Non-Oscillation Searches of Neutrino Mass in the Age of Oscillations

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1. Massive Neutrinos and β-Spectrum

The nuclear β-spectrum with emission of $N$ (undetected and not too heavy) massive $\nu$'s is the weighted sum of individual $\beta$-spectra (of $\nu$':s is the weighted sum of individual $\beta$-spectra (unless the mixing of $\nu$'s is too small, that its effect is invisible). We assume that this does not happen; thus, a single parameter describes the modifications of the nuclear β-spectrum. However, we stress again that a single parameter suffices if the spectrum is "not resolved".

The parameter $m^2_{\nu_e}$ can be compared with $M^2_{ee} = |\sum_j |U^2_{ej}| \times m_j \exp(i\xi_j)|^2$ (the ee-entry of the Majorana neutrino mass matrix, squared) that leads to $0\nu2\beta$.

Note that:
- The presence of the Majorana phases $\xi_j$, that can produce cancellations in $M_{ee}$;
- The different dependence on $|U^2_{ej}|$: Individual contributions scale as $\delta M_{ee} = |U^2_{ej}| \times m_j$, while $\delta m_{\nu_e} = |U_{ej}| \times m_j$. Thence, the 1st parameter is more severely suppressed than the 2nd by $|U^2_{ej}|$.

2. The Connection with Oscillations

Mainz and Troitsk Collaborations pushed the limit on $m_{\nu_e}$ down to 2.2 eV, and there are plans under discussion to reach the 200–400 meV level. Being at the Neutrino Oscillation Workshop, it is natural to ask what we expect for $m^2_{\nu_e}$, if neutrino do oscillate. With little algebra:

$$m^2_{\nu_e} = \sum_j |U^2_{ej}| \times m^2_j = \sum_{j>1} |U^2_{ej}| \times \Delta m^2_{ij} + m_1^2 \equiv \delta m^2 + m_1^2$$

(1)
we separate the part of $m_{\nu_2}^2$ that we can obtain from oscillations (namely, $\delta m^2$, which is $\geq 0$) from the rest, irrelevant to oscillations (namely, $m_1^2$, the squared mass of the lightest neutrino).

To proceed, we will consider certain scenarios of oscillations and neutrino mass spectra. Motivated by existing indications of oscillation [1, 2], we select 6 cases with 4-ν ($((N-1)!$ level permutations) and 6 cases with 3-ν (implies to discard one of the indications). The caption of Tab. 1 and two examples should suffice to clarify our terminology: 1) The spectrum SAL is the 4-ν spectrum, where the splitting $\Delta m^2_{21}$ is related to solar neutrinos, $\Delta m^2_{32}$ to atmospheric neutrinos, $\Delta m^2_{43}$ to LSND. 2) The spectrum SA does not account for LSND, and entails 3-ν. We assume that a “sterile” neutrino plays a role, but only in the 4-ν cases. There are 3 main cases:

1. $\Delta m^2$ LARGE. This happens for the 4-ν spectra ALS, LSA, LAS [3], and for the 3-ν spectra AL and LS, where $\delta m = 400 - 1400$ meV. Indeed, the $\nu_e$ state has to stand above the “LSND mass gap”, because it must be involved in the solar doublet of levels, or (only for the AL case) because we know that the atmospheric doublet is mostly $\nu_\mu - \nu_\tau$. This is the most appealing case for the future experiments that aim at finding an effect of massive neutrinos in $\beta$-decay spectra. However, all these 5 spectra might have troubles with SN1987A $\nu$’s [4]. In fact, the mixing of $\vartheta_{e\mu}$ that we need to explain LSND produces resonant MSW conversion [5] of $\nu_\mu$ into $\nu_e$. This implies an average energy of the dominant class of events ($\nu_{e\mu} \rightarrow e^+ n$) significantly larger than expected, that does not seem to be what data suggest.

2. $\Delta m^2$ MEDIUM. There are 5 sub-cases: (1) The first two spectra are SAL and 4SL. For them, $\delta m \sim (\Delta m^2_{lsnd})^{1/2} \times \vartheta_{ee} = 50 - 180$ meV. In fact, the mixing that lead to appearance in LSND is in these schemes [6] $\vartheta_{e\mu} \approx \vartheta_{ee} \times \vartheta_{\mu\mu}$, the product of those mixings that would lead to disappearance in Bugey [7], $\vartheta_{ee}$, and in CDHS [8], $\vartheta_{\mu\mu}$. (The final LSND data do not contradict this, but the bound is almost saturated). (2) Then we have the spectrum LA. $\delta m$ is tunable up to $120 - 180$ meV, since one can arrange the lighter state to be $\nu_1 \approx \nu_e + \vartheta_{ee} \nu_\tau + \vartheta_{e\mu} \nu_\mu$; the mixing $\vartheta_{e\mu}$ is fixed by LSND, while $\vartheta_{ee}$ (that is what matters for us) is only loosely constrained by Bugey. (3) Next case is SL; again, $\delta m$ is tunable. If $\nu_2 = \nu_\mu + \vartheta_{e\mu} \nu_e + \ldots$, $\delta m = 20 - 50$ meV, if $\nu_3 = \nu_\tau + \vartheta_{ee} \nu_e + \ldots$, instead, $\delta m = 120 - 180$ meV. (4) The naive expectation for the SLA spectrum is $\delta m^2 = \Delta m^2_{lsnd} \times \vartheta_{e\mu}^2$, but in fact $\delta m$ can be larger, if:

$$\nu_e \approx n + \vartheta_{e\mu} N + \vartheta_{ee} N_\perp, \quad \nu_\mu \approx N + \vartheta_{\mu\mu} n_\perp - \vartheta_{e\mu} n$$

this case shows that $\delta m^2$ can go up $\Delta m^2_{lsnd} \times \vartheta_{e\mu}^2$ [n is a linear combination of $\nu_1$ and $\nu_2$, $N$ is a

1. This case is special, also because it does not permit to arrange cancellations for $M_{ee}$. In the other four cases, it is instead possible to arrange a cancellation for $0 \nu 2 \beta$, but the solar mixing has to be large.

2. The electron density in the SN core is so large (e.g., when compared with solar densities) that can lead to an MSW resonance for any of the $\Delta m^2$’s, LSND and atmospheric included.
linear combination of $\nu_3$ and $\nu_4$, and the orthogonal states have obvious notations, still keeping the probability of appearance $P_{e\mu} \sim 4 \times \varphi_{e\mu} \times \sin^2 \varphi$, and the probability of disappearance $P_{ee} \sim 1 - 4 \times \varphi_{e\mu} \times \sin^2 \varphi$ (5) Last case is the spectrum $A_S$, where the trivial identification $\delta m = (\Delta m_{atm}^2)^{1/2} = 40 - 80 \text{ meV}$ holds. We remind the reader that this case is among the targets of next generation $0\nu 2\beta$ experiments, indeed $M_{ee}^2 \geq \Delta m_{atm}^2 \times (1 - \sin^2 2\theta_{sol})$. SN1987A bounds can be avoided (at the price of a fine tuning of the relevant mixing).

3. $\delta m^2$ SMALL. This includes only the 3-$\nu$ spectrum $SA$, when $\delta m^2 = \Delta m_{sol}^2 \times |U_{e2}^2| + \Delta m_{atm}^2 \times |U_{e3}^2| = (2.5 - 20 \text{ meV})^2$ (LMA has been assumed). If solar oscillations are confirmed, but MiniBooNE should not support LSND findings, this case would be quite (most?) likely. For easy reference, the results of the discussion above are reported in one table:

Table 1
Summary of the expectations on $\delta m$ (=lower bound on $m_{\nu_e}$ from oscillations, Eq. [4]). The letters of the acronyms stand for $L=\Delta m_{lsnd}^2$, $A=\Delta m_{atm}^2$, $S=\Delta m_{sol}^2$; the order in which they are written (from left to right) indicates how the $\Delta m^2$'s appear in the given neutrino mass spectrum (from lighter to heavier one).

| $\delta m$ [meV] | SPECTRUM |
|-----------------|-----------|
| 400 - 1400      | ALS, LSA, LAS, AL, LS |
| 50 - 180        | SAL, ASL |
| 20 - 180        | SLA, LA, SL |
| 40 - 80         | AS |
| 2.5 - 20        | SA |

3. Discussion
Oscillations lead to consider neutrino mass; this could be related with $\mu \rightarrow e\gamma$, proton decay, etc. But perhaps, the most direct connections are those with the $0\nu 2\beta$ decay, and possible distortions of the $\beta$-decay spectra. In this view, we considered the parameter $m_{\nu_e}^2$ and discussed the expectations on that part of it, $\delta m^2$, related with oscillations (Eq. [3]). We have outlined a troublesome connections of those schemes that predict the largest values of $\delta m^2$ with SN1987A neutrinos. Still, $\delta m^2$ could be relatively large (perhaps observable in future setups) if LSND indications are due to $\bar{\nu}_e$ appearance. This is strictly connected with $\bar{\nu}_e$ disappearance, since the implied mixing $\varphi_{ee}$ is the parameter that matters for $\beta$-decay spectra. If LSND signal is not due to oscillations, $m_{\nu_e}^2$ and $m_{\nu_\mu}^2$ could be identified for practical purposes: Only “quasi degenerate” neutrinos could significantly modify $\beta$-spectra, unless the 50 meV level is attained (which at present seems quite difficult).

In conclusion, we stress again that the expectations for $m_{\nu_e}^2$ are closely related with oscillations: LSND indications of flavor appearance; neutrinos from SN1987A and future type II SN’s; existence of sub-dominant $\nu_e$ mixing... and, in many (but not all) cases, also with the rate of the neutrinoless double beta transition.

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