IL NUOVO CIMENTO Vol. 37 C, N. 1 Gennaio-Febbraio 2014
DOI 10.1393/ncc/i2014-11701-y

Colloquia: IFAE 2013

Solar neutrino physics: Status and perspectives

V. Antonelli and L. Miramonti

Dipartimento di Fisica Università di Milano e INFN, Sezione di Milano
Via Celoria 16, Milano, Italy

ricevuto l'1 Ottobre 2013

Summary. — In the last decade, following the "annus mirabilis" 2002, solar neutrino experiments and analyses allowed an accurate determination of oscillation parameters and started the study of the lower part of the neutrino energy spectrum. An anomaly seems to show up in the vacuum-to-matter transition region, indicating the need for a more detailed analysis of this part of the spectrum. We discuss the potentialities of present and future experiments to measure the low energy components of the *pp* cycle and the CNO neutrinos and discriminate between the high and low Z solar models, thus solving the metallicity problem.

PACS 26.65.+t – Solar neutrinos.
PACS 96.60.Jw – Solar interior.
PACS 14.60.Pq – Neutrino mass and mixing.
PACS 95.30.Cq – Elementary particle processes.

A change of paradigm took place in the last years in neutrino physics and the attention was focused on appearance experiments and artificial sources. However, solar neutrino experiments continued to produce data. Important results were obtained by SNO II (the salt phase) and SNO III (addition of ^{3}He filled proportional chambers) and the data of SNO I and II were reanalyzed (LETA). A "SNO only" analysis indicates a best fit point in the "LOW" region, but it moves to the usual LMA (Large Mixing Angle) solution after the inclusion of KamLAND and (or) Borexino data. A 2011 SNO three phases combined analysis offered an accurate determination of ^{8}B flux ($5.25 \pm 0.16(\text{stat})^{+0.11}_{-0.13}(\text{syst}) \times 10^6\,\text{cm}^{-2}\,\text{s}^{-1}$), consistent with the Solar Standard Models (SSMs) predictions for both the high and the low Z versions. SuperKamiokande new data and analyses (SK II and III) essentially confirmed SK I studies of day-night asymmetry and of ^{8}B neutrinos energy spectrum and were compatible with SNO results. Since September 2008 SK IV is taking data, with a faster data acquisition system, a reduced error on flux and new event selection parameter. The reactor experiment KamLAND (KL) was essential, using the 2002-'04 data, to exclude the no-oscillation hypothesis at 99.6% C.L. and, with the addition of more data (till '07) and improved analyses, KL measured values of the mixing parameters in agreement with the solar ν experiments, but in slight tension towards higher values of $\tan^2\theta_{12}$ and Δm^2_{12} with respect to the solar analysis.

This tension is reduced considering the 3-flavour oscillation with the value of θ_{13}, different from zero, which has been recently measured at accelerators (T2K and MINOS) and reactors (DAYA-BAY, DOUBLE-CHOOZ and RENO). The extracted values of the mixing parameters were confirmed by the global phenomenological analyses performed in 2012 [1], which showed a general agreement among each others.

All the quoted experiments studied the high energy solar ν spectrum (above 4–5 MeV) and up to 5 years ago the low energy spectrum was studied only by radiochemical experiments. Borexino has been the first real time experiment exploring the sub-MeV region. A first measurement of ^{7}Be signal was performed already after 9 months of data taking and, after the 2009 calibration campaign, the value of ^{7}Be rate was measured as $46.0 \pm 1.5(\text{stat}) \pm 1.3(\text{syst}) \frac{\text{counts}}{\text{day} \times 100\,\text{tons}}$, which still cannot discriminate between the high and low Z SSMs. Borexino also studied the low energy ^{8}B spectrum. The *pep* neutrinos flux, being strongly constrained by the solar luminosity and strictly linked to the *pp* component, is fundamental to test the SSMs. Also CNO neutrinos are essential to determine the solar core metallicity. Despite their relevance, till 2011 no direct measurement of *pep* and CNO neutrinos was available. To measure the electron recoil energy spectrum from *pep* neutrinos, Borexino collaboration developed a new analysis technique, a Three-Fold Coincidence (TFC), to reduce the most challenging background source, the β^+ emitter ^{11}C produced in the scintillator by muons and ^{12}C nuclei interactions. The results published in 2012 were a *pep* rate of $3.1 \pm 0.6(\text{stat}) \pm 0.3(\text{syst}) \frac{\text{counts}}{\text{day} \times 100\,\text{tons}}$, corresponding to a flux $\phi = (1.6 \pm 0.3) \times 10^8\,\text{cm}^{-2}\,\text{s}^{-1}$, and a limit for CNO flux $\phi < 7.7 \times 10^8\,\text{cm}^{-2}\,\text{s}^{-1}$.

The obtained neutrino fluxes are in general agreement with the SSMs. The accuracy on ^{7}Be and ^{8}B fluxes is driven by Borexino and SNO (SK), while *pp* and *pep* determinations mainly come from the luminosity constraint. Most of the fluxes fall in the middle between the high and low Z predictions and hence they cannot be used to discriminate between these two different versions of the SSMs. Despite the steps forward of these years, there is still the need for a clarification of some features of the oscillation mechanism, like the transition between the vacuum dominated and the matter enhanced regions; there seems to be a partial deficit of low energy ^{8}B neutrinos. Moreover a direct *pp* measurement, or at least a more stringent *pep* determination is requested for a more stringent test of SSMs. Important contributions to low energy neutrino spectroscopy could come in the near future from Borexino (thanks to a purification campaign and new signal extraction techniques) and SNO+, a new experiment in SNOLAB using SNO with the substitution of deuterium with liquid scintillator. Taking advantage of the larger mass and rock overburden with respect to Borexino and, therefore, of the better signal/background ratio, SNO+ is expected to reach a 5% accuracy on *pep* flux and interesting results for CNO, that, combined with a better determination of ^{8}B flux, might solve the metallicity problem. In the far future improvements could come by multipurpose experiments, designed to search for neutrinoless double β decay, proton decay and WIMPS, but also suitable to study the low energy part of *pp* and the CNO cycles. Having large masses and high radiopurity, they should reach a lower energy threshold and discriminate a low signal from background, as in the case of next generation scintillators (from the traditional organic with new technological devices to the ones using new materials, like noble gases). The different experiments potentialities are deeply discussed by our collaboration in [2].

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The authors would like to thank C. Pena-Garay and A. Serenelli, who contributed to the analysis on which this paper is mainly based.

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