Study of Low Energy Neutrinos From Sun and Earth With Borexino

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Abstract

The Borexino is a unique detector able to study neutrino interactions with a threshold below 1MeV thanks to the unprecedented radiopurity reached by it. So it has been possible to measure for the first time the solar neutrino fluxes from the ^{7}Be and pep nuclear reactions and consequently to study the neutrino oscillation in vacuum and in the transition region. The neutrinos from ^{8}B with a lower threshold down to 1 MeV has been also measured and an upper limit of the flux from the CNO cycle has been reached . The measurement of these fluxes allowed a good check of the Solar Standard Model predictions.

Finally Borexino has obtained evidence of geoneutrinos with 4.2 sigma confidence level.

1. Why the solar neutrinos ?

I would like first of all to set the study of the solar neutrinos within the physics framework and to explain why this issue has been and is so important in order to understand two crucial problems in the astro-particle physics: the *Sun physics* and the *Neutrino physics*.

During about 40 years John N. Bahcall and various coworkers have developed the Standard Solar Model (SSM), which describes the Sun structure and behavior. The SSM seems very robust also because it agrees with phenomena, which take place in the Sun [1]. One of them is the helioseismology, which studies solar disruptions producing longitudinal waves which propagate within the Sun. The behaviors connected with these phenomena well agree with the SSM previsions. Of course some open problems still remain and I will discuss them later.

The SSM predicts also the neutrino fluxes emitted by the nuclear fusion reactions, which take place within the Sun, and are responsible of the Sun shining.

Despite the very low probability of the neutrinos to interact with matter, it is possible to detect them by means of experiments properly designed.

The first experiment, which measured the solar neutrino flux, has been Homestake, installed in the Homestake mine in South Dakota, which has taken data from 1970 until 1994. It was a radiochemical experiment: the solar neutrinos (all belonging to the electronic family-see later) strike Clorine nuclei producing Argon nuclei, which decay back to Clorine, emitting electrons. These reactions can take place only if the incident neutrino pertains to the electronic family (see later). The result of this experiment has been that the measured flux is definitively smaller that what expected by the SSM [2].

This discrepancy between model and experimental data produced what has been called the "*Solar Neutrino Problem* (SNP)". Other radiochemical experiments, as e.g. Gallex (1991-1997) confirmed the Homestake result [3].

The cause of the SNP could be twofold: either in the SSM there is some wrong assumption and therefore the neutrino flux is lower than predicted, or there is some new

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effect in the neutrino physics, beyond the prevision of the paradigmatic Standard Model of the elementary particles.

Later real time experiments detecting the Cherenkov light produced by the neutrino interactions in water, as Superkamiokande in Japan and SNO (Sudbury Neutrino Observatory) in Canada, have been carried out. These experiments studied the solar neutrino flux with a threshold > 5 MeV, recently reduced by SNO to 4.2 MeV of the neutrino energy. The difference between the radiochemical experiments and the real time experiments is that the first ones are unable to measure the energy of the incident neutrino and therefore they can measure only the total neutrino flux integrated from the threshold, while the real time experiments can measure separately the neutrino fluxes produced by the different solar nuclear reactions.

In 2001 SNO succeeded to demonstrate experimentally that the SSM previsions on the neutrino flux are correct and that the SNP is due to a new phenomenon beyond the elementary particle Standard Model, i.e. the neutrino *oscillation* [4]. I will give later a short outline of this phenomenon, which is described in the Altarelli's talk in this meeting. Here I want only to emphasize that the neutrino oscillation clashes with the Standard Model for two aspects: the neutrino mass is not zero and the neutrino family mark (so called *flavor*) can be violated.

The Cherenkov experiments, SNO and SuperKamiokande, due to the high threshold, succeeded to study only 1/10000 of the solar neutrino flux, corresponding to the highest part of the neutrino energy spectrum; therefore the by far largest part of the solar neutrino flux was remaining unexplored. This implies in addition a further limitation.

The oscillation can take place in vacuum and in matter: in vacuum in the travel between Sun and Earth (so called "just so"), in matter escaping from the Sun through the solar matter. No evidence has been observed until now that neutrinos are oscillating in the Sun-Earth travel, while SNO reached evidence that the neutrinos with energy > 5 MeV oscillate in the Sun matter. But when the energy of the solar neutrinos is below 0.8-1.0 MeV, the mechanism of the oscillation in vacuum prevails. Therefore, depending on the neutrino energy, three behaviors are possible in the neutrino oscillations: in vacuum, in matter and in a transition region between the two previous regimes. SNO and Superkamiokande, with a threshold >5 MeV can explore only the oscillation mechanism in matter.

It is evident at this point that another experiment was needed, able to study the solar neutrinos at very low energy, hopefully below 1 MeV. This was a very challenging enterprise because the natural radioactivity of any materials emits photons and particles which produce much more interactions in a detector than the rare neutrino interactions, thus fully hidden them. Therefore the first and more important effort has been to reduce the interactions due to the radiation emitted by the radioactive decay from any source to levels comparable to the neutrino rate. Thus Borexino is born and, as I will describe shortly in the following headings, the Borexino collaboration succeeded to reach an unprecedented radiopurity, allowing a very good success.

2. A brief recall of the neutrino properties.

The neutrinos (ν) are elementary particles having no charge and very small mass. In addition they interact with matter via weak interactions: their cross section is very small

and therefore the neutrinos can cross the Sun, the Earth and the Universe without to be perturbed. As a consequence the neutrinos are remarkable probes to study regions not reachable otherwise: just an example, the photons produced in the central region of the Sun need ~ 100000 years to escape, while to neutrinos few seconds are enough.

The neutrinos are *leptons*, one of the two families of the elementary particles. The leptons are divided in three sub-families; each of them contains one lepton and one neutrino, which is produced either with or from the decay of this lepton of its own subfamily. Therefore there are tree different types of neutrino: electron neutrino (ν_e) produced together the electron in the beta decay, muon neutrino (ν_μ) which is one of the decay product of the lepton called muon, and finally the tau neutrino (ν_τ) also produced in the tau decay. Of course, as for all particles, to each lepton corresponds its antiparticle. Therefore the positron e^+ is the anti-electron, the $\bar{\nu}_e$ is the anti-neutrino electron, etc..

The lepton maintains its sub-family mark (called *flavour*) in its interactions and decays without exceptions: this was what the physicists believed until some years ago, before the discovery of the phenomenon called "neutrino *oscillation*". In this phenomenon the neutrino can change its flavor during its travel between the production and the detection points (see the Altarelli's talk in this conference). It can arrive in vacuum and in matter.

In the oscillation phenomenon the probability of transition from a flavor to another one depends on the ratio *L/E*, where L is the distance between the production site and the detector, and E is the neutrino energy: higher L/E, greater the probability. Therefore, the solar neutrinos are an ideal tool to study the neutrino oscillation, because L is very large and E is very small (from a few keV to ~ 16 MeV).

In the oscillation and in particular in the effect so called MSW (from the authors: Mikheiev, Smirnov, Wolfenstein) [5] the oscillation is vacuum driven or matter enhanced depending on the product $n_e E$, where n_e is the electron density of the matter crossed by the neutrinos and E is the neutrino energy. If $n_e E$ is high, the oscillation in matter is dominant, while if this product is small the oscillation is vacuum driven. In the Sun n_e can be considered constant and therefore the oscillation regime (vacuum or matter) depends only on the neutrino energy.

The previsions of the oscillation model [5,6], adopted now as paradigmatic, for the ν_e survival probability is shown in figure 1; three regions are shown: the vacuum dominated region at low neutrino energy, the matter enhanced at higher energy, and a transition region in between.

The main parameters of the oscillation are the difference of masses squared between neutrinos (really between the mass eigenstates) and an angle, called "mixing angle".
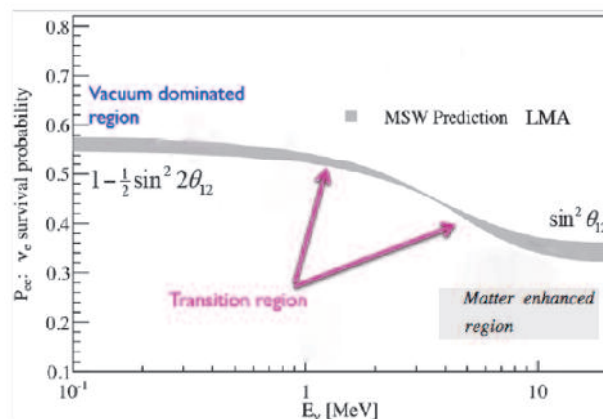

Figure 1.The ν_e survival probability as foreseen by the oscillation model MSW (see text)
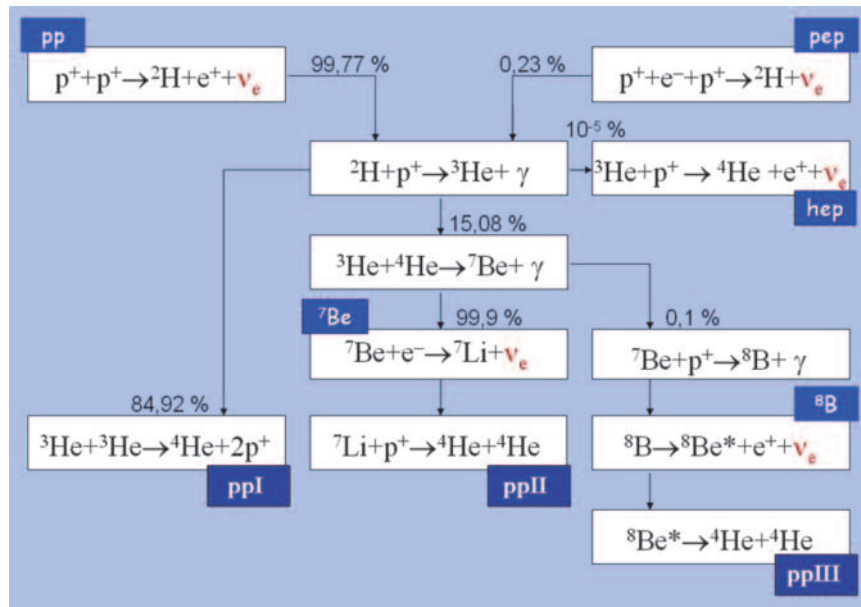
3. The Solar neutrinos

Figure 2 Nuclear reaction sequence within the Sun.

The Sun emits a huge amount of electron-neutrinos. Their flux on the Earth is about 60 billion per cm^2 per second. They are produced by two chains of nuclear fusion reactions, the dominant one (99.77%) starting with the fusion of two Hydrogen nuclei. In figure 2 the solar reaction chains are shown. We can observe that the reactions called: *pp*, *pep*, *hep*, ^7Be, ^8B produce ν_es

In addition a cycle, called *CNO*, which in the Sun produces <1% of the total energy, is considered dominant in the massive stars (with a mass >10-15 Sun masses) by the astrophysicists, but experimental proof of it never has been reached.

The energy spectrum of the solar neutrinos (figure 3) ranges from 0 to ~18 MeV, but the by far highest flux is concentrated below 1 MeV.
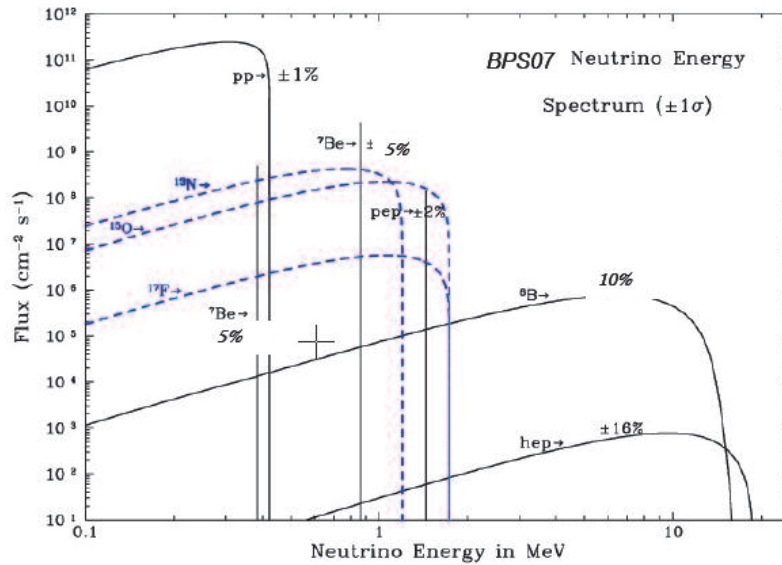
Figure 3 Energy spectrum of the solar neutrinos

The Sun mechanisms have been studied by the Standard Solar Model (SSM), developed during the last 30-40 years. The father of this model is the US physicist John N. Bahcall. The SSM is now very robust; nevertheless some problem are still present. One of them is the so called "*metallicity* puzzle".

Solar surface abundances are determined from analyses of photosphere atomic and molecular spectral lines. The associated solar atmosphere modeling has been done in one dimension in a time-independent hydrostatic analysis that incorporates convection (GS98). A much improved 3D model of the solar atmosphere has been developed later, which better reproduces line profiles and brings the Solar abundances into better agreement with other stars in the neighborhood (AGS05). Due to this improved analysis, the solar surface contains 30-40% less carbon, nitrogen, oxygen, neon and argon than previously believed.

But, where the problem is? The one dimensional approach is in excellent agreement with the study of the so called *helioseismology*, while the three dimensional approach is in disagreement. The helioseismology, as already said in the paragraph 1, is the study of the propagation of the longitudinal waves produced by important disruptions taking place in the Sun.

The two different approaches GS98 (high metallicity) and AGS09 (low metallicity) have some influences also on the solar neutrino fluxes (Table 1). We can observe that the cycle CNO shows the highest difference and the ^{7}Be and ^{8}B fluxes have a ~10% and ~20% of discrepancy, respectively between high and low metallicity [6]. Therefore precise experimental measurements of the solar neutrino fluxes can help in fixing this SSM puzzle.

Table 1. Solar neutrino fluxes following the GS98 (high metallicity) and AGS09 (low metallicity) approaches

ν flux	GS98	AGS09	$cm^{-2} s^{-1}$
pp	5.98 (1±0.006)	6.03 (1±0.006)	x 10^{10}
pep	1.44 (1±0.012)	1.47(1±0.012)	x 10^8
hep	8.04 (1±0.30)	8.31 (1±0.30)	x 10^3
^{7}Be	5.00 (1±0.07)	4.56 (1±0.07)	x 10^9
^{8}B	5.58 (1±0.14)	4.59 (1±0.14)	x 10^6
^{13}N	2.96 (1±0.14)	2.17 (1±0.14)	x 10^8
^{15}O	2.23 (1±0.15)	1.56 (1±0.15)	x 10^8
^{17}F	5.52 (1±0.17)	3.40 (1±0.16)	x 10^6

The solar neutrinos are also an ideal tool to measure the survival probability of the electron-neutrino. In fact their spectra cover the three oscillation regions as shown in figure 4.
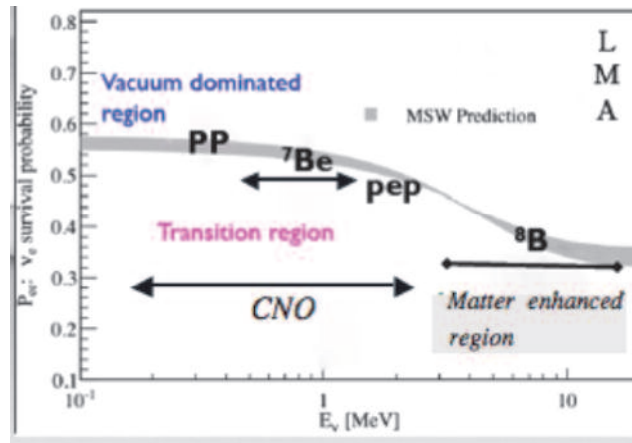
Figure 4 ν_e survival probability compared with the energy ranges of the neutrino fluxes produced in the various nuclear reactions in the Sun.

The measure of the shape of the transition region is important also because this shape is very sensitive to possible Non Standard Neutrino Interactions, a model developed by the theorists also in order to explain the neutrino oscillations.

3. The Borexino experiment

The Borexino detector has been designed with the aim to study the solar neutrinos below 1 MeV. As already said in the paragraph 1, the other experiments in real time defined a threshold much higher; the reason of the high threshold was due to the natural radioactivity, which is present everywhere, in the environment, in the construction materials used in the detector. The highest energy reached by the natural radioactivity is about 3 MeV (Tallium nuclides) and, taking into account also the resolution of the reconstruction energy, a setting of the threshold at ~ 5 Mev is a proper choice.

Therefore the first worry of the Borexino designers has been the background due to the natural radioactivity; a second worry concerned the resolution reachable in the reconstruction of the neutrino event energy and position. To fulfill the second worry liquid scintillator has been chosen as detecting material due to its high light yield which allows good measurement resolutions.

For what concerns the background we can note that one ton of liquid scintillator collects about 0.5 neutrino events/day of the ^{7}Be flux, corresponding to an activity of $\approx 5 \cdot 10^{-9} \; Bq/kg$. The regular air and water show a radioactivity level of 10-20 Bq/kg, and the rocks, 100-1000 Bq/kg. Therefore a gain of 10-11 orders of magnitudes was required!

To be shielded from the cosmic rays the detector is installed in the Gran Sasso underground laboratory in the Italian Apennines, with ~ 1400 m of rock overburden. 1.2 cosmic muons per m^2 and per hour, in addition to the neutrinos, survive traveling across the mountain.

The structure of the detector is shown in figure 5. A big Water Tank (Diameter: 18m; Height: 16.5 m) contains 2100 m^3 of highly purified water and a stainless steel sphere (SSS) with 13.7 m of diameter. The water functions as a shield with respect to the radiations (gammas and neutrons) emitted by the rocks and the air of the underground laboratory. In the water tank a muon veto is installed (Outer Detector) with 208 photomultipliers.

The SSS functions as a support of 2212 photomultipliers and contains 1300 m^3 of a liquid aromatic compound (pseudocumene): in the centre of it, 300 m^3 of this compound, added with a 1.4 g/l of a so called fluor, is contained in a very transparent nylon vessel

(Inner Detector), 125 μm thick. The 300 m³ are a two component liquid scintillator, which is the actual detecting material.

The more external 1000 m³ contained in the SSS are added with a quencher to avoid light emission when particles are crossing them; their role is to equal the scintillator density in order to produce a negligible buoyancy on the very thin nylon vessel. The choice of a so thin nylon walls is due to the need to reduce as much as possible the radiation emission from the residual radioactivity present in the nylon. Nevertheless, to study the neutrino interactions, a smaller Fiducial Volume, 100 m³ of volume, is defined to shield the residual background and in particular the one emitted by the vessel walls. A vessel balloon is installed between the Inner vessel and the photomultipliers as a barrier against the radon emitted by them and by the stainless steel of the SSS.
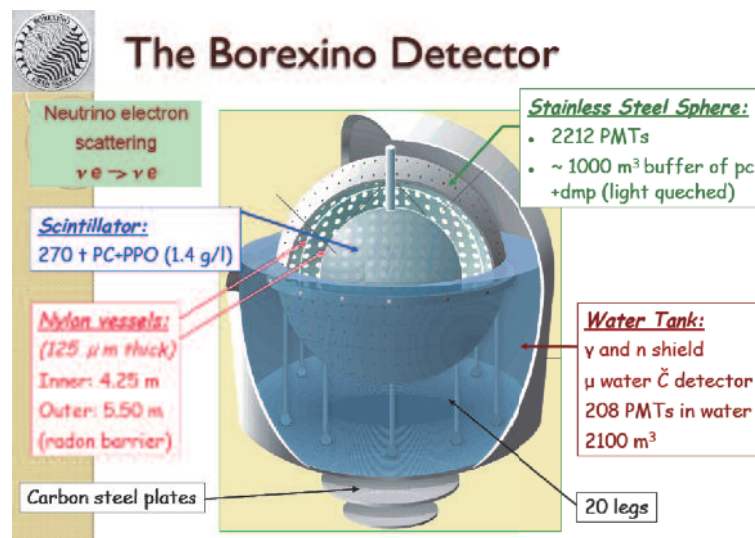

Figure 5 A dummy of the Borexino detector.

The Borexino collaboration in five years of research succeeded to develop new technologies to purify the scintillator from the radioactive elements. These technologies

allowed to achieve an unprecedented low radioactive level. Also the Nitrogen used to strip the noble gasses from the scintillator, as for instance the Radon, has been purified reaching a very low percentage of Radon, Argon and Krypton, always present in air. In addition special procedures have been adopted during the detector installation: the fabrication and the installation have been carried out in clean rooms, the detector itself has been equipped as a clean room, the plants have been assembled in Nitrogen or in Argon atmosphere, all components have been developed on purpose or very carefully selected; for the scintillator the crude oil has been taken only from very old layers, to have very low ^{14}C content.

All these efforts have been very successful: the radio-purities so obtained are a record in the world research. The results are presented in Table 2, where they are compared with the regular unpurified components.

Table 2 Radiopurity levels reached in Borexino (last column) compared with the regular ones.

	Material	Typical conc. of the unpurified materials	Final radiopurity levels
^{14}C	scintillator	^{14}C/^{12}C$<10^{-12}$	^{14}C/^{12}C$\sim 2\ 10^{-18}$
^{238}U,^{232}Th equiv.	- Hall C dust - stainless. steel - nylon	10^{-5} -10^{-6} g/g	10^{-17}/10^{-18} g/g
K_{nat}	Hall C dust	$\sim 10^{-6}$ g/g	$<3\ 10^{-14}$ g/g
^{222}Rn	- external air. - air underground	~ 20 Bq/m^3 ~ 40-100 Bq/m^3	<1mBq/m^3
^{85}Kr ^{39}A	in N$_2$ for stripping	~ 40 ppt ~ 10 ppm	~ 0.16 mBq/m^3 ~ 0.5 mBq/^{m3}
- ^{222}Rn -^{238}U,^{232}Th equiv. - ^{226}Ra	LNGS - Hall C water	Few kBq/m^3 $\sim 10^{-10}$ g/g 2 Bq/m^3	~ 30 mBq/m^3 $\sim 10^{-14}$ g/g

The neutrino interactions detected in Borexino are the elastic scattering $\nu_e + e^- \rightarrow \nu_e + e^-$. The hardware threshold is fixed at ~ 60 keV, while the software one is defined between 160 and 200 keV of the electron recoiled energy. These very low thresholds are allowed by the very low radioactivity levels of the detector .

The light yield of the scintillator is very good : 10^4 photons/MeV, corresponding to ~500 photoelectrons/MeV if we take into account the optical coverage and the photomultiplier quantum efficiencies. The resolution of the energy reconstruction is $\dfrac{5\%}{\sqrt{E(MeV)}}$ from 200 keV to 2 MeV; the position of the events within the detector is reconstructed via the photomultiplier timing with an uncertainty: $\Delta(x,y,z) = 10 - 12\,MeV$.

For further details of the Borexino detector see reference [7].

4. Results on solar neutrinos

In fig. 6 the energy spectrum of the collected events is shown. The row data are plotted, once the cosmic muons and the muon induced events are rejected, and a cut on the fiducial volume has been introduced at R=3 m from the centre of the detector (~ 100 m^3 of scintillator). The various contributions are also shown as they result from a global fit. We can observe that, in addition to the neutrinos from the nuclear reactions in the Sun (^{7}Be, pp, pep, CNO), also residues of radioactive contaminants are present (^{85}Kr, ^{210}Bi, ^{210}Po, ^{11}C). It has to be noted that the fit shown in figure 6 is devoted to ^{7}Be; therefore pp, pep and CNO are fixed at the SSM expectations. The ^{7}Be and pep nuclear reactions produce mono-energetic neutrinos and, as a consequence, the recoiled electrons from the

ν−e elastic scattering show the typical Compton edge, a shoulder at the end of their energy distribution.

Various tools are available to fight against these residual contaminants. Alpha particles are identified by means of the property of the scintillator molecules to decay more slowly in case of alphas than in case of electrons and gammas. Therefore the nuclides, as ^{210}Po, which are alpha emitters, can be rejected.

The ^{11}C is continuously produced by the residual cosmic muons crossing the overburden. It decays into ^{11}B+e$^+$+ν$_e$ with a lifetime of 29.4 minutes. It can be rejected via a threefold coincidence among the incident muon, the positron emitted in the ^{11}C decay and a neutron (s) which is produced in the muon interaction: it looses energy traveling in matter and after ~ 250 μs is captured by a proton, producing a deuteron with the emission of 2.2 MeV gamma.

Finally the ^{85}Kr fitted rate can be checked by identifying the following decay: $^{85}Kr \rightarrow {}^{85}Rb^* \rightarrow {}^{85}Rb$ with the emission of a 173 keV β and a 514 keV γ with a delay of
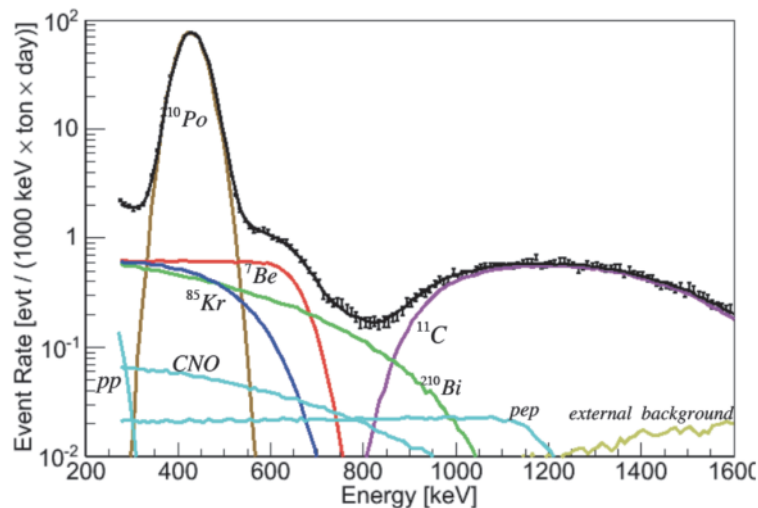

Figure 6. Spectrum of the row data collected by Borexino, once rejected the muons and the events muon induced. Fiducial volume: R<3m.

1.464 μs. Unfortunately this decay has a branching ratio of only 0.46%; therefore a high statistics has to be collected to have a good check.

In three years of data taking Borexino has reached the following results:

i) a precise measurement of the solar neutrino flux from ^{7}Be at 862 keV. The rate is 46.0±1.50 (stat.)±1.55(syst.) counts/day and 100 tons The first error is the statistical error obtained by the fit, the second one is the systematic error due to the uncertainties introduced by the cuts, the fitting methods, the energy scale. The corresponding un-oscillated flux is: $\Phi(^{7}$Be$)=(3.1\pm0.25)\ 10^{9}$cm^{-2}s^{-1} ; the ratio to the SSM prevision is: f_{Be}=0.97±0.05±0.07 [8].

ii) for the 7Be flux also the day/night effect has been investigated. This effect is due to the following mechanism: the solar ν_es traveling within the solar matter are partially converted into $\nu_\mu$and ν_τ; during the night they cross the Earth to reach the detector and some part of them can be reconverted into ν_e. In the ^{7}Be case this effect is null: the result obtained by Borexino is: A_{ND}=-0.001±0.012(stat.)±0.007(syst.) [9]
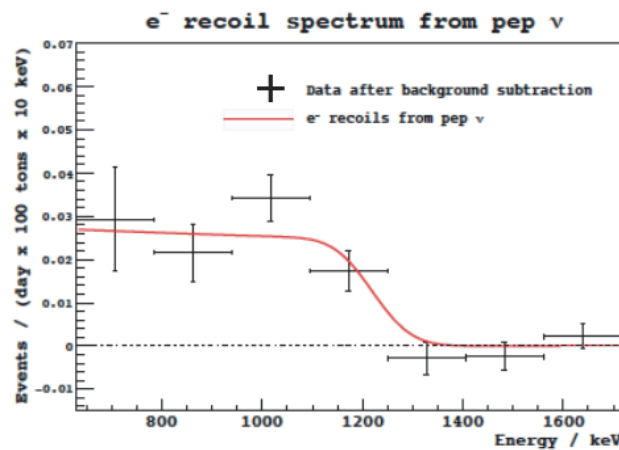

Figure 7. Energy spectrum of the neutrino interactions in the pep region once the backgrounds subtracted.

iii) Borexino succeeded to measure also the flux from the pep reaction. This is particularly difficult due to the rate, which is less than 1/10 of the ^{7}Be one. A very refined analysis was needed. In figure 7 the experimental data, once the background subtracted (crosses), are fitted with a continuously line: the Compton edge of the pep recoiling electrons is evident. The measured rate is: 3.13±0.05(stats.)±0.23(syst.) cpd/100 tons, the un-oscillated flux, Φ(pep)=(1.6±0.3) 10^8 cm^{-2}s^{-1}, and the ratio to the SSM expectation, f_{pep}=1.1±0.2[10].

iv) the analysis of the neutrinos produced by the CNO cycle is very hard because its energy spectrum has a shape similar to the ^{210}Bi one. Borexino succeeded to disentangle a stringent upper limit : rate(CNO)<7.6 cpd/100 tons, Φ(CNO)<(7.4 10^8 cm^{-2}s^{-1}), f_{CNO}<1.4 [10].

v) Borexino has measured also the neutrinos from ^{8}B, with a lower energy threshold down to 3.0 MeV (3.2 MeV neutrino energy), obtaining a total flux of 2.4±0.4 (stat.)±0.1(syst.) 10^6 cm^{2}s^{-1} [11].

5. Impact of Borexino results on the neutrino and Sun physics.

I discuss here only two important insights in the neutrino physics due to the Borexino results on solar neutrinos.

The first concerns the survival probability of the electron-neutrino. In the figures 8a and 8b the ν_e survival probability is shown before (a) and after (b) Borexino. Before Borexino only the high energy region of the solar neutrino spectrum was measured, corresponding to the oscillation in matter. At lower energy only two scattered points with

large errors are plotted: they have been obtained by subtracting the ^{8}B flux from the integrated flux measured by the radiochemical experiments.

In figure 8b the same plot includes the Borexino data. Borexino has measured the survival probability in vacuum regime via the ^{7}Be flux, constraining also the pp expectation. Both ^{7}Be and pp show small errors and validate the prevision of the oscillation model (MSW).

At high energy two points are plotted, one is an average of SNO and Superkamiokande results over 5 MeV of threshold; the second one, the average of Borexino and SNO (>3.2 and >4.2 MeV neutrino energy, respectively). Using the Borexino results we can calculate the ratio between the survival probability in vacuum and in matter: $\dfrac{P_{ee}^{vac}}{P_{ee}^{matter}} = 1.62 \pm 0.26$

Finally Borexino started the study of the transition region with the pep flux and the low threshold ^{8}B measurements. Unfortunately the statistics is still not enough to understand if the shape of the survival probability in this energy range is close to the prediction of the MSW model.
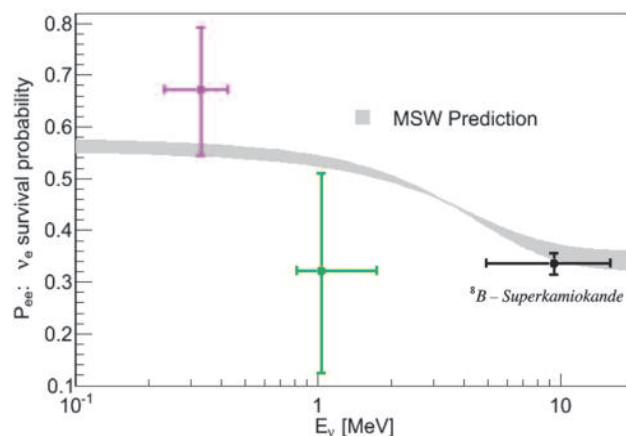

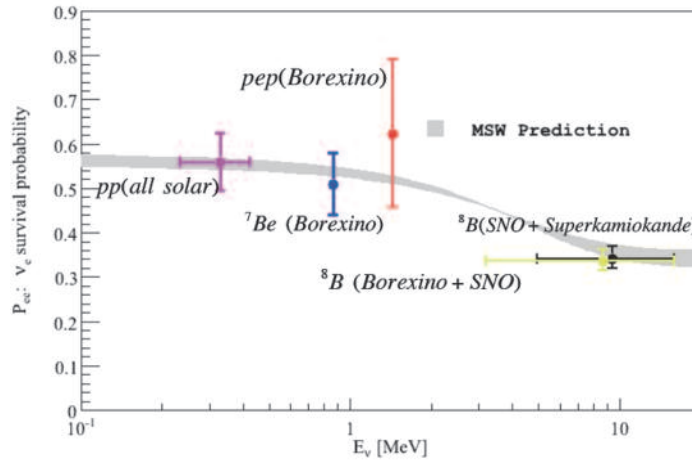Figure 8a. ν_e survival probability before Borexino

Figure 8b. ν_e survival probability after Borexino

The best fit values of the oscillation parameters, the mass difference Δm^2 and the mixing angle θ, using all solar experiments before Borexino plus the Kamland results on reactor antineutrinos succeed to isolate a parameter range called "Large Mixing Angle (LMA)". This operation needs the assumption that neutrinos and antineutrinos have the same behavior. Adding the Borexino data it is possible to isolate the LMA region without the antineutrino data thus without any assumption (CPT conservation).

The results of Borexino give also a good validation of the SSM, because the measured fluxes are in agreement, within the errors, with its previsions. Unfortunately the experimental errors and the uncertainties of the solar model do not allow yet to discriminate between high and low metallicity.

6. Geoneutrinos

The geoneutrinos are antineutrinos emitted in radioactive decays taking place in the Earth interior. The radioactive nuclei present in the Earth are the Uranium and Thorium decay chains and the ^{40}K nuclide. In each decay of these radioactive elements antineutrinos and radiation energy are emitted; this energy is fully converted in heath. It is important to know how much of the total Earth heat is due to the radioactive decays and how many of them take place in the Crust and how many in the Mantle.

The geoneutrino flux is very low (~1.5 events every two months in Borexino) and therefore its measurement is hard; on the other hand the antineutrino interactions are very well tagged (inverse beta decay) and so it is possible to discriminate them with respect to the background due to the natural radioactivity and to the neutrino interactions. But another background is due to the antineutrinos produced by the nuclear reactors, which show an energy spectrum partially superimposed to the geoneutrino energy. Borexino is well favored because at the Gran Sasso site the flux from reactor antineutrinos is relatively small.

A first hint on the existence of the geoneutrinos has been obtained by KamLAND with an evidence of ~2 sigma. Later Borexino reached the first actual evidence a ~4.2 sigma [12], followed more recently by KamLAND with a similar evidence [13]. A joint analysis of Borexino and KamLAND results give the indication that the radioactive decays can produce about ½ of the total Earth heat.

7. Conclusions

In three years of data taking Borexino obtained the first measurement of the solar neutrino fluxes from the ^{7}Be and pep reactions. In addition a stringent upper limit for the

neutrinos from CNO has been reached. In this way the oscillation in vacuum has been studied and the MSW oscillation model has been validated in that regime.

The pep flux measurement and the ^{8}B neutrinos studied by Borexino with a lower threshold down to 3.2 MeV, neutrino energy, are a starting point for the study of the transition region shape. Unfortunately the statistics is not yet enough to check the possible existence of non standard neutrino interactions. On the other hand the Borexino results are in excellent agreement with the expectations of the Standard Solar Model.

The day/night effect is null in the ^{7}Be region following the Borexino data and this allows the isolation of the oscillation parameters without taking into account the reactor antineutrino results and therefore without the assumption of no CPT violation in the neutrino sector.

Borexino is now proceeding to a re-purification campaign to reach a radiopurity even better of the present one. A further data collection during 3-4 years would allow to reduce the error of the pep and ^{8}B over 3 MeV fluxes, allowing a good study of the transition region. In addition the present goal is addressed to obtain the experimental proof of the existence of the CNO cycle, which will allow also the solution of the metallicity puzzle.

Finally Borexino reached the experimental evidence of geoneutrinos at 4.2 sigma of confidence level. Further data will allow a better evaluation of the Earth heat produced by the radioactive e decays in the Earth interior.

References

[1] see for example: Bahcall, J.N., Status of Solar models, 1997, Proceed. of the XVII Int. Conf. on Neutrino Physics and Asprophysics, 56-70

[2] Cleveland, B.T., et al.,1998, Ap.J. **496**, 505

[3] Hampel W. et al., 1999, Phys. Lett.B **447**, 127

[4] Ahmad Q.R. et al, 2001 Phys. Rev. Lett. **87**, 071301

[5] Mikheyev S.P. and Smirnov A.Yu., 1985 Sov. J.Nucl. Phys. **42**, 913; Wolfenstein L., 1978, Phys. Rev. D **17**, 2369

[6] Serenelli A.M. et al., 2010, arXiv:1104.16.39v1 [astro-ph]

[7] Alimonti G. et al., 2009 Nucl. Instrum. and Meth A **600**, 58

[8] Bellini G. et al.,2011 Phys. Rev. Lett. **107**, 141302

[9] Bellini G. et al, 2012 Phys. Lett. B, **707**, 22

[10] Bellini G. et al, arXiv: 1110.3230[hep-ex], accepted for publication on Phys. Rev. Lett.

[11] Bellini G. et al, 2010 Phys. Rev.D **82**, 033006

[12] Bellini G. et al, 2010 Phys. Lett.B **683,** 299

[13] Gando A et al. 2011 nature geo-science. Ngeo **1205** 1