$ events on a magnetic tracking detector. A momentum analyzer called the Drift Chamber Beta-ray Analyzer (DCBA)[142] is a tracking detector operated in a uniform magnetic field of around 1 kG. Various isotopes can be installed within the detector, if the source can be fabricated into a thin plate. Presently, the collaboration is considering ^{82}Se, ^{100}Mo, and ^{150}Nd because of their high Q-values. A tracking region on each side of a source plate includes anode-, potential- and cathode-wires. The drift region is filled with 1-atm helium gas mixed with small amounts of a quench gas. A β ray emitted from a source plate makes a helical track in the region between anode and cathode wire planes. Anode signals are read out with Flash Analog to Digital Converter (FADC). The three-dimensional reconstruction of a helical track is available using data from the electron drift time (corresponding to the X-coordinate), an anode wire position (Y) and the ratio of signals from both sides of an anode wire (Z). Momentum of each β ray is derived from the curvature of the track. Since financial support for DCBA has not been approved yet, the construction schedule is unknown. Electron tracks of 1 MeV were studied using internal conversion electrons from ^{207}Bi, which was installed in a prototype called DCBA-T. We are making efforts to improve the Z-position resolution so as to obtain better energy resolution. Another developing item is to accommodate source plates, as much as possible, in a limited chamber volume. Research into cleaning the source material is also proceeding.

The future DCBA experiment will consist of 40 modules. One module comprises a drift chamber of about 1.8 m^3 volume containing the source plates surrounded by a solenoid magnet with maximum field of 1.6 kG. In the chamber, 30 tracking regions cover 29 source plates. The total source-plate area is 25 m^2 in each module. For a source-plate thickness of 60 mg/cm^2, the source weight is 15 kg for each module. Therefore total source weight is 600 kg, corresponding to about 6600 mol and 5400 mol for ^{82}Se and ^{100}Mo, respectively, which are enriched to 90%. For a natural Nd source, about 200 mol of ^{150}Nd will be installed. Assuming an efficiency of event detection of 0.3, a background rate of 1 event/module/year, and a measuring time of 5 years; the half-life sensitivities are approximately calculated to be 3×10^{26} yr for ^{82}Se, 2×10^{26} yr for ^{100}Mo and 9×10^{24} yr for ^{150}Nd in natural Nd. If 90% enriched ^{150}Nd is available in the future by the method of Atomic Vapor Laser Isotope Separation, it is possible to obtain 1×10^{26} yr for ^{150}Nd.

EXO

The **E**nriched **X**enon **O**bservatory[143] is being set-up to study the double beta decay of ^{136}Xe. EXO is a collaborative effort currently involving groups from Caltech, Carleton University (Canada), Colorado State University, ITEP Moscow (Russia), Laurentian University (Canada), SLAC, Stanford University, University of Alabama, University of California Irvine, Universite de Montreal (Canada), Universite de Neuchatel and Universite de Yverdon (Switzerland). The collaboration aims to use up to 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. A concise description of the project has been published in [143].

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. Ba happens to be the atomic species produced in the double beta decay of ^{136}Xe. 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 towards the very large detector.

EXO plans to test Majorana neutrino masses as small as 10 to 40 meV using this scheme [143] that should ensure extremely high background rejection power. This sensitivity covers neutrino masses derived from the atmospheric mass spitting. A degenerate or inversely hierarchical neutrino mass pattern can thus be tested with EXO.

^{136}Xe is a particularly convenient isotope for a very large double beta decay experiment. It combines a large Q-value with ease (and low cost) enrichment, the absence of long lived radioactive isotopes, ease of purification and the possibility of transfer from one detector to another in the case new technology would become available. In addition purification can be achieved on-line so that more refined purification system may be introduced as they become needed. Finally, together with the enabling possibility of final state identification that is the hallmark of EXO, ^{136}Xe has the longest $2\nu\beta\beta$half life among all high Q-value $\beta\beta$-unstable nuclides (at least factor 6.5 longer than e.g. ^{76}Ge).

With its 200 kg of source strength the EXO prototype detector will already represent the largest existing double beta decay experiment. Recently evidence for a Majorana neutrino mass of $0.44^{+0.14}_{-0.20}$ eV (errors given at 3σ c.l.) has been claimed by a part of the Heidelberg component of the Heidelberg-Moscow experiment [103]. Should this claim turn out to be correct the EXO prototype expects to observe 43^{+33}_{-30} $0\nu\beta\beta$ decays per year when using the same matrix element calculation as reference [103]. Assuming that funding continues to be available in a timely fashion, the prototype detector is expected to be commissioned at Stanford in the Winter 2004-5 and be transferred to WIPP in the Summer 2005. The development of the barium extraction and tagging will continue in parallel, together with the work on a GXe TPC. After initial operation of the prototype the technology for the large detector will be chosen and its design finalized.

MOON

MOON (Molybdenum Observatory Of Neutrinos)[150] is a "hybrid" $\beta\beta$ and solar ν_e experiment with ^{100}Mo. It aims at studies of $\langle m_{\beta\beta}\rangle$ with a sensitivity near 30 meV by measuring $0\nu\beta\beta$ decays of ^{100}Mo and the charged current ^{7}Be solar ν_e with an accuracy of about 10% by inverse β decays of ^{100}Mo. The $\beta\beta$ decays to the ground and excited states are measured in prompt coincidence for the $0\nu\beta\beta$ studies. The large Q=3.034 MeV results in a large phase-space factor to enhance the $0\nu\beta\beta$ rate and a large energy to place the $0\nu\beta\beta$ signal above most background. MOON is a spectroscopic study of two β rays. As such, its capability to measure the energy and angular correlations for the two β rays can help identify the $0\nu\beta\beta$ mechanism. It capability for a tight localization of $\beta\beta$ events in space and time is crucial for selecting $0\nu\beta\beta$ and reducing background.

A possible configuration of the MOON apparatus is a super module of hybrid plate and fiber scintillators with ^{100}Mo isotope mass totaling about 1 ton. One module of this apparatus consists of a thin (20 mg/cm^2) Mo film interleaved between X-Y fiber planes and a plate scintillator. The fiber scintillators enable one to get the position resolution (1/K $< 10^{-8}$ pixels per ton) and the scintillator plate provides an energy resolution ($\sigma \approx$2.2% at 3 MeV). A different detector option under consideration consists of foils within liquid Ar to obtain better energy resolution. Research has shown (1) that for the small plate scintillator, σ = 2.2% , FWHM: 5% for $0\nu\beta\beta$ including light attenuation, for MOON, (2) the position resolution of 3.2×10^9, and (3) the feasibility of using centrifugal separation of MoF_6 gas to produce ^{100}Mo enrichment of 85-90% in ton-scale quantities. Currently a proto-type MOON (MOON 1) is under construction (2003-2005). A proposal for MOON is planned by 2006.

The MOON sensitivity can be evaluated as follows. The source is 1 ton of Mo with 85%^{100}Mo. The $0\nu\beta\beta$ efficiency after energy and angle cuts is 0.28. The background from $2\nu\beta\beta$ in the $0\nu\beta\beta$ window during 5 years after cuts is 5.5(42) events for an energy resolution of σ=2.2(3)% (FWHM 5(7)%). Here σ=2.2% is estimated based on the R&D data from a small-scale prototype and ELEGANT V, while 3% is a conservative value including a 50% factor. The background from cosmogenic isotopes and natural isotopes are less than 0.5 events. Then the $0\nu\beta\beta$ yield of $\sqrt{background}$ is 2.3(6.4), corresponding to a half life 22 (7.7)$\times10^{26}$. The mass sensitivities are, respectively, 13 (22) meV. Here the matrix element of $|M_{0\nu}| = 3$ is estimated by referring to the recent 3 calculations. The MOON apparatus has the $\beta\beta$source separated from the detector, and therefore can be used for other $\beta\beta$ isotopes such as ^{82}Se, ^{150}Nd and ^{116}Cd as well by replacing Mo isotopes with other isotopes.

Majorana

The Majorana Collaboration proposes to field 500 kg of 86% enriched Ge detectors[149]. By using segmented crystals and pulse-shape analysis, multiple-site events can be identified and removed from the data stream. Internal backgrounds from cosmogenic radioactivities will be greatly reduced by these cuts and external γ-ray backgrounds will also be preferentially eliminated. Remaining will be single-site events like that due to $\beta\beta$. The sensitivity is anticipated to be 4×10^{27} y.

Several research and development activities are currently proceeding. The collaboration is building a multiple-Ge detector array, referred to as MEGA, that will operate underground at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, NM USA. This experiment will investigate the cryogenic cooling of many detectors sharing a cryostat in addition to permitting studies of detector-to-detector coincidence techniques for background and signal identification. A number of segmented crystals are also being studied to understand the impact of segmentation on background and signal. Recently, these segmented detectors have shown that the radial information provided by PSD is indeed orthogonal to the azimuthal information provided by the segmentation. The segmentation studies, or SEGA program, consists of one 12-segment enriched detector and a number of commercially available segmented detectors. Presently, commercially available segmented detectors are fabricated from n-type crystals. Such crystals are much more prone to surface damage and thus more difficult to handle when packaging inside their low-background cryostats. Hence the collaboration is also experimenting with segmenting p-type detectors.

The Majorana design uses Ge detectors within a low-mass, electroformed Cu cryostat. Electroformed Cu is very free of radioactive contaminants. However, just how radio-pure the Cu is remains unknown. Hence, the collaboration plans to form Cu underground and study its radiopurity to a sensitivity below previous limits.

Bare Ge Crystals

The GENIUS collaboration[145] proposed to install 1 t of enriched bare Ge crystals in liquid nitrogen. By eliminating much of the support material surrounding the crystals in previous experiments, this design is intended to reduce backgrounds of external origin. Note how this differs from the background-reduction philosophy associated with pulse-shape analysis coupled with crystal segmentation. The primary advocates for this project indicate[103] that its motivation has been questioned by their own claim of evidence for $0\nu\beta\beta$decay. Even so, the GENIUS test facility[146] is being operated to demonstrate the effectiveness of operating crystals naked in liquid cryogen.

Another group at the Max Plank Institute in Heidelberg, however, is proposing to pursue a similar idea. They have recently submitted a Letter of Intent[151] to the Gran Sasso Laboratory. They propose to collect the enriched Ge crystals from both the Heidelberg-Moscow and IGEX expeiments and operate them in either liquid nitrogen or liquid argon. As a second phase of the proposal, they plan to purchase an additional 20-kg of enriched Ge detectors (most likely segmented) and operate with a total of 35 kg for about 3 years. Finally, they eventually plan to propose a large ton-scale experiment. It should be noted that this collaboration and the Majorana collaboration are cooperating on technical developments and if a future ton-scale experiment using ^{76}Ge proceeds these two groups will most likely merge and optimally combine the complementary technologies of bare-crystal operation and PSA-segmentation.

Nanocrystals

Some elements may be suitable for loading liquid scintillator with metallic-oxide nanoparticles. Since Rayleigh scattering varies as the sixth power of the particle radius, it can be made relatively small for nanoparticles of radii below 5 nanometers. Particles of this size have been developed and commercial suppliers of ZrO_2, Nd_2O_3 *etc.* are available. Absorption of the materials must also be taken into account, but some of the metal oxides such as ZrO_2 and TeO_2 are quite transparent in the optical region because of the substantial band gaps in these insulators. Some members of the SNO collaboration[152] have been studying a configuration equivalent to filling the SNO cavity with a 1% loaded liquid scintillator or approximately 10 t of isotope after the present heavy water experiment is completed. The group is currently researching the optical properties of potential nano-crystal solutions. In particular, one must demonstrate that sufficient energy resolution is achievable with liquid scintillator.

Super-NEMO

The currently operating NEMO-3 detector uses a tracking-calorimeter technique to detect $\beta\beta$. The source, is not the detector, but rather a thin foil located in the middle of a tracking chamber. This tracking chamber, which is made of geiger-drift cells, is surrounded by a calorimeter (scintillators with low radioactivity PMTs). The first of two long runs to search for $0\nu\beta\beta$ decay began in February of 2003 with 7 kg of ^{100}Mo and 1kg of ^{82}Se. Additionally, 2 kg of various foils were placed in the detector to study $2\nu\beta\beta$ decay and backgrounds. The first run will last approximately five years. So far a comprehensive study of the effects of various shields has been undertaken. The second run, again for five years, is currently planned to operate with 20 kg of ^{82}Se. The ^{82}Se is of particular interest because the $2\nu\beta\beta$ decay lifetime is 10 times that of ^{100}Mo and thus may contribute less as a background to $0\nu\beta\beta$ decay.

There has been an unexpected background from radon, which is currently being fixed with a radon tent and a "radon trapping factory". Data collection free of the radon background will start in Fall 2004. The energy resolution is 250-keV FWHM at 3 MeV. Assuming the radon is eliminated with the radon tent and an efficiency of 14%, the background will be 5x10^{-4} counts/keV/kg/yr. This yields $T^{0\nu}_{1/2} > 5 \times 10^{24}$ in five years with $\langle m_{\beta\beta}\rangle < 200 - 500$ meV. During the second run with 20 kg of ^{82}Se, an efficiency of 14% and a background of 5x10^{-5} counts/keV/kg/yr, the expected results in five years should be $T^{0\nu}_{1/2} > 3 \times 10^{25}$ yr and $\langle m_{\beta\beta}\rangle < 100 - 200$ meV.

The recent progress of the NEMO-3 program[153] has culminated in excellent $2\nu\beta\beta$ results. In particular, the energy spectra from ^{100}Mo contain approximately 10^5 events and are nearly background free. These data permit, for the first time, a precise study of the spectra. In fact, there is hope that the data (Sutton 2004) will demonstrate whether the $2\nu\beta\beta$ transition is primarily through a single intermediate state or through a number of states[158].

A much bigger project is currently being planned that would use 100 kg of source. The apparatus would have a large footprint however and the Frejus tunnel where NEMO-3 is housed would not be large enough to contain it. Currently the collaboration is studying the design of such a detector.

XMASS

The XMASS collaboration[155, 159] plans to build a 10 t natural Xe liquid scintillation detector. They expect an energy resolution of 3% at 1 MeV and hope to reach a value for $T^{0\nu}_{1/2} > 3.3 \times 10^{27}$ y. This detector would also be used for solar-neutrino studies and a search for dark matter.

Borexino CTF

In August of 2002, operations at the Borexino experiment resulted in the spill of scintillator. This led to the temporary closure of Hall C in the Gran Sasso Laboratory and a significant change in operations at the underground laboratory. As a result, efforts to convert the Counting Test Facility (CTF) or Borexino itself into a $0\nu\beta\beta$ experiment[137, 154] have been suspended[160].

How many $\beta\beta$ Experiments are Required?

In view of the importance and scale of new generation $0\nu\beta\beta$experiments, internationally cooperative efforts in both experiment and theory are quite important. Thus it is reasonable to suggest a concentration of the limited resources on a few $\beta\beta$experiments However, it is critical to use different experimental techniques and isotopes to demonstrate the effect has really been seen and also to extract the most critical physics conclusions. It is therefore necessary to build a number of detectors and the reasons are enumerated here.

1. The observation of a statistically significant signal in a single experiment might not be considered a discovery without clear confirmation from other independent experiments utilizing different isotopes.
2. A nuclear matrix element is necessary to deduce $\langle m_{\beta\beta}\rangle$from a measured $0\nu\beta\beta$rate. Since theoretical calculations of $|M_{0\nu}|$may include a substantial uncertainty, one needs experiments on different isotopes to extract a reliable value for the effective mass.
3. Although light-neutrino exchange is the most natural explaination for $0\nu\beta\beta$if it exists, there are other possibilities. The relative matrix element values for different nuclei depend on the mechanism. Furthermore the matrix element situation is encouraging and one can anticipate a great improvement in the calculation precision. Therefore, measurements in several nuclei might be the most straight-forward way to provide insight into the mechanism of $0\nu\beta\beta$.
4. There are a number of different techniques being proposed for future experiments. Each has been previously used as effective prototypes for the proposals and therefore remains a strong candidate for future effort. However, the sensitivity of any given proposal depends strongly on its background estimate. It remains to be seen which of the technologies will successfully attain the required background. In addition, certain technologies provide capabilities such as measurments of the opening angle, individual electron energies, or the daughter production. These will not only help understand and remove background but they may also provide insight into the mechanism of $0\nu\beta\beta$.

VII. CONCLUSIONS

Study of the neutrinoless double beta decay and searches for the manifestation of the neutrino mass in ordinary beta decay are the main sources of information about the absolute neutrino mass scale, and the only practical source of information about the charge conjugation properties of the neutrinos. Thus, these studies have a unique role in the plans for better understanding of the whole fast expanding field of neutrino physics.

In this report we summarized the various aspects of the problem. We explained first the relation of the information that can be obtained from the analysis of $0\nu\beta\beta$ and β decay experiments with the parameters describing neutrino oscillations and the absolute neutrino mass scale. We then discussed the nuclear structure issue and the uncertainty in determining the neutrino mass from a measured $0\nu\beta\beta$ decay rate. We also briefly discussed the role of neutrino mass in cosmology, and the corresponding constraints on neutrino masses based on astrophysical observations.

The remaining part of the report was devoted to the description of the existing and planned experiments. We described the present situation in $0\nu\beta\beta$ and tritium beta decay, and in particular the recent, so far unverified, claim of the $0\nu\beta\beta$ decay discovery. We concentrated then on the future plans for both areas of research.

The situation in the direct neutrino mass searches using tritium β decay is relatively simple. There is only one realistic plan a very large new beta spectrometer which is being built in Germany. This KATRIN experiment has a design sensitivity approaching 200 meV. If the neutrino masses are quasi-degenerate, as would be the case if the recent double-beta decay claim proves true, KATRIN will see the effect. Although KATRIN is predominately a European effort, there is significant US participation. The design and construction of this experiment is proceeding well and we enthusiastically recommend the continuing strongly support of this program.

There are many proposals, and even more ideas, for much larger $0\nu\beta\beta$ decay experiments than the existing ones. We outlined and justified in the report the strategy that we believe should be followed:

1. A substantial number (preferably more than two) of 200-kg scale experiments (providing the capability to make a precision measurement at the quasi-degenerate mass scale) with large US participation should be supported as soon as possible. We estimate that the timescale of such experiments is 3-5 years, and that each such experiment will cost approximately \$10M-\$20M.

2. Concurrently, the development toward ∼1-ton experiments (*i.e.* sensitive to $\sqrt{\Delta m^2_{\rm atm}}$) should be supported, primarily as expansions of the 200-kg experiments. The corresponding plans for the procurement of the enriched isotopes, as well as for the development of a suitable underground facility, should be carried out. The US funding agencies should set up in a timely manner a mechanism to review and compare the various proposals for such experiments which span research supported by the High Energy and Nuclear Physics offices of DOE as well as by NSF. Each such experiment will cost approximately $50M-$100M and take 5-10 years to implement.

3. A diverse R&D program developing additional techniques of $0\nu\beta\beta$ decay study should be supported.

The field of neutrino physics has made great strides recently. We believe that the study of $0\nu\beta\beta$ decay in particular could very well be the next one where significant discoveries will be made.

VIII. ACKNOWLEDGEMENTS

This working group's co-chairs are Steven Elliott (elliotts@lanl.gov)and Petr Vogel(pxv@caltech.edu). The members of the working group are Craig Aalseth (Craig.Aalseth@pnl.gov), Henning Back (hback@vt.edu), Loretta Dauwe (dauwe@umich.edu), David Dean (deandj@ornl.gov), Guido Drexlin (guido.drexlin@ik.fzk.de), Yuri Efremenko (efremenk@larry.cas.utk.edu), Hiro Ejiri (ejiri@rcnp.osaka-u.ac.jp, ejiri@spring8.or.jp), Jon Engel (engelj@physics.unc.edu), Brian Fujikawa (bkfujikawa@lbl.gov), Reyco Henning (RHenning@lbl.gov), Jerry Hoffmann (hoffmann@physics.utexas.edu), Karol Lang (lang@mail.hep.utexas.edu), Kevin Lesko (ktlesko@lbl.gov), Tadafumi Kishimoto (kisimoto@km.phys.sci.osaka-u.ac.jp), Harry Miley (harry.miley@pnl.gov), Rick Norman (norman11@llnl.gov), Silvia Pascoli (pascoli@physics.ucla.edu), Serguey Petcov (petcov@he.sissa.it), Andreas Piepke (andreas@bama.ua.edu), Werner Rodejohann (werner@sissa.it), David Saltzberg (saltzbrg@physics.ucla.edu), Sean Sutton (ssutton@MtHolyoke.edu), Ray Warner (ray.warner@pnl.gov), John Wilkerson (jfw@u.washington.edu), and Lincoln Wolfenstein (lincolnw@heps.phys.cmu.edu).

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