Frontiers of Low Energy Neutrino Physics and Astrophysics

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Abstract. Low energy neutrino physics and astrophysics has represented one of the most active field of particle physics research over the past decade, accumulating important and sometimes unexpected achievements. After reviewing some of the most recent impressive successes, the future perspectives of this exciting area of neutrino research will be discussed.

1. Introduction

Under the broad characterization of the title of this talk three very active areas of neutrino physics are grouped: solar neutrinos, geo-neutrinos and supernova neutrino detection. In the following I will try to characterize the current status and achievements of each of them, besides highlighting the relevant perspectives in the imminent and long term future.

Solar neutrinos research is a mature field of investigation which over the past four decades has accumulated fundamental successes in the particle physics arena. Originally conceived as a powerful tool to deeply investigate the core of our star, solar neutrinos underwent a very successful detour to particle physics, heavily concurring to the successful demonstration of the neutrino oscillation phenomenon, according to the MSW mechanism [1][2]. The solar experiments were also paramount to determine with high accuracy the Δm_{12}^2 and $\sin^2 \theta_{12}$ parameters of the PMNS mixing matrix governing the oscillation in the solar sector [3], with the recent fascinating promise, stemming from the joint analysis of the reactor and solar data, of an early indication of a non zero subleading θ_{13} angle [4]. Hence this extremely rich and successful chapter of particle physics produced a large part of the solid foundations upon which the next era of precision measurements of the neutrino oscillation parameters will be built. Furthermore, once completed the mission of unveiling the oscillating nature of neutrinos, solar experiments are now back to the original concept of testing the functioning mechanism of the Sun; in this context important insights are awaited from the running and future experiments, of special relevance to address the current issue regarding the surface metallic content of the Sun [5].

Geo-neutrino science, instead, is a much more recent experimental field, though rich of profound potential implications. The suggestion of the possible detection of antineutrino from the intrinsic radioactivity of the Earth dates back to the early times of the first neutrino detection from Cowan and Reines and is due to Gamow. Only 50 years later the reactor antineutrino experiment KamLAND [6] provided the first, and for the moment the only, indication of the observation of antineutrinos from Earth. This pioneering measurement, proving the technical feasibility of geoneutrino detection, paves the way for a series of planned future experiments with the ambitious goal to use the accurate measurements of the antineutrino flux to probe the characteristics of the interior of our planet.

The observation of the neutrino burst from the Supernova 1987A, performed by the Kamiokande [7], IMB [8] and Baksan [9] detectors, represented in the last century a fundamental breakthrough: for the first time the last moments of a dying star were observed through the copious neutrino flux which accompanies such a cosmic thunderstorm. After that, a great deal of studies showed how the accurate determination of the supernova neutrinos can represent an extraordinarily powerful tool to investigate the evolution of the supernova mechanism; this led to the establishment of an ambitious program for the efficient capture of neutrinos from a galactic star explosion, which not only sees a growing number of experiments potentially able to perform such a task, but also their strategic alliance in a worldwide network, SNEWS, which will greatly enhance the probability of a successful detection of the eagerly awaited "galactic firework", when it will occur.

2. Solar neutrinos

It is now well known, after several decades of theoretical and experimental investigations, that neutrinos are abundantly produced in the core of the Sun. They originate from the nuclear reactions that power our star, producing the energy required to sustain it over the billions of years of its life. Two different chain reactions occur at the temperatures characteristic of the core of the Sun, the so called pp chain and CNO cycle, respectively. Actually for the sun the vast majority of the energy (>98%) is coming from the pp chain, while the CNO contribution is estimated to less than 1.6 %.

The effort to produce a model able to reproduce fairly accurately the solar physical characteristics, as well as the spectra and fluxes of the several produced neutrino components, was led for more than forty years by John Bahcall [10]; this effort culminated in the synthesis of the so called Standard Solar Model (SSM), which represents a true triumph of the physics of XXth century, leading to extraordinary agreements between predictions and observables. Such a beautiful concordance, however, has been somehow recently spoiled as a consequence of the controversy risen regarding the surface metallic content of the Sun, stemming from a more accurate 3D modeling of the Sun photosphere. Therefore, there are now two versions of the SSM, according to the adoption of the old (high) or revised (low) metallicity of the surface [11].

From the experimental side, solar neutrino experiments also represent a successful 40 years long saga, commenced with the pioneering radiochemical experiments, i.e Homestake, Gallex/GNO and Sage, continued with the Cerenkov detectors Kamiokande/Super-Kamiokande in Japan and SNO in Canada, and with a last player which entered very recently the scene, Borexino at the Gran Sasso Laboratory, which introduced in this field the liquid scintillation detection approach.

It is well known that for more than 30 years the persisting discrepancy between the experimental results and the theoretical predictions of the Solar Model formed the basis of the so called Solar Neutrino Problem, which in the end culminated with a crystal clear proof of the occurrence of the neutrino oscillation phenomenon, via the MSW effect. In particular, the joint analysis of the results from the solar experiments and from the KamLAND antineutrino reactor experiment pin points with high accuracy the values of the oscillations parameter within the LMA (large mixing angle) region of the MSW solution [3].

So, given this epochal achievement, which surely makes the solar neutrino study one of the more productive particle physics area over the past decade, one may wonder if there are future interesting perspectives for this field, and if yes, which they are. In the following I will illustrate the answer to this question by browsing through the main existing and planned solar experiments, underlining the future plans of each of them.

2.1 Borexino

I start this review with the most recent project, Borexino at the Gran Sasso Laboratory [12], a scintillator detector which employs as active detection medium 300 tons of pseudocumene-based scintillator. The intrinsic high luminosity of the liquid scintillation technology is the key toward the goal of Borexino, the real time observation of sub-MeV solar neutrinos through νe elastic scattering, being the ^{7}Be component the main target. However, the lack of directionality of the method makes it impossible to distinguish neutrino scattered electrons from electrons due to natural radioactivity, thus leading to the other crucial requirement of the Borexino technology, e.g. an extremely low radioactive contamination of the detection medium, at fantastic unprecedented levels.

The active scintillating volume is observed by 2212 PMTs located on a 13.7 m diameter sphere and is shielded from the external radiation by more than 2500 tons of water and by 1000 of hydrocarbon equal to the main compound of the scintillator (pseudocumene), to ensure zero buoyancy on the Inner Vessel containing the scintillator itself. Of paramount importance for the success of the experiment are also the many purification and handling systems, which were designed and installed to ensure the proper manipulation of the fluids at the exceptional purity level demanded by Borexino.

When data taking started in May 2007, it appeared immediately that the daunting task of the ultralow radioactivity was successfully achieved, representing *per se* a major technological breakthrough, opening a new era in the field of ultrapure detectors for rare events search.

The exceptional purity obtained implies that, once selected by software analysis the design fiducial volume of 100 tons and upon removal of the muon and muon-induced signals, the recorded experimental spectrum is so clean to show spectacularly the striking feature of the ^{7}Be scattering edge, i.e. the unambiguous signature of the occurrence of solar neutrino detection.

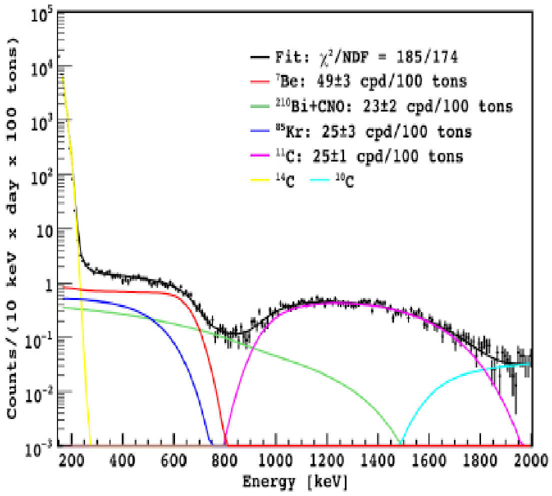

Figure 1. Fit of the experimental Borexino spectrum

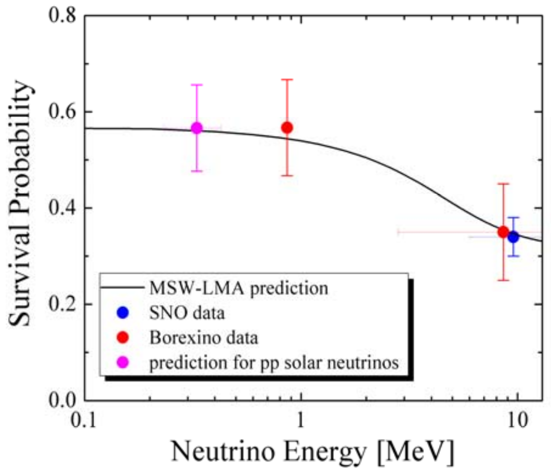

Figure 2. Low energy validation of the MSW-LMA solution provided by Borexino

For the quantitative extraction of the ^{7}Be flux, the spectrum is fitted to a global signal-plus-background model. The fit output for the 192 days data sample released up to now by the Collaboration [13] is reported in Fig. 1 (the results in the legenda are conventionally expressed in counts/day/100 tons of scintillator). Taking into accounts the systematic uncertainties, the ^{7}Be evaluation is 49 ± 3_{stat}± 4_{sys} counts/day/100 tons, hence a 10% precision measurement, which translates into a ^{7}Be flux of (5.08 ± 0.25) $\cdot 10^{9}$ cm^{-2}s^{-1}, very well in agreement with the prediction of the BPS08(GS98) Standard Solar Model [11]. For comparison, the detected count rate in case of absence of oscillations would have been 74 ± 4 counts/day/100 tons. The resulting electrons survival probability at the ^{7}Be energy is P_{ee}=0.56± 0.10.

In Fig. 2 the MSW predicted P_{ee} is shown, together with three experimental points, i.e the ^{8}B from the previous Cerenkov data, the ^{7}Be Borexino point and the pp datum as drawn by the comparison of Borexino with the Gallium experiments: altogether from this figure we can conclude that Borexino on one hand spectacularly confirms the MSW-LMA solar neutrino oscillation scenario, and on the other provides the first direct measurement of the survival probability in the low energy vacuum MSW regime.

Other measurements provided by the experiment in its first two years of operation, and discussed in [14], are the ^{8}B spectrum with a threshold as low as 2.8 MeV, the absence of day-night asymmetry (as predicted by the MSW-LMA solution) in the ^{7}Be region, and a limit on the neutrino magnetic moment at the level of 5.4 x 10^{-11} μ_B.

Many further solar measurements are prospectively possible in the next years of running of the detector. ^{7}Be can be pin pointed to an accuracy of 5% (with respect to the 10% uncertainty of the measurement reported here), providing the final, high accuracy, low energy validation of the MSW-LMA solution; moreover the statistics of the ^{8}B neutrino study will be increased, and the possibility to investigate the extremely challenging pep and CNO fluxes will be pursued. This last task will require to cope with the background represented by the ^{11}C cosmogenic signals, exploiting the triple fold coincidence strategy already devised by the Collaboration in [15].

Finally, the extremely low ^{14}C level, coupled to the good achieved energy resolution, opens also a possible exploration window between 200 and 240 keV in which the observation of the fundamental pp flux can be attempted.

2.2 Solar Neutrino Observatory

The SNO (Solar Neutrino Observatory) experiment [16], located in Sudbury, Canada, is now completed, with the heavy water being returned to the owner until the very last drop. Based on multiple CC, NC and elastic scattering detection of solar neutrinos, the key advance provided by SNO in the field was the model independent proof that neutrinos from the Sun undergo flavour conversion. The experiment evolved through three phases, characterized by different detection procedures of the neutrons signalling the occurrence of the neutral current reactions: a pure heavy water phase, a salt phase and the final ^{3}He counters stage.

The estimated NC, CC and ES fluxes over the three phase are statistically in agreement, with the exception of the ES measure of the ^{3}He stage, lower than the previous results, but consistent with being a downward statistical fluctuation. Also, in the latest ^{3}He measurement procedure the ratio NC/CC resulted equal to 0.301 ±0.033, slightly lower than the previous phases. While including these updated data in the global solar + KamLAND analysis, the SNO collaboration finds $\Delta m^2 = 7.59^{+0.19}_{-0.21} \times 10^{-5} eV^2$, $\phi_{8B} = 4.91 \times 10^6 cm^2 s^{-1} (\pm \approx 7\%)$ and $\theta_{12} = 34.4^{+1.3}_{-1.2}$ deg [3]. It has to be noted, in particular, that the error on the θ_{12} angle has been reduced of almost a factor two by the ^{3}He measurement, as effect of the different systematic and minimal correlation of the NC and CC measures in this phase.

Despite the fact that the SNO measurements are over, still very important outputs are expected from the further study of the accumulated data. In particular the Collaboration is now focused to the so called LETA (low energy threshold) analysis, whose purpose is to push the analysis threshold down to 3.5 MeV (electron kinetic energy). To do so it is required to model accurately down to that energy the several background components, they are 17, that can be identified within the data and which accompany the three CC, NC and ES signal components. In Fig.3 how such a modelling can be accomplished is shown on a basis of a Monte Carlo estimate. More insights in this exciting possibility are expected from the talk of SNO [17].

It should be added that the LETA analysis will be extremely beneficial on one hand in further tightening the error both on θ_{12} and on ϕ_{8B} , and on the other, in the context of a full 3 ν analysis, in shedding more light on the recently emerged hint [4] for a non zero θ_{13} .

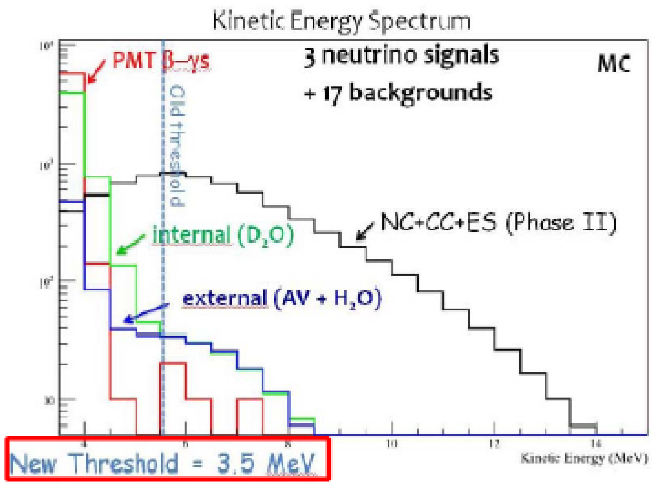

Figure 3. Perspectives for threshold reduction in the SNO analysis

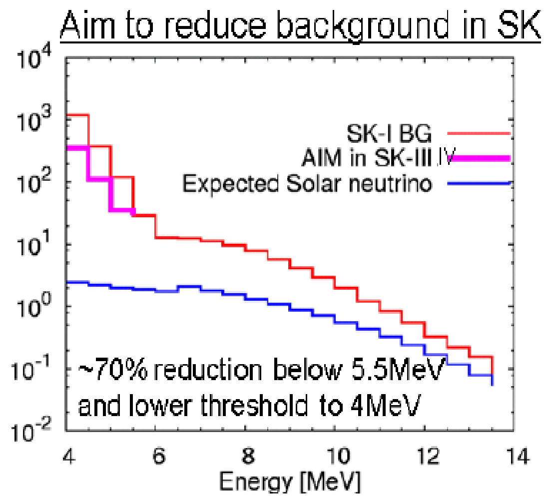

Figure 4. Perspectives for threshold reduction in the future SK data taking

2.3 Super-Kamiokande

Super-Kamiokande [18] is still currently taking data. The long history of this detector started in 1996 and evolved through four phases: the first phase lasted until the PMT incident of November 2001 and produced the most accurate measure up to now of the ^{8}B flux via the ES detection reaction. The phase II with reduced number of PMTs, from the end of 2002 to the end 2005, confirmed with larger error the phase I measurement. After the refurbishment of the detector back to the original number of PMTs, the third phase lasted from the middle of 2006 up to the middle of 2008. After that, an upgrade of the electronics brought the detector into its fourth phase, ready for the T2K beam experiment. It is important to highlight the evolution of the energy threshold (total electron energy) in all the phases: 5 MeV in phase I, 7 MeV in phase II, 4.5 MeV in phase III and 4 MeV targeted for phase IV.

The reduction of the threshold for ^{8}B acquisition and analysis is crucially linked to the radiopurity of the detector, being the radon in the Fiducial Volume the main limitation in this respect. Analysis of the data of the phase III is very promising in term of finally achieving the 4.5 MeV threshold, while the Collaboration is working further on the background to reach the ultimate goal of 4 MeV in the phase IV. Fig. 4 exemplifies the background suppression already achieved in the FV.

The low energy threshold results that Super-Kamiokande will eventually produce will be, similarly to what illustrated for SNO, of paramount importance to further probe the LMA-MSW solution, in particular if the expected upturn of the low energy portion of the ^{8}B spectrum will be identified. It is worth remind that such an up-turn is the expected imprint on the spectrum of the transition of the electron survival probability from the high energy matter-dominated region to the low energy vacuum-driven regime. Said in other words, the low threshold determination of the ^{8}B spectrum is a way to probe directly the transition portion of the survival probability curve.

In the framework of this effort, the Collaboration plan to reach a 2 sigma level of discovery (or exclusion) of the spectrum upturn after two years of data taking in the phase IV with reduced background [19].

2.4 Gallium experiments

In this review of the current status of the solar experiments it cannot be forgotten the important role still played by one of the pioneering Gallium experiments, Sage, which is continuing taking data at the Baksan Laboratory. Based on 50 tons of metallic Gallium, after 18 year of data taking the cumulative result is of $65.4^{+4.0}_{-4.1}$ SNU (Solar Neutrino Units), mainly due to the contribution of pp neutrinos. Extractions continue regularly every 4 weeks. The Sage results can be combined with those of the Gallex and GNO experiments at Gran Sasso (now over) 67.5 ± 5.1 SNU , giving as grand result of the Gallium experiments 66.1 ± 3.1 SNU, to be compared with the SSM prediction of $126.^{+9}_{-7}$ SNU [20][21].

The experiments have been calibrated respectively with ^{51}Cr (Gallex) and ^{37}Ar (Sage) sources. Interestingly, in both cases the ratio of the measured over predicted rates is substantially less than unity, e.g. 0.88 ± 0.08 for Gallex and 0.86 ± 0.08 for Sage. The combined value of 0.87 ± 0.05 deviates from 1 more than two sigmas. Although not statistically conclusive, the combination of these experiments suggests that the predicted rates is overestimated. The most likely hypothesis is that the cross sections for neutrino capture to the lowest two states in ^{71}Ge, both of which can be reached using either ^{51}Cr or ^{37}Ar sources, have been overestimated.

A new source experiment in SAGE will shed light on such an inconsistency. For this it is necessary to arrange a ^{51}Cr neutrino source with activity of 2 MCi or higher, an optimized two-zone spherical target in the detector, and to carry out the measurement with an accuracy of 4 − 4.5%. These goals are part of future experimental program in SAGE [22].

2.5 Future experiments

A series of new solar experiments are being planned or prepared, with some of them likely ready to produce very interesting new results in the imminent future, e.g. KamLAND and SNO+.

KamLAND, after the epochal results achieved with the reactor antineutrino experiment [23], is aggressively moving towards the solar phase of its program. To do so the Collaboration requires to suppress the otherwise overwhelming low energy background, which would definitively prevent the identification of solar neutrinos. The achievement of this target is based upon the on-line purification of the liquid scintillator via a dedicated purification system: two purification cycles have been already accomplished, bringing the background to a level close to that needed specifically for the detection of ^{7}Be neutrinos. The collaboration is actively debating whether to continue with the purification or start the measure without further actions on the scintillator, resorting to the analysis for the final discrimination between the solar signal and the background. Anyhow, independently from this decision, KamLAND will be very likely the second experiment after Borexino to produce sub-MeV real time detection of solar neutrinos.

The first target of the detector are the ^{7}Be neutrinos, followed by the pep and CNO neutrinos, for which a special deadtimeless electronics has been installed, able to detect with high efficiency neutrons and thus providing the basis for the triple fold coincidence mentioned above, in the framework of Borexino, for ^{11}C suppression.

SNO+ [24] is the new experiment that will replace SNO. It is a liquid scintillator detector, as well, that can go on line soon thanks to the massive re-use of the SNO hardware. In particular the adoption of a new liquid scintillator, linear alkyl benzene, featuring the great advantage of being acrylic-compatible, will allow the re-use of the SNO acrylic vessel. Only the support system will have to be built from scratch in order to cope with the different buoyancy condition with respect to the heavy water situation. The other major piece of equipment to realize is the purification system. The project has been funded for these major items on June 2009, with the perspective to start data taking in 2011. The solar phase will be targeted mainly to pep and CNO detection, profiting of the depth of SNOLAB which suppress enormously the cosmogenic ^{11}C background. It should be, however, highlighted that the main goal of SNO+ will be the double beta decay with Neodymium dissolved in the scintillator, and currently it is not yet decided whether the solar phase will come before or after the Neodymium phase.

While KamLAND and SNO+ represent the imminent and near future perspectives for new sub-MeV solar neutrino results, it should be mentioned that there are other experiments in the R&D phase with great potentialities for future interesting outputs in this field. In this framework a special mention is due to LENS [25], which is the modern version of the old brilliant idea for an Indium experiment. The experimental tool used for the detection of solar neutrinos is the tagged capture of ν_e's on ^{115}In via charged current : $\nu_e + ^{115}In \rightarrow ^{115}Sn^* + e^- \rightarrow ^{115}Sn + 2\gamma$. The low Q of the reaction (114 keV) allows in principle the full solar neutrino spectroscopy, including the pp neutrinos, see Fig. 5. Time and space coincidence, the former intrinsic to the detection reaction and the latter realized via a granular detector design, will be the key to suppress the radioactive backgrounds as well as the inherent background from the beta decay of ^{115}In. R&D results very promising in term of stability of the Indium loaded scintillator and background rejection have been recently presented [26].

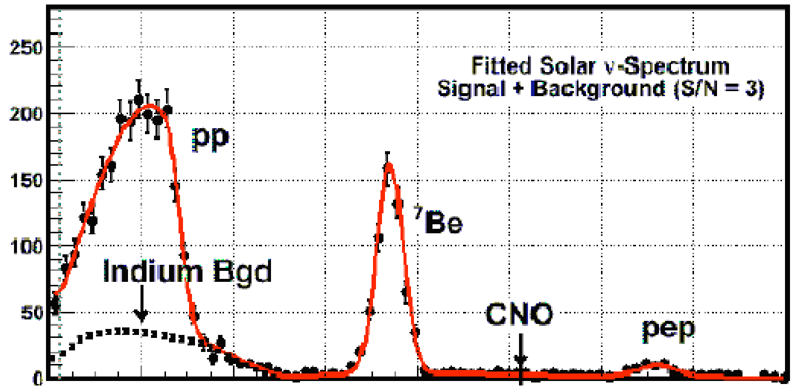

Figure 5 – Solar spectrum as would be detected by LENS

Other three projects that deserve to be mentioned are CLEAN, XMASS and MOON. They are multidisciplinary projects which have within their potential physics reaches double beta decay, dark matter and solar neutrino investigations.

The basic idea of CLEAN [27] is to take advantage of the fact that both neon or argon scintillate when exposed to radiation. When an energetic charged particle (such as the recoil from a neutrino-electron scattering event) passes through the liquid noble gas, it will produce scintillation light in the extreme ultraviolet range, that can be detected using a combination of a wavelength shifting fluor and a photomultiplier tube. Liquid neon has a number of advantages for detecting neutrinos or other weakly interacting particles. Because neon has no long-lived isotopes, it has no inherent radioactivity to create backgrounds in a sensitive detector. This separates neon from heavier noble gases which do contain radioactive isotopes and from organic scintillator materials which inevitably contains beta radiation from ^{14}C. Neon also has very low binding energies to a variety of surfaces, allowing it to be effectively purified of radioactive contaminants using cryogenic traps. Another advantage is its relative density compared to liquid helium; neon can be used efficiently as a self-shielding medium, while also allowing a smaller detector volume. These characteristics render neon a well suited choice as a neutrino detection medium.

The current effort of the Collaboration is towards the installation within 2009 of a 360 kg detector for dark matter investigation at SNOLAB. In perspective, a 50 tons device targeted especially to the pp solar neutrino detection could be installed at the planned DUSEL underground facility in US.

The original concept of XMASS was proposed in 2000 [28] as a multi-purpose astroparticle and neutrino experiment. A liquid Xenon detector with a 10 ton effective mass can look for dark matter and double beta decay and can also measure solar pp-neutrinos through neutrino electron scattering, as much as CLEAN. As a phase-I experiment, a small scale detector dedicated to look for dark matter, where the mass of the inner volume surrounded by PMTs is 857kg and the fiducial mass is 100~200kg, is being prepared and installed at the Kamioka mine in Japan.

The double beta decay and solar neutrino project MOON [29] is based on ^{100}Mo. The merits of using ^{100}Mo for solar ν's study are the large capture rate and the high selectivity for the low energy ν's. The low threshold energy of 0.168 MeV and the large response for the solar-ν absorption allow observation of low energy sources such as pp and ^{7}Be. The pp and ^{7}Be ν's are captured only into the ground state of ^{100}Tc. The solar ν signal can be selected by requiring delayed coincidence with the successive β decay of ^{100}Tc, and thus natural and cosmogenic backgrounds are reduced substantially.

Research and development programs of solid and liquid scintillators for the MOON detector are in progress. A possible option for the solid scintillator is a supermodule of hybrid plate and fiber scintillators. One module consists of a plate scintillator and two sets of X-Y fiber scintillator planes, between which a thin ^{100}Mo film of about 20 - 50 mg cm^{-2} is interleaved. The fiber scintillators coupled with multi-anode photomultiplier tubes (PMT's) enable one to get the necessary position resolution, the scintillator plate (X-Y plane) with multiple PMT's at both X and Y sides provides an adequate energy resolution to satisfy the physics goals.

3. Geoneutrinos

Geo-neutrinos, the antineutrinos from the progenies of U, Th and ^{40}Kdecays in the Earth, bring to the surface information from the whole planet, concerning its content of radioactive elements. Their detection can shed light on the sources of the terrestrial heat flow, on the present composition, and on the origins of the Earth.

Although geo-neutrinos were conceived very long ago, only recently they have been considered seriously as a new probe of our planet, as a consequence of two fundamental advances that occurred in the last few years: the development of extremely low background neutrino detectors and the progress on understanding neutrino propagation.

Geoneutrinos potentially can unlock many interesting unanswered questions regarding our planet: what is the radiogenic contribution to terrestrial heat production? How much is the content of U and Th in the crust and in the mantle, respectively? What is hidden in the Earth's core, e.g a geo-reactor or ^{40}K, etc? And finally, is the standard geochemical model (denoted as BSE) consistent with geo-neutrino data?

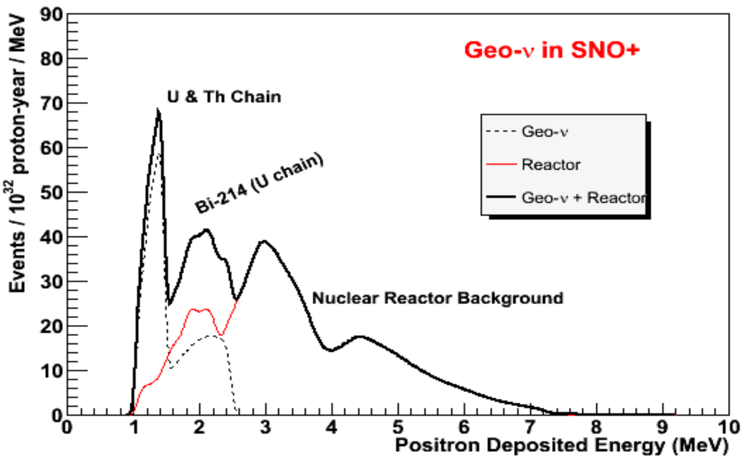

Figure 6. Example of a typical expected geoneutrino spectrum in a scintillation detector, together with the reactor background

In particular this last question would ideally require multiple measurements carried out in several locations of the Earth's surface, to be compared with the theoretical predictions of geoneutrino flux (different groups performed such calculations, which are each other in agreement at the 10% level [30][31][32]).

A dangerous potential background for geoeneutrinos are anti-neutrinos from reactor; in Fig. 6 the global spectral expectation for a standard scintillator detector is shown (the example is drawn for SNO+).

The first and for the moment the only published geoneutrino measure comes from the KamLAND scintillator experiment [6]. The detection occurs via the classical inverse beta reaction $\overline{\nu_e} p \rightarrow e^{+} n$, signaled by the delayed 2.2 MeV gamma stemming from the subsequent neutron capture on protons. In terms of Terrestrial Neutrino Unit, a geoneutrino unit similar to the solar SNU unit, the flux measured by KamLAND is equal to $38.9^{+14.4}_{-14.2}$ TNU, corresponding to 75 ± 27 geoneutrino events both from the U and Th chain. This results compares well with the model prediction of 36.9 TNU, though the uncertainty is large, at the level of 37%.

The main virtue of the pioneering result of KamLAND is the demonstration that geoneutrinos can be detected, opening the door to the a completely new branch of geosciences. In the future other experiments are expected to confirm the neutrino detection from KamLAND. Borexino is supposed to be the first, being already running and thus accumulating geo-neutrino events, with the Collaboration intending to release the data when a solid three sigma evidence will be achieved.

But many other planned large scintillator detectors (e.g. SNO+, LENA, HANOHANO, EARTH…) have geo-neutrino measurements among their primary goals (a recent review is presented in [33], se also [34]), thus the coming years will likely see the rapid growth of this innovative way to study our planet.

4. Supernova neutrinos

On February 23, 1987 the Kamiokande [7], IMB [8] and Baksan [9] detectors recorded for the first (and up to now the only) time a pulse of neutrinos from a supernova, the famous SN1987A. Despite the small number of recorded signals, 11, 8 and 5 respectively, plenty of information were squeezed from them, providing substantial confirmations and new insights on the supernova mechanism. On the basis of this success, it can be anticipated that further deep insights and details of the supernova birth and evolution will be gained when the next burst will be observed, especially if the supernova will occur at the typical galactic distance from the Earth of 10 kpc, compared to the 50 kpc distance of the SN19877A, which indeed was located in the Large Magellanic Cloud.

A number of multipurpose detectors, some already running and some still in the construction phase, will detect the next supernova neutrinos. Among the current detectors, Superkamiokande is surely the largest with its 32000 tons of water. For a 10 kpc distant supernova it will observe about 7300 $\overline{\nu_e} p \rightarrow e^+ n$ events, ~300 $\nu + e \rightarrow \nu + e$ scattering events, ~360 ^{16}O neutral current gamma events and ~100 ^{16}O charged current events. The scattering events will identify the supernova direction with an accuracy of about 5°. The large statistics of inverse beta events, instead, will allow the precise energy spectrum measurement, enabling the possibility to discriminate among various proposed models.

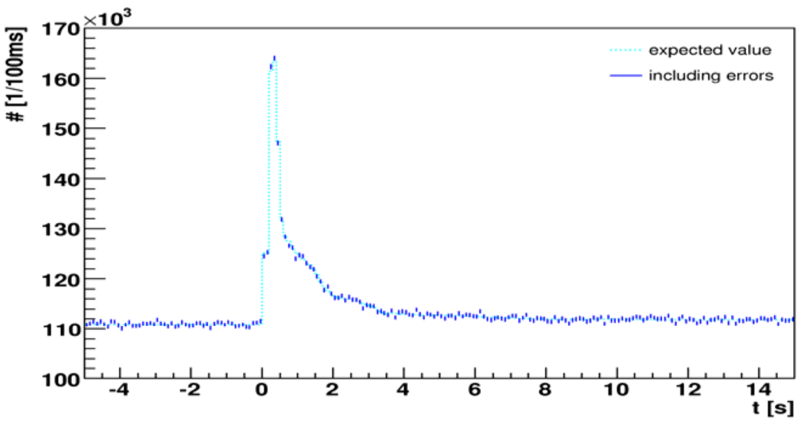

Figure 7. Simulation of a neutrino burst at the IceCube detector for a 10 kpc distant supernova

At Gran Sasso since 1992 the LVD detector is in operation: it is a segmented liquid scintillator type apparatus with 840 counters and a total target mass of 1000 tons. It can detect about 300 $\overline{\nu_e} p \rightarrow e^+ n$ events for the reference 10 kpc supernova . The energy threshold of the counter is 4 MeV and it can tag neutrons with an efficiency of 50 ±10%. The online trigger efficiency is more than 90% for a distance less than 40 kpc.

KamLAND, Borexino and the future SNO+ are single volume liquid scintillation detectors with 1000, 300 and 1000 tons of detection medium, respectively. They feature several interactions channels; by normalizing the expected number of events for a 10 kpc supernova to a target mass of 1000 tons, the predictions are ~300

$\overline{\nu_e} p \rightarrow e^+ n$ events, several tens of CC and NC events on ^{12}C and about 300 $\nu p \rightarrow \nu p$ NC events. This last interaction, being not affected by neutrino oscillations, has the very interesting capability to measure the initial spectrum originated by the supernova explosion.

The South Pole IceCube detector has a giga-ton target volume, with the photosensors arranged in a three dimensional structure. The entire inventory of strings (75) will be deployed by 2011. In this detector the observation of a supernova burst will not occur via individual neutrino observation, but through the coherent increase of the PMT dark noise. As a consequence, the detector can measure the time variation of the energy release fairly accurately, see Fig. 7.

Finally, it has to be highlighted that Super-Kamiokande, LVD, IceCube and Borexino are part of the SNEWS consortium (Supernova Early Warning System), which, upon detection of a neutrino burst, sends prompt alerts to astronomers to trigger the optical observation of the potential identified source. More detailed information on this topic can be found in [35].

5. Conclusion

Low energy neutrino physics and astrophysics is a field that, despite the many successes already accumulated, is promising for the future many more exciting results.

Solar neutrino investigation is reaching the stage in which the precise spectroscopy of the whole low energy spectrum is a real possibility, up to a level that makes it feasible the check of the SSM, hence paving the path for resolving the discrepancy between high Z and low Z models

An entire new area of investigation is represented by the geoneutrinos study, which exploits the more powerful detectors aimed at the solar neutrino detection to open a completely new window on the mysteries of the interior of the Earth

Supernova neutrino experiments are already a powerful large family with new members expected to join in the near future, and hence if Nature will arrange for us a “galactic firework”, surely we will not miss the fun!

6. Acknowledgements

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