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Neutrino physics

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Summary. — A brief review of the status of neutrino masses and mixings is presented, with emphasis on Italian contributions to this field of research.

PACS 14.60.Lm – Ordinary neutrinos (ν_e, ν_μ, ν_τ).
PACS 14.60.Pq – Neutrino mass and mixing.
PACS 13.15.+g – Neutrino interactions.

1. – Introduction

Neutrino physics has witnessed a dramatic revolution in the last decade, after the discovery of atmospheric ν_μ oscillations in 1998. Such a breakthrough, as well as further decisive results on ν masses and mixings, have greatly raised the level interest in this field, with $O(10^3)$ "neutrino" preprints released per year, as shown in fig. 1.

The rapid pace experienced in the last few years should not make us forget that neutrino physics is, in general, an exercise in patience. As a matter of fact, the three most basic neutrino questions have been formulated long ago in the past century:

- How small is the neutrino mass?
  (W. Pauli, E. Fermi, '30s);

- Can a neutrino turn into its own antiparticle?
  (E. Majorana, '30s);

- Do different ν flavor change ("oscillate") into one another?
  (B. Pontecorvo; Maki, Nakagawa and Sakata, '60s).

However, only the last question has been positively solved, while hard work is still going on to answer the others. In this talk, I shall briefly review the current status of the field (as of 2009), by using the above questions as a template, and emphasizing recent Italian contributions. For more extensive and detailed overviews, the reader is referred to [1-5], as well as to the book [6] and to the website [7].

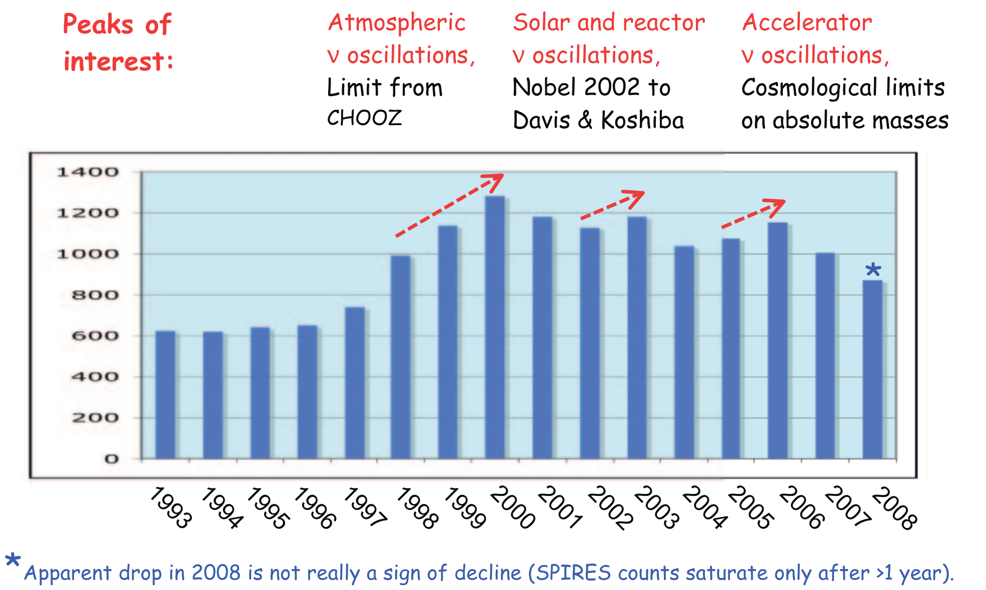

Fig. 1. – Yearly distribution of preprints with "neutrino(s)" in the title, from the SPIRES database. Relevant peaks of interest are also indicated.

2. – Pontecorvo's question: Do different ν flavors oscillate into one another?

The short answer is: Yes. We have learned, from the results of beautiful experiments, that the neutrino flavor states (ν_α) mix with neutrino mass states (ν_i),

$$(\nu_e,\, \nu_\mu,\, \nu_\tau)^T = U(\nu_1,\, \nu_2,\, \nu_3)^T, \tag{1}$$

via a unitary matrix U, parametrized in terms of mixing angles θ_{ij} and a CP phase δ as

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{2}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$.

In general, the oscillation amplitudes are governed by the θ_{ij}'s, while the oscillation phases are determined by the squared mass differences δm^2 and $\Delta m^2 \gg \delta m^2$, defined as

$$(m_2^2,\, m_2^2,\, m_3^2) = \frac{m_1^2 + m_2^2}{2} + \left(-\frac{\delta m^2}{2},\, +\frac{\delta m^2}{2},\, \pm\Delta m^2\right), \tag{3}$$

where the case $+\Delta m^2$ refers to the "normal" (quark-like) hierarchy with $m_3 > m_{1,2}$, while the case $-\Delta m^2$ refers to the "inverted" hierarchy with $m_3 < m_{1,2}$.

Assuming standard interactions, the mass-mixing parameters (δm^2, $\pm\Delta m^2$, θ_{ij}, δ) completely define the ν flavor evolution, even in complicated cases involving forward

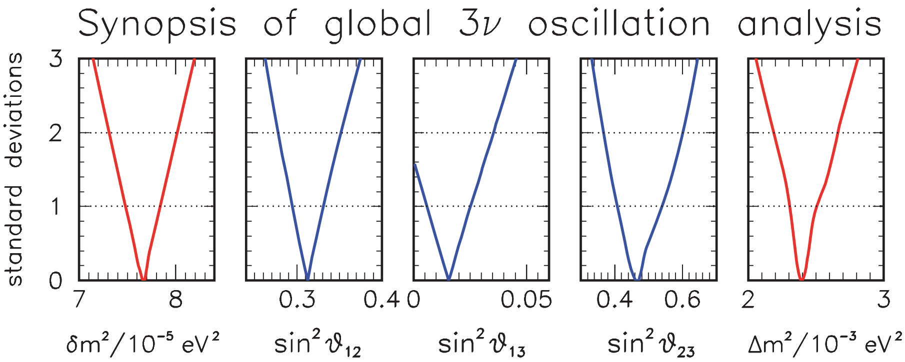

Fig. 2. – Global 3ν oscillation analysis, from [10]: bounds on the mass-mixing oscillation parameters, in terms of standard deviations from the best fit. Note the slight preference for $\sin^2\theta_{13} > 0$.

scattering on fermion backgrounds (provided that their density profile is known). In general, the Hamiltonian H of ν flavor evolution is then the sum of three terms,

$$H = H_{\text{vacuum}} + H_{\text{matter}} + H_{\nu\nu}, \tag{4}$$

where the first one (H_{vacuum}) is kinematical, while the second one (H_{matter}) embeds effects of neutrino interactions in matter (*e.g.*, in the Earth or in the Sun), and the third one ($H_{\nu\nu}$) describes neutrino-neutrino interactions (only relevant in high-density conditions such as core-collapse supernovae [8]).

A more detailed answer to Pontecorvo's question is then: We know several of the oscillation parameters governing H, but not all of them. Indeed, there are robust upper and lower limits on the squared mass differences δm^2 and Δm^2, as well as on the two angles θ_{12} and θ_{23}; however, nothing is known about the mass spectrum hierarchy [sign (Δm^2)] or the CP phase (δ). Equation (2) makes it clear that, in order to access leptonic CP violation, the mixing angle θ_{13} must be nonzero. At present, this angle is bounded from above by the celebrated CHOOZ reactor neutrino data [9] (plus additional, subdominant data from a variety of different experiments [1]), and the possibility that $\theta_{13} = 0$ is still open, although perhaps slightly disfavored (see below).

Figure 2 shows updated results on the mass-mixing parameters, as derived from a global analysis of world neutrino oscillation data [10]. The results are shown in terms of standard deviations n_σ from the best fit (where $n_\sigma = \sqrt{\Delta\chi^2}$ after χ^2 marginalization). Table I summarizes the same results in numerical form.

The parameters (δm^2, θ_{12}), which govern oscillations in the (ν_1, ν_2) sector, are constrained by solar and (long-baseline) reactor neutrino experiments in the ν_e disappearance channel. In this sector, the Borexino solar neutrino experiment at Gran Sasso can also address additional issues [11]: 1) test of H_{matter} in the Sun (already observed); 2) test of radiogenic Earth models via detection of geoneutrinos (in progress); 3) test of the standard solar model via CNO-cycle neutrino detection (under study). The latter test may benefit from accurate cross-section data of astrophysical interest, as measured by the LUNA facility at Gran Sasso [12]. In general, probing the Sun and the Earth interior with neutrinos is an important and interdisciplinary science goal.

TABLE I. – *Global 3ν oscillation analysis, from* [10]*: best-fit values and allowed n_σ ranges for constrained mass-mixing oscillation parameters. The parameters δ and* sign (Δm^2) *are unconstrained by current data.*

Parameter	$\delta m^2/10^{-5}\,\mathrm{eV}^2$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$	$\Delta m^2/10^{-3}\,\mathrm{eV}^2$
Best fit	7.67	0.312	0.016	0.466	2.39
1σ range	7.48–7.83	0.294–0.331	0.006–0.026	0.408–0.539	2.31–2.50
2σ range	7.31–8.01	0.278–0.352	< 0.036	0.366–0.602	2.19–2.66
3σ range	7.14–8.19	0.263–0.375	< 0.046	0.331–0.644	2.06–2.81

The parameters $(\Delta m^2, \theta_{23})$, which drive oscillations in the (ν_2, ν_3) sector, are constrained by atmospheric and (long-baseline) accelerator neutrino experiments in the ν_μ disappearance channel. The expected $\nu_\mu \to \nu_\tau$ appearance signal is currently being tested by the OPERA experiment at Gran Sasso [13]. In this sector, significantly more accurate determinations of the oscillation parameters are expected in the T2K accelerator experiment in Japan, which has just started beam operations (with an Italian participation to the near detector) [14].

In general, better constraints on the ν oscillation parameters are important to discriminate among various theoretical models for the ν mass matrix, see [15] and references therein. For instance, some approximate numerical relations have been noted, including the so-called "tri-bimaximal mixing pattern," $(\sin^2\theta_{12}, \sin^2\theta_{23}, \sin^2\theta_{13}) \simeq (1/3, 1/2, 0)$, and the "quark-lepton complementarity," $\theta^q_{12} + \theta^\nu_{12} \simeq \pi/4$. Do such relations represent accidental facts, or signals of underlying symmetries [15]? More accurate data will help to probe and disentangle different theoretical options, and possibly suggest new ones.

It is worth recalling that, from T2K onward, better or novel determinations of the oscillation parameters may face the problem of "degeneracies" or "clones," namely, of multiple solutions in the oscillation parameter space $(\delta m^2, \pm\Delta m^2, \theta_{ij}, \delta)$. The strategies needed to select the "true" solution (via measurements at different neutrino energies, pathlengths, and oscillation channels) are actively being investigated, in order to optimize the choice of future neutrino facilities and their synergies [16].

The selection of the true hierarchy [sign (Δm^2)] via oscillations might be particularly difficult. In general, one needs to observe an "interference" between oscillation effects induced by $\pm\Delta m^2$ and by another quantity Q entering—with a known sign—the Hamiltonian H of eq. (4). Barring new neutrino states or interactions, there are then only three possibilities: i) $Q = \delta m^2$; ii) $Q =$ matter density; or iii) $Q =$ neutrino density. The first option might be explored, in principle, with very accurate reactor experiments [17], but, in practice, the required sensitivity seems too demanding. The second option might occur via peculiar collective effects on observable supernova neutrino spectra [18], provided that a galactic core-collapse event is detected with high statistics in high-resolution experiments. The third option seems to be accessible in future accelerator beams traversing long paths in the Earth crust (*e.g.*, a T2K upgrade [14] with a far detector in Korea), provided that θ_{13} is not too small.

A measurement of (or better limits on) θ_{13} is crucial to determine not only the mass hierarchy but also future directions in neutrino oscillation physics and in leptonic CP violation searches. For this reason, there is great interest in improving θ_{13} constraints. Recently, it has been observed that atmospheric ν data, as well as solar plus long-baseline reactor data, may provide two weak hints in favor of $\theta_{13} > 0$; their global combination amounts to a 90% CL preference (1.6σ) for $\theta_{13} > 0$ [19], as displayed in the central panel of fig. 2. Shortly before this Workshop, another possible hint in favor of $\theta_{13} > 0$ has been provided (at a roughly similar confidence level) by preliminary $\nu_\mu \to \nu_e$ appearance results in the MINOS accelerator experiment [20]; combining together all such "hints," we get the following best estimate of $\sin^2\theta_{13}$ [21]:

$$\sin^2\theta_{13} \simeq 0.02 \pm 0.01 \quad (\text{All } \nu \text{ data, 2009}). \tag{5}$$

If correct, the above 2σ indication in favor of nonzero θ_{13} may be upgraded to the $\sim 3\sigma$ level by further results from existing experiments [21]. However, the first decisive, direct measurement (or limit) for θ_{13} in the above range is expected in next-generation reactor experiments such as Double-CHOOZ [22], which will exploit a near-far detector combination to improve the sensitivity down to $\sin^2\theta_{13} \simeq 0.01$. (It is an unfortunate circumstance, in my opinion, that the Italian engagement in reactor ν oscillation searches did not proceed after the CHOOZ experience [9].)

3. – How small is the neutrino mass? (Fermi). Is $\nu \equiv \overline{\nu}$? (Majorana)

These two basic—and still unsolved—questions are somewhat entangled. In fact, the only realistic probe of the spinorial nature of massive neutrinos (either Dirac, $\nu \neq \overline{\nu}$; or Majorana, $\nu = \overline{\nu}$) is the process of neutrinoless double-beta decay ($0\nu\beta\beta$), which takes place only for Majorana neutrinos and is also sensitive to their masses [23].

In general, absolute neutrino masses can be probed by three main observables. The first, classical one is the spectral endpoint in β decay, sensitive to the so-called "effective electron neutrino mass" m_β,

$$m_\beta = \left[\sum_i |U_{ei}|^2 m_i^2\right]^{1/2} = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{1/2}. \tag{6}$$

The second observable is the effective "Majorana neutrino mass" $m_{\beta\beta}$ in $0\nu\beta\beta$ decay,

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|, \tag{7}$$

where $\phi_{2,3}$ are additional unknown parameters (Majorana phases). The third observable is the sum of neutrino masses, which affects the formation of large-scale structures in standard cosmology:

$$\Sigma = m_1 + m_2 + m_3. \tag{8}$$

At present, there are only safe upper bounds on these absolute mass parameters, at the eV level for m_β, and in the sub-eV range for $m_{\beta\beta}$ and Σ, see [10] for a recent review.

Various Italian groups are at the forefront of absolute ν mass searches, with important contributions to: i) construction of highly sensitive $0\nu\beta\beta$ decay experiments at Gran Sasso, namely, CUORE [23] and GERDA [24]; ii) leading roles in the recently started PLANCK satellite mission [25], which will measure cosmic wave background anisotropies

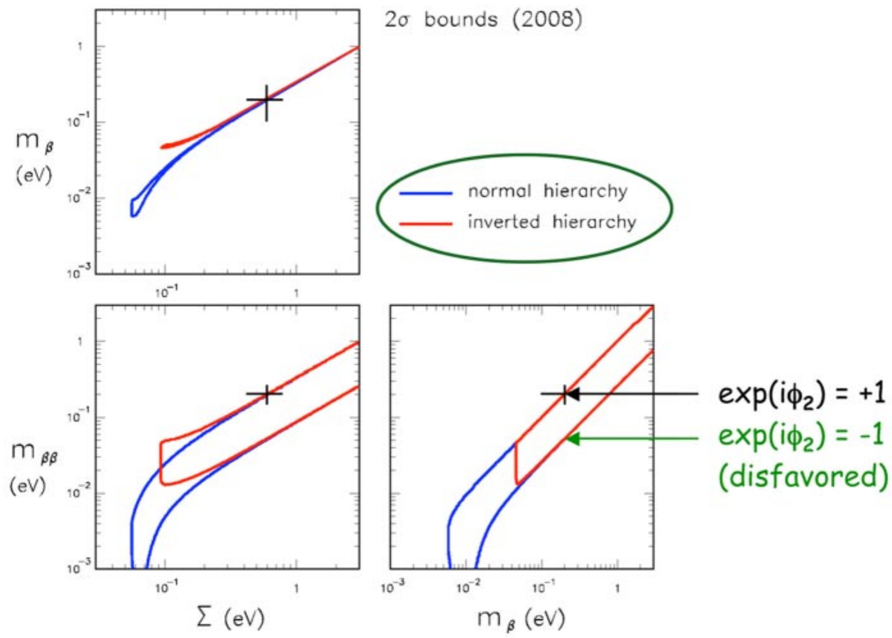

Fig. 3. – (Colour on-line) In each panel, representing a projection of the $(m_\beta,\, m_{\beta\beta},\, \Sigma)$ parameter space, the slanted bands show the regions allowed by current oscillation data at 2σ in normal hierarchy (blue) and inverted hierarchy (red). The crosses represent hypothetical future data according to eq. (9). See [10] and references therein for a discussion of this kind of plots.

and infer cosmological parameters (including Σ) with unprecedented accuracy; and iii) intense R&D activity to reach the deep sub-eV range for m_β with calorimetric techniques in the MARE Project [26].

For small neutrino masses, the observables $(m_\beta,\, m_{\beta\beta},\, \Sigma)$ have, in principle, some sensitivity to the hierarchy, which vanishes in the degenerate mass limit (when all the masses are much larger than their splittings). In the next decade, there are good chances to explore the degenerate and (part of) inverted hierarchy cases, while the normal hierarchy case entails the smallest values of $(m_\beta,\, m_{\beta\beta},\, \Sigma)$ and is, thus, much more challenging.

Let us entertain a very optimistic possibility, namely, that the ν masses are degenerate and just below current limits, *e.g.*, $m_1 \simeq m_2 \simeq m_3 \simeq 0.2$ eV. In this hypothetical case, absolute neutrino mass signals would then be "around the corner," and next-generation experiments could measure, *e.g.*, (with 1σ fractional errors):

$$(9) \quad m_\beta \simeq 0.2\,(1 \pm 0.5)\ \text{eV}, \qquad m_{\beta\beta} \simeq 0.2\,(1 \pm 0.3)\ \text{eV}, \qquad \Sigma \simeq 0.2\,(1 \pm 0.5)\ \text{eV}.$$

These mock nonoscillation data, combined with real oscillation data (see fig. 3) would allow: i) a 25% accurate determination of the absolute ν mass scale at 0.2 eV; and ii) first hints on the Majorana phase ϕ_2 in eq. (7), with a preference for $\phi_2 \simeq 0$ over $\phi_2 \simeq \pi$ for this specific dataset. Therefore, at least in principle, next-generation experiments might provide important clues about both the absolute mass scale and the Majorana nature of neutrinos. Needless to say, progress will be harder for smaller ν masses.

From the theoretical viewpoint, further work is needed to reduce the $0\nu\beta\beta$ nuclear matrix uncertainties at the safe level of $< 30\%$ assumed in eq. (9). Concerning Σ, one should not forget that it comes from a data fit to the standard cosmological model, whose main components (dark energy and dark matter) are still of unknown origin; therefore, the robustness of future Σ constraints should be tested in detail upon model variations.

4. – Conclusions and prospects

In the slow process of solving basic questions, ν physics has recently reached important goals which raised peaks of interest (fig. 1). Future "peaks" may include: further oscillation probes (*e.g.*, ν_τ and ν_e appearance); measurements of the unknown θ_{13}, δ, sign(Δm^2), m_β, $m_{\beta\beta}$, Σ; theoretical understanding of underlying structures. In addition, one should not forget possible surprises (new ν states or interactions) and detection of new astrophysical ν sources [27, 28]—not discussed herein for brevity. The qualified Italian contribution to ν physics will make such progress most interesting.

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