Status of 3ν and 4ν scenarios

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Some aspects of the current neutrino oscillation phenomenology are briefly discussed, with emphasis on the status of mass-mixing parameters relevant for scenarios with three active neutrinos (3ν), and with an additional fourth sterile neutrino (4ν).

1. Introduction

At present, the best evidence in favor of ν oscillations comes from the Super-Kamiokande (SK) atmospheric ν experiment [1], corroborated the MACRO and Soudan2 measurements [2]. The SK data, in general, indicate that (at least) two mass eigenstates (say, ν_j and ν_i) are nondegenerate ($\Delta_{ji} \equiv |m^2(\nu_j) - m^2(\nu_i)| > 0$), and that ν_j is mixed with active flavor states ($\nu_{e,\mu,\tau}$) and, possibly, with a fourth sterile state (ν_s),

$$\nu_j = A_e\,\nu_e + A_\mu\,\nu_\mu + A_\tau \nu_\tau + A_s\,\nu_s \ , \qquad (1)$$

where one has $|A_\mu|^2 \sim O(1/2)$ from the data and $|A_e|^2 + |A_\mu|^2 + |A_\tau|^2 + |A_s|^2 = 1$ from unitarity.

I briefly review some mixing scenarios relevant for atmospheric ν phenomenology, pointing out also their interplay with solar ν's [3] and with LSND [4], as well as some outstanding issues. Such scenarios are parametrized in Table 1, where ψ, ϕ, and ξ are appropriate neutrino mixing angles ($s = \sin$, $c = \cos$), and m^2 is the relevant atmospheric ν squared mass difference ($m^2 = \Delta_{ji}$) in the various cases (see [5–7] for details on the 2ν, 3ν, and 4ν notation).

Assuming 2ν mixing, the present atmospheric data [1] provide us with two solid bounds,

$$2\nu\ (\text{atm.}) \ : \left\{ \begin{array}{lcl} \log_{10} \dfrac{m^2}{\text{eV}^2} & \simeq & -2.5 \pm 0.3 \ , \\ \sin^2\psi & \simeq & 0.50 \pm 0.17 \ , \end{array} \right. \qquad (2)$$

that are not significantly modified [6,7] when passing to 3ν and 4ν scenarios.[1]

[1] It is more appropriate to quote $\sin^2\theta$ (or $\tan^2\theta$) rather than $\sin^2 \mathbf{2}\theta$, especially in contexts where physics can be asymmetric in the two octants of a mixing angle θ [5,6].

Table 1
Atmospheric ν mixing cases considered in this talk.

Case	ν_j	m^2	$\lvert A_e\rvert$	$\lvert A_\mu\rvert$	$\lvert A_\tau\rvert$	$\lvert A_s\rvert$
2ν	ν_2	Δ_{21}	—	s_ψ	c_ψ	—
3ν	ν_3	Δ_{32}	s_ϕ	$c_\phi s_\psi$	$c_\phi c_\psi$	—
4ν	ν_4	Δ_{43}	—	s_ψ	$c_\xi c_\psi$	$s_\xi c_\psi$

Outstanding 2ν issues: (i) Can the m^2 uncertainty be significantly reduced before future long-baseline projects [1,8]? (ii) Is $\nu_{\mu,\tau}$ mixing exactly maximal ($\sin^2\psi = 1/2$) or not? (iii) Besides monotonic μ disappearance, can we also observe one μ disappearance+appearance cycle [9]?

2. 3ν mixing

In atmospheric ν phenomenology, the small squared mass difference $\delta m^2 \equiv |m_2^2 - m_1^2|$ is often neglected. In this case, $m^2 \equiv |m_3^2 - m_{1,2}^2|$ and an extra angle ϕ is needed to describe (ν_e, ν_3) mixing (see Table 1). Detailed analyses of SK data show that the bounds in Eq. (2) are basically preserved for unconstrained ϕ [6], and that an upper limit can be placed on $\sin^2\phi$. Such limit is significantly strengthened by the CHOOZ reactor results:

$$3\nu \quad : \quad \sin^2\phi \lesssim 0.31\ (\text{SK})\ , \qquad (3)$$

$$3\nu \quad : \quad \sin^2\phi \lesssim 0.04\ (\text{SK} + \text{CHOOZ})\ . \qquad (4)$$

The bounds (2)–(4) are compatible with all typical solutions to the solar ν problem. Figure 1 presents the current solutions in the $\nu_{1,2}$ mass-mixing plane $(\delta m^2, \tan^2\omega)$, at fixed values of ϕ ($\omega = \theta_{12}$). Unfortunately, there is still an embarrassing multiplicity of allowed $(\delta m^2, \omega)$ regions

[3,10]. However, such regions typically favor relatively small values of ϕ, thus providing a nontrivial, independent consistency check of the bounds (3,4) in 3ν scenarios.

Outstanding 3ν issues: (*i*) Can SK atmospheric data reveal $\sin^2\phi \neq 0$ [1] ? (*ii*) If $\phi \neq 0$, how far can we push the experimental sensitivity to Earth matter effects [11] and to sign($\pm m^2$) [12–14] ? (*iii*) Are there subleading effects (e.g., CP violation [12–14]) induced by δm^2 on atmospheric ν oscillations (or, conversely, by m^2 on solar ν oscillations) ? (*iv*) Can the multiplicity of solar ν solutions be reduced in the near future [3,15–17]?

3. 4ν mixing

Attempts to reconcile all the solar, atmospheric, and LSND pieces of evidence for oscillations require 4ν scenarios with one sterile neutrino ν_s, and mass spectra of the kind "2+2" [18] or "1+3" [18,19]. In the 2+2 case, the atmospheric ν mixing can be approximately described as in the third line of Table 1, involving the usual $(m^2, \sin^2\psi)$ parameters plus an additional mixing $\sin^2\xi$ [20]. For $\sin^2\xi = 0$ $(=1)$, the atmospheric oscillation channel is purely $\nu_\mu \to \nu_\tau$ $(\nu_\mu \to \nu_s)$; intermediate values of $\sin^2\xi$ correspond instead to mixed active+sterile oscillations. A recent analysis of SK atmospheric results [7,20] in the 2+2 scenario shows that the bounds in Eq. (2) are not significantly modified, and that there is room for relatively large values of $\sin^2\xi$:

$$4\nu:\ \sin^2\xi \lesssim 0.67 \text{ (SK atm.)}. \tag{5}$$

This result shows that, although SK [1] (as well as MACRO [2]) disfavors pure sterile oscillations ($\sin^2\xi = 1$), one could have sizable sterile mixing besides the standard $(\nu_\mu \to \nu_\tau)$ mixing [20].

Independently, one can study how the usual $(\delta m^2, \omega)$ solar ν solutions are modified for generic $\sin^2\xi$ in 4ν models [18]. It turns out that solar ν data prefer relatively large values of $\sin^2\xi$ [18]. One can roughly say that, at present,

$$4\nu:\ \sin^2\xi \gtrsim 0.3 \text{ (solar)}\ , \tag{6}$$

up to variations related to the chosen solution.

Therefore, unlike the 3ν case, the 4ν case shows some "tension" between atmospheric (5) and solar (6) results—not strong enough, however, to prevent their combination. From (5,6) one might get a possible indication for nonzero ν_s mixing,

$$4\nu:\ \sin^2\xi \sim 0.5 \pm 0.2 \text{ (solar + atm data)}\ , \tag{7}$$

which favors maximal amplitude of both active and sterile channels in atmospheric and solar 4ν oscillations ("fourfold maximal mixing" [7]).

Outstanding 4ν issues: (*i*) (*i*) Will the solar-atmospheric data "tension" be weakened or not by future data? (*ii*) Can we detect matter effects associated to ν_s mixing [20] ? (*iii*) How can we discriminate the 2+2 and 1+3 spectra [18,19] ?

4. Conclusions

The bounds from atmospheric 2ν oscillations in the $\nu_\mu \to \nu_\tau$ channel [Eq. (2)] are robust, and are preserved by 3ν and 4ν extensions. In 3ν scenarios, the SK+CHOOZ data provide a bound [Eq. (4)] on the amplitude of ν_e mixing. In 4ν scenarios, the solar+atm data are still compatible with nonzero ν_s mixing within present uncertainties [Eq. (7)]. Further theoretical and experimental work is needed to nail down the atmospheric ν mixing amplitudes in Table 1, as well as to reduce the multiplicity of solar ν solutions in Fig. 1.

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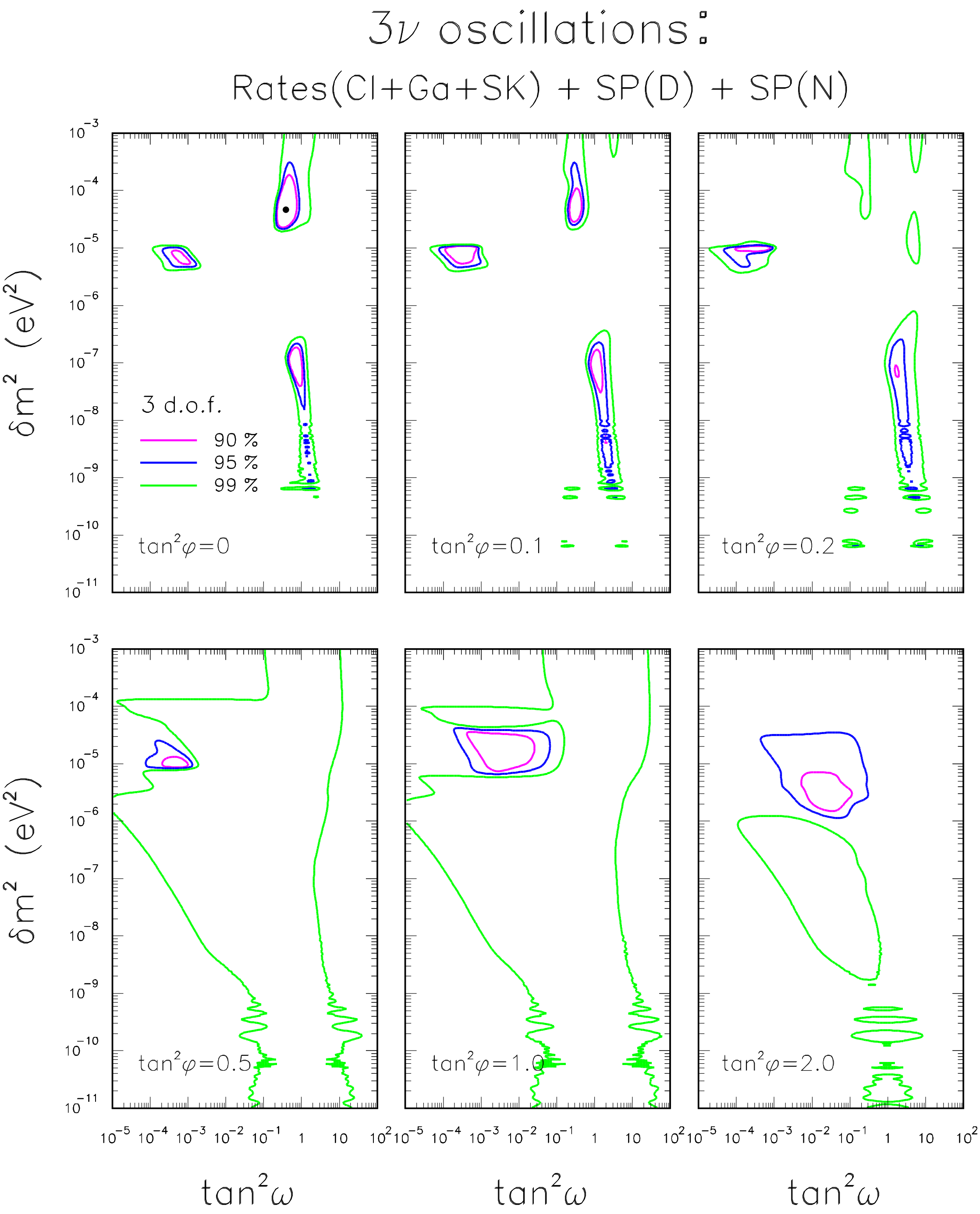

Figure 1. 3ν solutions to the solar neutrino problem for six representative values of the angle $\phi = \theta_{13}$. The case $\phi = 0$ (first panel) corresponds to 2ν oscillations. Data: Rates from Homestake, GALLEX+SAGE+GNO, and SK; day and night energy spectrum from SK (updated as of 2000 summer conferences). Solar Model: BP98 SSM.