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GLOBAL DETERMINATION OF MIXING PARAMETERS FROM SOLAR AND REACTOR NEUTRINOS AND FUTURE PERSPECTIVES

P. Aliani[a], **V. Antonelli**[b,c], R. Ferrari[b,c],
M. Picariello[b,c], E. Torrente-Lujan[d]

(a) Université Libre de Bruxelles, Bruxelles (Belgium)
(b) Dipartimento di Fisica, Università di Milano
(c) INFN, Sezione di Milano
(d) Universidad de Murcia (Spain) and CERN Theory Division

Contents

- Solar and reactor ν played a central role in neutrino physics. Proof that ν are massive and oscillating particles, but still important open questions: exact mixing parameters determination; detailed spectrum analysis; study of the low part of the spectrum.
- The "Solar Neutrino Problem"
  - Pre and post-SNO situation
- The reactor neutrinos
  - KamLAND
- Our analysis:
  - Mixing models
  - Phenomenological study: numerical codes and statistical analysis
- Mixing parameters determination (masses and angles)
- Possible future scenarios
- Comments and conclusions

Solar ν Experiments

- 1st indication of deficit in solar ν reaching the detector from radiochemical experiments: Homestake (since the '70s; β decay by ^{37}Cl) and SAGE, Gallex/GNO (Ga instead of Cl)

- From end '90th confirmation by Kamiokande and SK $\nu_e - e^-$ elastic scattering in H_2O (sensitive only to ν from ^{8}B ed hep)

- SNO. D_2O Cherenkov detector. Simultaneous observation of: (CC: $\nu_e + d \to e^- + p + p$), (NC: $\nu_x + d \to \nu_x + n + p$) and (ES: $\nu_x + e^- \to \nu_x + e^-$).
  - 2001: 1st data from SNO (CC e ES)
  - 2002-2005: New data from SNO (including NC). Salt addition: improvement of NC detection efficiency. ⇒ 1st direct measurement of ^{8}B solar ν flux. Confirmation of SSM validity; proof of oscillation hypothesis and mixing parameters determination

Reactor neutrino experiments

- Well known E and baselines. In a 2 flavor analysis the survival probability for ν ($\bar{\nu}$) of fixed flavor is:

$$P_{ii} = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\,\Delta m^2(eV^2)\,L(Km)}{E(GeV)}\right)$$

- Previous reactor experiments CHOOZ and Palo Verde short and medium baselines ($L \simeq 1Km$) and E of a few MeV: couldn't access mass differences smaller than $10^{-3}eV^2$. No indications of $\bar{\nu}_e$ disappearance. ⇒limitations on the mixing parameters. Upper limit for θ_{13}: ⇒ Double CHOOZ; future generation experiments.

KamLAND

- Reactor $\bar{\nu}$ exp. with medium energy and baseline. $E \geq 1.8MeV$; baseline $\simeq 139 - 214Km$. Expected $\simeq 550$ events/year. Able to test most of LMA.
- Balloon with liquid scintillator, contained with a spherical vessel and surrounded by photomult.
- $\bar{\nu}$ detected via $(\bar{\nu}_e + p \to e^+ + n)$. Time and position coincidence between e^+ signal and the one of neutron capture $(n + p \to d + \gamma(2.2MeV))$.

KamLAND (KL) results

- December 2002: First data published
- Summer 2004:Updated data with increased statistics. 515 days of total live time. Ratio observed/(expected no oscillation) events $R = 0.658 \pm 0.044(stat) \pm 0.047(syst)$.
  Spectrum distortion (at low frequencies) found at 99.6% C.L. → The "No oscillation models" are strongly disfavoured.
  Best fit: $(tan^2\theta, \Delta m^2) = (0.46, 7.9 \times 10^{-5} eV^2)$.
  Future: reducing systematics and increasing statistics KL may improve Δm^2 determination with a factor 2, but the angle discrimination could at most be comparable with the solar one.
- 2005: First detection of geoneutrinos
- Planned ^7Be solar ν detection. Needed further purification for ^{85}Kr and $^{210}Bi/^{210}Po$.

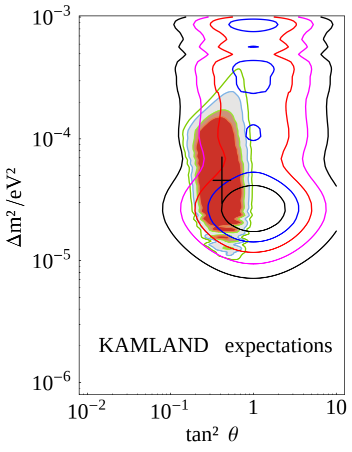
Our Analysis

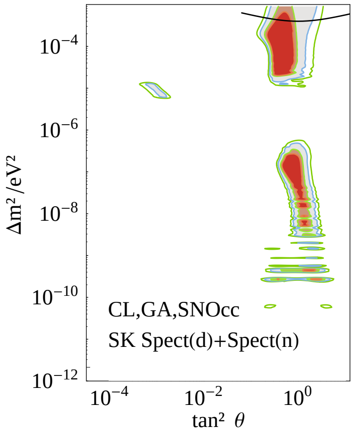
(**NPB** 634 (2002) 393; **PRD** 67 (2003) 013006; **New J. Phys.** 5 (2003) 2; **PLB** 549 (2002) 325; **JHEP** 02 (2003) 025; **AIP Conf. Proc.** 655 (2003) 103; **PRD** 69 (2004) 013005; hep-ph/0309156; cs.ce/0307053; hep-ph/0406182; **NPB** (Proc. Suppl.) 143 (2005) 4833)

- Study of all solar ν and KamLAND data.
- Main aim: -Determine oscillation mixing parameters and potentialities of running and forthcoming experiments.
  Main results: pre and post-SNO mixing parameters determination; predictions for BOREXINO; Study of KL potentialities; analysis of the data of different SNO and KL phases.
- Strategy:
  -ν oscillation hypothesis
  -matter interaction effects for solar ν
  -comparison between the experimental results and the expected signal computed as a function of the mixing parameters
  -statistical analysis with χ^2 method.

Statistical and numerical analysis

- Determination of ν_e transition probability
- Response functions for each detector (efficiency, resolution, cross-sections).
- Ratio between the computed signal and the one predicted by SSM in absence of oscillation.
  $R_i^{th} = S_i^{th}/S_i^{SSM}$, i=Cl, Ga, SK, SNO
- Comparison with exp. ratio and χ^2 analysis
- Determination of χ^2_{min} and search for the mixing parameters satisfying the requirement:
  $\Delta\chi^2 = \chi^2(\Delta m^2, \theta) - \chi^2_{min} < \chi^2_n(C.L.)$
  These are the values allowed at a certain confidence level
- Production of exclusion plots.





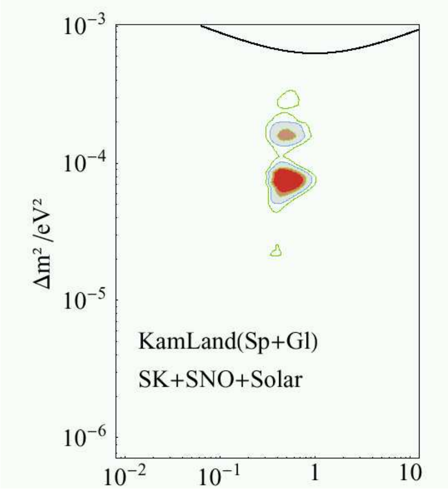
A bit of history

The 2001 situation (lower picture): including all radiochemical and SNO CC global signals and SK energy spectrum before 2002. Colored areas allowed at 90%,95%,99% and 99.7% C.L. .

After 1st SNO-NC data (upper picture): LMA favored. Minimum: $\Delta m^2 = 5.44 \times 10^{-5}$ eV^2; $\tan^2\theta = 0.40$.

Post KamLAND situation

- KamLAND(KL) confirmed the LMA solution of SNP. Combination of first KL and of Solar ν data selected 2 distinct regions inside the LMA: LMA-I $\left(\text{our values } \Delta m^2 = 7.1 \times 10^{-5} eV^2; \quad tan^2(\theta) = 0.47\right)$ and LMA-II



- After new analysis of SK data and mainly new KL and SNO salt data : LMA-II excluded at $\geq$ 99.9% C.L. and maximal mixing excluded at about 5 σ. SNO salt result: flux ratio CC/NC = 0.340 ± 0.023 (stat)$^{+0.029}_{-0.031}$ (syst).

  Combining KL and solar ν data:

  $(tan^2\theta, \Delta m^2) = \left(0.45^{+0.09}_{-0.07}, 8.0^{+0.6}_{-0.4} \times 10^{-5} eV^2\right)$.

Future perspectives

- Up to now and in near future solar and reactor ν only way to determine Δm^2_{12} and θ_{12}. Precise determination: important hints also for future ν factories, superbeams and beta-beams.

- Solar and reactor ν exp. still running: SAGE, SK, SNO:
  - SK detector should be reconstructed (and performance fully recovered) by 2006. Lower E threshold should go down to $\simeq 4$ MeV. Precise measurement of ^{8}B spectrum and eventual effects of non-zero θ_{13} mixing.
  - SNO: In its 3rd phase ^3He prop. counters for NC measurements → detailed study of ^{8}B and hep spectra.

- Up to now cristal clear evidence of oscillation but no clear signal of spectrum distortion and day-night asimmetry by SK and SNO. Important also future Mega-ton class cherenkov detector.

- Solar ν spectrum measured only above 5 MeV so far: E spectrum of more than 99% of solar ν not measured yet. pp and ^{7}Be solar ν measurements essential for the mixing parameters determination. Useful also CNO ν measurements (test of stellar evolution models)

- New solar ν experiments:
  -LENS and MOON (CC exp.)
  -BOREXINO and KamLAND plan to measure ^{7}Be ν
  - other $\nu - e$ scattering experiments: XMASS, HERON, CLEAN
  -idea of replacing heavy water by liquid scintillator at SNO to measure pep and CNO ν

Conclusions

- Solar and reactor ν experiments important in the past, mainly in the last 4-5 years, and still relevant today, both for θ_{12} and Δm^2_{12} determination and for potentialities of other experiments.
- Solar neutrino problem history and recent SK and SNO data. KamLand data.
- Analysis of our gorup: aims, results and strategy. Global analysis of all solar and reactor ν experiments in their different phases and study of their potentialities.
- Evolution of the mixing parameters determination in the last years and discussion of the present situation.
- Future scenarios. Precision neutrino ‘spectroscopy’. Search for signals of spectral distortion and day-nighyt asimmetry. Study of low energy part of solar neutrino spectrum.