Spectrum of neutrino masses and their nature in the light of present and future experiments.

M. Czakon, J. Studnik and M. Zralek

a Department of Field Theory and Particle Physics, Institute of Physics, University of Silesia, Uniwersytecka 4, PL-40-007 Katowice, Poland

b Depto. de Fisica Teorica y del Cosmos, Universidad de Granada, E-18071 Granada, Spain

The present experimental data on neutrino oscillations, neutrinoless double beta decay and tritium beta decay are collected together and possible mass ranges for Dirac and Majorana neutrinos are found. Four future experimental situations are investigated: both decay experiments give only upper bounds, one of them gives a positive result ($\langle |m_\nu| \rangle \neq 0$ or $m_3 \neq 0$), or finally both effective neutrino masses are different from zero ($\langle |m_\nu| \rangle \neq 0$ and $m_3 \neq 0$). Each scenario gives new information on neutrino masses and nature but only the last has a chance to resolve the problem and give some additional information on CP violation in the lepton sector.

The problem of neutrino mass spectrum and its nature is the most important issue in the lepton part of the Standard Model. What new information can we obtain from the last experimental results, and what are the future perspectives? Three kinds of experiments play a fundamental role in answering this question. Two are traditional and known for years: beta decay and neutrinoless double beta decay ($\beta\beta_{0v}$) of nuclei. Already Fermi [1] in 1934 and Furry [2] in 1939 realized that both processes are important to find the neutrino mass and nature. The third type constitute the neutrino oscillation experiments [3]. We strongly believe that neutrino oscillations are responsible for anomalies observed in solar [3], atmospheric [4] and LSND [5] experiments. There are trials of alternative explanations of the observations [6] but they require much more sophisticated assumptions (as for example the breaking of the equivalence principle, breaking of the special theory of relativity, the neutrino decay with life-time much below expectations or huge neutrino magnetic moments) and give much poorer fits to the data [7].

The end of the Curie plot in tritium beta decay has been observed since the late forties giving now a bound on the effective electron neutrino mass of $m_\beta \leq 2.8eV$ [6] and $m_\beta \leq 2.5eV$ [10] both with 95% c.l.. Although less pronounced, the problem of negative $m_3^2$ remains.

Trials of finding the neutrinoless double beta decay of even-even nuclei have also been conducted for years. The best result for the effective electron neutrino mass $\langle |m_\nu| \rangle$ bound comes from the last experiment with $^{76}Ge$. The Heidelberg-Moscow collaboration found that the half life time of $^{76}Ge$ is bounded as

$$T_{1/2}^{0\nu}(Ge) > 5.7 \times 10^{25} \text{ years},$$

which gives a bound of $\langle |m_\nu| \rangle < 0.2eV$ [13]. The derivation of this bound required the calculation of complicated nuclear matrix elements. A discrepancy of the order of a factor of 3 [12] between the independent studies has been found. As a consequence the uncertainty of $\langle |m_\nu| \rangle$ is of the order of $\sqrt{3}$.

Finally, the oscillation experiments give results on the basis of three different observations: solar [13], atmospheric [4] and LSND [5]. The results of the last of these, if correct and explained through neutrino oscillations require the introduction of a fourth sterile light neutrino species. The observation of the LSND collaboration has not been confirmed by KARMEN [14] and is partially excluded by Bugey [15] and BNL776 [16] experiments. In such circumstances we will assume that only three massive neutrinos exist which explain the solar and atmospheric neutrino anomalies. The case of four massive neutrinos can be studied in a similar way. Even with this assumption the oscillatory data has some ambiguities related in particular to the existence of several possible solutions of the solar neutrino problem. The values of $\delta m^2$ and $\sin^2 2\theta$ for the atmospheric and the four solar solutions (SMA MSW, LMA MSW, LOW MSW and VO) of the observed anomalies are collected in Table I. As there are definitely two scales of $\delta m^2$, $\delta m^2_{\text{atm}} \gg \delta m^2_{\text{sol}}$, two possible neutrino mass spectra must be considered (Fig. 1). The first, known as normal mass hierarchy ($A_3$) where $\delta m^2_{\text{sol}} = \delta m^2_{21} < \delta m^2_{32} \approx \delta m^2_{\text{atm}}$ and the second, inverse mass hierarchy spectrum ($A_{3}^{inv}$) with $\delta m^2_{\text{sol}} = \delta m^2_{31} < \delta m^2_{21} \approx -\delta m^2_{31}$. Both schemes are not distinguishable by present experiments. There is hope that next long base line experiments (e.g. MINOS, ICANOE) will do that.

The values of the allowed range of $\delta m^2$ and $\sin^2 2\theta$ in the Table I are presented with a 95% c.l.. As we will see the value of $\sin^2 2\theta$ plays a decisive role in our considerations. A value of $\sin^2 2\theta < 1$ is crucial. If we look at the data [21], we see that a maximal mixing is still possible at 99% c.l. for three solutions of the solar neutrino problem LMA, LOW and VO [21]. However, the best fit values, contrary to the atmospheric neutrino case, are smaller than 1. Still, it is possible that this is only a fluctuation and future better data are needed to solve this problem. Here we assume that the tendency observed in experimental data is real and future experiments will confirm that $\sin^2 2\theta < 1$.\[ \]
TABLE I. The allowed ranges and best fit values of $\sin^2 2\theta$ and $\delta m^2$ for the atmospheric and different types of solar neutrino oscillations.

| Experiment          | Allowed range $\delta m^2 [eV^2]$ | $\sin^2 2\theta$ | Best fits $\delta m^2 [eV^2]$ | $\sin^2 2\theta$ |
|---------------------|------------------------------------|------------------|-------------------------------|-----------------|
| Atmospheric neutrinos | $(1.5 - 7) \times 10^{-3}$         | 0.84 - 1         | $3.5 \times 10^{-3}$          | 1.0             |
| Solar neutrinos     |                                    |                  |                               |                 |
| MSW SMA [14,19]     | $(4 - 10) \times 10^{-6}$         | 0.001 - 0.01     | $5.2 \times 10^{-6}$          | 0.0065          |
| MSW LMA [14,19]     | $(1.5 - 10) \times 10^{-5}$       | 0.59 - 0.98      | $2.94 \times 10^{-5}$         | 0.77            |
| MSW LOW [20,21]     | $(7 - 20) \times 10^{-8}$         | 0.68 - 0.98      | $1.24 \times 10^{-7}$         | 0.9             |
| VO [22]             | $(0.5 - 8) \times 10^{-10}$       |                  | $4.42 \times 10^{-10}$        | 0.93            |

FIG. 1. Two possible mass spectra which can describe the oscillation data. Scheme $A_3$, normal mass hierarchy, has a small gap between $m_1$ and $m_2$ to explain the oscillation of solar neutrinos and a larger gap for the atmospheric neutrinos. In the inverse mass hierarchy scheme $A_3^{inv}$, $m_3$ is the lightest neutrino mass and $\delta m^2_{atm} = -\delta m^2_{31}$. Both schemes are not distinguishable by present experimental data. They will be discriminated by future experiments.

Two elements of the first row of the mixing matrix $|U_{e1}|$ and $|U_{e2}|$ can be expressed by the third element $|U_{e3}|$ and the $\sin^2 2\theta$

$$|U_{e1}|^2 = (1 - |U_{e3}|^2)^2 \left(1 + \sqrt{1 - \sin^2 2\theta}\right),$$

and

$$|U_{e2}|^2 = (1 - |U_{e3}|^2)^2 \left(1 - \sqrt{1 - \sin^2 2\theta}\right).$$

The value of the third element $|U_{e3}|$ is not fixed yet and only different bounds exist for it [23]. We will take the bound directly inferred from the CHOOZ experiment [24]

$$|U_{e3}|^2 < 0.04.$$  (4)

In spite of various complications and uncertainties even now we will get some information about the neutrino mass spectrum and their nature. We hope however, that such considerations with better data will give a key to the solution of the problem in the future.

For the three massive neutrino scenario (without LSND) the oscillation experiments give the lower bound on the highest mass of neutrinos

$$(m_{\nu})_{max} > \sqrt{\delta m^2_{atm}} \approx 0.06eV$$  (5)

and a bound on the absolute value of the difference of two masses

$$|m_i - m_j| < \sqrt{\delta m^2_{atm}}.$$  (6)
No upper bound on neutrino masses can be inferred from oscillation experiments alone. So, in the schemes in Fig 1, we only know that \(m_{3}\) is \(\geq 0.06\) eV, for \(A_{3}\) and \(A_{3}^{\text{inv}}\) schemes respectively.

The tritium beta decay measures the effective electron neutrino mass \(m_{\beta}\)

\[
m_{\beta} = \left[ \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \right]^{1/2},
\]

and no upper bound on neutrino masses can be given. We can only find that

\[
(m_{\nu})_{\text{min}} \leq m_{\beta} \leq (m_{\nu})_{\text{max}}
\]

where \((m_{\nu})_{\text{min}}\) denotes the lowest neutrino mass. In practice this means that \((m_{\nu})_{\text{min}} < 2.5\) eV, but \((m_{\nu})_{\text{max}}\) can be very large. Connecting both the tritium beta decay data and the oscillatory data we can find the following upper bound on the neutrino mass \[25\]

\[
\sqrt{\delta m_{\text{atm}}^2} \leq (m_{\nu})_{\text{max}} \leq \sqrt{(m_{\beta})^2 + \delta m_{\text{atm}}^2}.
\]

This means that the mass of the heaviest neutrino must be somewhere in between 0.06 eV and 2.5 eV.

The estimations which we get up to now do not depend on the neutrino nature. It is well known that the electron energy distribution in nuclei beta decay and flavor oscillations do not distinguish Dirac from Majorana neutrinos \[26\]. Therefore, the bounds (Eqs. 5, 6 and Eq. 9) are valid for both neutrino types. This is not the case of the neutrinoless double beta decay of nuclei. This decay is only possible for a massive Majorana neutrino \[27\]. Neglecting all other mechanisms which can participate in the process we can derive a bound on

\[
|\langle m_{\nu} \rangle| \equiv \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|.
\]

Alone, this bound is of little value since it only means that

\[
0 \leq |\langle m_{\nu} \rangle| \leq (m_{\nu})_{\text{max}}.
\]

Let us now consider however all three experiments together \[28\]. If neutrinos are Dirac particles then \(|\langle m_{\nu} \rangle| = 0\) and we do not have any additional information from \((\beta \beta)_{0\nu}\). All we can say about masses of Dirac neutrinos follows from \(\frac{1}{2} H\) decay and oscillation experiments and is given by Eqs. 3 and Eq. 8.

If neutrinos are Majorana particles then the bound on \(|\langle m_{\nu} \rangle|\) works and we can find new restrictions. For three neutrinos in the scheme \(A_{3}\) (Fig. 1) we have

\[
|\langle m_{\nu} \rangle| = \left| U_{e1}^2 (m_{\nu})_{\text{min}} + U_{e2}^2 e^{2i\phi_2} \sqrt{(m_{\nu})_{\text{min}}^2 + \delta m_{\text{sol}}^2} + U_{e3}^2 e^{2i\phi_3} \sqrt{(m_{\nu})_{\text{min}}^2 + \delta m_{\text{sol}}^2 + \delta m_{\text{atm}}^2} \right|,
\]

and similarly in the case of the scheme \(A_{3}^{\text{inv}}\). Three parameters defined above are unknown, \((m_{\nu})_{\text{min}}\) and the Majorana \(CP\) violating phases \(\phi_2\) and \(\phi_3\). We are not able to predict the value of \(|\langle m_{\nu} \rangle|\) but lower \(|\langle m_{\nu} \rangle|_{\text{min}}\) and upper \(|\langle m_{\nu} \rangle|_{\text{max}}\) limits as function of \((m_{\nu})_{\text{min}}\) can be obtained. In Fig. 2 (scheme \(A_{3}\)) and Fig. 3 (scheme \(A_{3}^{\text{inv}}\)) \(|\langle m_{\nu} \rangle|_{\text{min}}\) is shown as function of \((m_{\nu})_{\text{min}}\) for the four possible solutions of the solar neutrino anomaly \[29\]. The shaded regions give the uncertainties of the results caused by the allowed region of input parameters (mostly \(\sin^2 \theta\)). For the SMA MSW solution the 95\% c.l. range of \(|\langle m_{\nu} \rangle|_{\text{min}}\) is described by one curve in the adopted logarithmic scale.
FIG. 2. Scheme $A_3$. The curves of $|\langle m_\nu \rangle|_{\text{min}}$ for the different solar neutrino oscillation solutions were obtained with the values of $\sin^2 2\theta_{\text{sun}}$ quoted in the text and $|U_{e3}|^2 = 0.01$. The shaded region is given by the largest range in Table I, that is the range for the LMA solution. For the SMA solution the 95% c.l. range (.001-.01) is described by one curve in the present scale.

FIG. 3. Scheme $A_{3}^{\text{inv}}$. The curves were obtained with the same assumptions as in Fig. 2.

FIG. 4. $m_\beta$ as function of $m_\nu$ ($m_\nu$)$_{\text{min}} = [\kappa'^2 - (1 - |U_{e1}|^2)\delta m_{\text{solar}}^2 - |U_{e3}|^2\delta m_{\text{atm}}^2]^{1/2}$, with oscillation parameters changing in the range specified in Table I. The solar neutrino solution is the LMA MSW. The difference is visible only for $\kappa' < 0.1eV$.
Present Experimental Data

We see that already with the present experimental data the possible values of $|\langle m_\nu \rangle|_{\text{min}}$ depicted in Fig. 2 and Fig. 3 exceed the bound on $|\langle m_\nu \rangle|$

$$|\langle m_\nu \rangle|_{\text{min}} > 0.2eV,$$

(13)

for some values of $(m_\nu)_{\text{min}}$. This means that Majorana neutrinos with masses above some $(m_\nu)_{\text{min}}$ are forbidden. The limiting mass depends on the solution to the solar neutrino problem and on the adopted value of $\sin^2 2\theta$ and $|U_{e3}|^2$. For the SMA MSW solution in both $A_3$ and $A_3^{\text{nu}}$ schemes $(m_\nu)_{\text{min}} = 0.22eV$. For LMA, LOW and VO with $(\sin^2 2\theta)_{\text{max}} = 0.98$ and $|U_{e3}|^2 = 0.01$, $(m_\nu)_{\text{min}} = 1.5eV$ [22, 30].

We see that the bound on the effective mass $|\langle m_\nu \rangle|$ given by the present $(\beta\beta)_{0\nu}$ experiments restricts the range of possible Majorana neutrino masses. This range depends on the maximal value of $\sin^2 2\theta$, and for

$$\sin^2 2\theta > \frac{1 - 2|U_{e3}|^2}{(1 - |U_{e3}|^2)^2}$$

(14)

is the same as for Dirac neutrinos [30].

Future Perspectives

Future improving results of neutrino experiments will give better information on neutrino mass spectra. The improvements that are important for our purpose and are realistic are the following

- Concerning neutrino oscillations [31]
  - the problem of the sterile neutrino should be solved
  - a single solution of the solar neutrino problem should be found and the value of $\sin^2 2\theta$ should be given with better precision
  - the allowed range of $\delta m^2_{\text{atm}}$, $\delta m^2_{\text{sol}}$ and $|U_{e3}|$ will be reduced.

- Concerning $(\beta\beta)_{0\nu}$ decay [32]
  - there are plans of going down with the effective Majorana mass down to $|\langle m_\nu \rangle| \approx 0.006eV$ in two stages, first $|\langle m_\nu \rangle| \approx 0.02eV$ (GENIUS I) and later $|\langle m_\nu \rangle| \approx 0.006eV$ (GENIUS II).
  - two possibilities should be envisaged with different impact on this study. The pessimistic option is that the decay of $^{76}Ge$ will not be observed and only a new bound on $|\langle m_\nu \rangle|$ will be found. The optimistic, the decay is discovered and a value $|\langle m_\nu \rangle| \in (0.2 - 0.006)eV$ is inferred.

- Concerning the $^3H$ decay [33]
  - two Collaborations [11], [10], [33] plan to go down with the value of $m_\beta$ below 1$eV$ and perhaps even down to 0.6$eV$.
  - once more two scenarios can happen. A distortion in the electron kinetic energy will not be found and a new bound will follow, $m_\beta < 0.6eV$. On the optimistic side, such a distortion will be observed, the problem with $m_\beta^2 < 0$ will be solved and the tritium $\beta$ decay will give a value of $m_\beta = \kappa' \in (0.6 - 2.5)eV$.

We will now discuss four different possibilities (i) two bounds $|\langle m_\nu \rangle| < 0.006eV$ and $m_\beta < 0.6eV$ exist, (ii) $|\langle m_\nu \rangle| < 0.006eV$ and $m_\beta \approx \kappa'$, (iii) $|\langle m_\nu \rangle| \approx \kappa$ but $m_\beta < 0.6eV$, and finally (iv) $|\langle m_\nu \rangle| \approx \kappa$ and $m_\beta \approx \kappa'$.

Ad. (i) $|\langle m_\nu \rangle| < 0.006eV$, $m_\beta < 0.6eV$

Nothing special happens, the accepted range of Dirac and Majorana neutrino masses will become smaller. The bound on $m_\beta$ gives the possible range of Dirac neutrino masses

$$0.06eV < (m_\nu)_{\text{max}} \leq 0.6eV.$$ 

(15)

The bounds on $|\langle m_\nu \rangle|$ (depicted in Fig. 2 and Fig. 3) give a small space of Majorana neutrino masses. Once more the maximal value of $(m_\nu)_{\text{min}}$ depends on $(\sin^2 2\theta)_{\text{max}}$ and $|U_{e3}|^2$, which at that time should be known much better. Taking as an example for $|\langle m_\nu \rangle| < 0.006eV$ with $|U_{e3}|^2 = 0.01$, only two values of $(\sin^2 2\theta)_{\text{max}}$
in a close future will be very small. because the problem of neutrino nature will not be solved and the chance to find the spectrum of Majorana neutrinos will be very small. We see that a much smaller range of Majorana neutrino masses will be accepted than in the Dirac case. The scheme \( m^A_{\nu} \) will be excluded for SMA (LMA) by GENIUS I (GENIUS II) (see Fig. 3). This is a very pessimistic scenario because the problem of neutrino nature will not be solved and the chance to find the spectrum of Majorana neutrinos in a close future will be very small.

Ad. (ii) \( |\langle m_{\nu}\rangle| < 0.006eV \) and \( m_{\beta} \approx \kappa' \)

If a value of \( m_{\beta} \approx \kappa' \) is found the situation changes considerably. With the oscillation parameters and \( m_{\beta} \approx \kappa' \) we can calculate the spectrum of neutrinos. The only accepted scheme is \( A_3 \). It gives

\[
m_1 = (m_{\nu})_{\text{min}} = [\kappa'^2 - (1 - |U_{e1}|^2) \delta m^2_{\text{solar}} - |U_{e3}|^2 \delta m^2_{\text{atm}}]^{1/2},
\]

and

\[
m_2 = |(m_{\nu})^2_{\text{min}} + \delta m_{\text{solar}}^2|^{1/2},
\]

\[
m_3 = |(m_{\nu})^2_{\text{min}} + \delta m_{\text{atm}}^2|^{1/2}.
\]

In Fig. 4 we show the \( (m_{\nu})_{\text{min}} \) as function of \( m_{\beta} \approx \kappa' \) where the oscillation parameters change within their allowed range given in Tab. 1. For \( (m_{\nu})_{\text{min}} \geq 0.1eV \), practically \( (m_{\nu})_{\text{min}} \approx \kappa' \). The difference is visible only for very small \( (m_{\nu})_{\text{min}} \). This means that the experimental error on \( \kappa' \) is the only significant source of the variation range of \( (m_{\nu})_{\text{min}} \). The mass spectrum obtained from Eq. (18), (19) and (20) does not depend on the neutrino nature. If neutrinos are Majorana particles, the value of \( (m_{\nu})_{\text{min}} \) obtained from \( H_1 \) decay can be used to find the range of possible values of \( |\langle m_{\nu}\rangle| \). In Fig. 5 we depicted \( |(m_{\nu})|_{\text{max}} \) and \( |(m_{\nu})|_{\text{min}} \) for two possible solutions of the solar neutrino problem, SMA (Fig. 5A) and LMA (Fig. 5B) in double logarithmic scales. The bound of \( |(m_{\nu})|_{\text{min}} \sim (0.6 - 0.8)eV \) gives the range of possible \( |\langle m_{\nu}\rangle| \) values which follows from crossing the space allowed by oscillation experiments.

\[
|\langle m_{\nu}\rangle|_{\beta}^{\text{min}} \leq |\langle m_{\nu}\rangle| \leq |\langle m_{\nu}\rangle|_{\beta}^{\text{max}},
\]

If the experimental bound on \( |\langle m_{\nu}\rangle| \) from \((\beta\beta)_0\) decay is below the \( |(m_{\nu})|_{\text{min}}^{\text{max}} \) range, then neutrinos can not be Majorana particles. If it is larger, the problem of neutrino nature is not solved.

Ad.(iii) \( |\langle m_{\nu}\rangle| \approx \kappa, m_{\beta} < 0.6eV \).

It is quite probable that this scenario will happen. In this case the neutrinos are Majorana particles. In Fig. 3A
If the value of $|\langle m_\nu \rangle|$ is found in the second stage of the GENIUS experiment $|\langle m_\nu \rangle| \approx 0.01 - 0.005eV$ the $(m_\nu)_{\min (\beta\beta)_{\nu}} = 0$. With the range of possible $(m_\nu)_{\min}$ the result on $m_\beta$ from tritium $\beta$ decay can predicted. In practice $m_\beta$ should also satisfy the inequalities given by Eq.(22). If the experimental limit on $m_\beta$ is larger than $(m_\nu)_{\min (\beta\beta)_{\nu}}$, the theory with three Majorana neutrinos is consistent. If, what is less probable, the experimental limit on $m_\beta$ is smaller than $(m_\nu)_{\max (\beta\beta)_{\nu}}$ then the theory with three Majorana neutrinos is ruled out.

Ad.(iv) $|\langle m_\nu \rangle| \approx \kappa$, $m_\beta \approx \kappa'$.

This is the best, but on the other side, the least probable scenario. The value of $|\langle m_\nu \rangle| \neq 0$ defines the neutrino as a Majorana particle. The value $m_\beta \neq 0$ gives their mass spectrum. Comparing both bands with the region of $|\langle m_\nu \rangle|$ allowed by the oscillation data (Fig. 3) is a check of internal consistency of the theory. With precise data the crossing of the three regions can be used to specify the values of the CP breaking Majorana phases $\varphi_1$ and $\varphi_2$ (Eq.(12)). If the two bands $|\langle m_\nu \rangle|$ and $m_\beta$ cross the oscillation region near $|\langle m_\nu \rangle|_{\max}$, two phases are equal $\varphi_1 = \varphi_2 \approx n\pi$. This means that all three Majorana neutrinos have the same CP parity $\eta_{CP} = +1$ and the symmetry is conserved. If the two bands cross the oscillation region near $|\langle m_\nu \rangle|_{\min}$ once more the CP symmetry is satisfied with $\eta_{CP}(\nu_1) = -\eta_{CP}(\nu_2) = -\eta_{CP}(\nu_3) = 1$. Finally, if all three regions cross somewhere in between, the phases $\varphi_1$ are nontrivial and the CP symmetry is broken.

In conclusion

Present experimental data define the region of neutrino mass. The heaviest Dirac neutrino mass must be somewhere in the range $0.06eV \leq (m_\nu)_{\max} \leq 2.5eV$. The analogous range for Majorana neutrinos depends on the solution of the solar neutrino problem and is $0.06eV \leq (m_\nu)_{\max} \leq 0.26eV$ for SMA and $0.06eV \leq (m_\nu)_{\max} \leq 1.5eV$ for the LMA scenario. A better future bound on the effective mass in the neutrinoless double $\beta$ decay and the tritium $\beta$ decay would give better limits on Dirac and Majorana neutrino masses but the problem of the mass spectrum and their nature will still not be solved. The situation will change significantly if at least one of the experiments gives a positive result and $|\langle m_\nu \rangle|$ or $m_\beta$ will be different from zero. The most difficult scenario, where both experiments give positive results is the one where (i) the nature of neutrinos, (ii) their mass spectrum, (iii) the consistency of the theory and (iv) the CP breaking Majorana phases can be found.
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