Methodology of experimental search for neutrinos from solar flares in Borexino detector

V S Atroshchenko, L A Borodikhina, M A Toropova
National Research Center "Kurchatov Institute", Akademika Kurchatova square 1, Moscow, 123182, Russia
E-mail: toropovam@yandex.ru

Abstract. Solar flares are sudden variations in brightness observed near the Sun’s surface. Some theoretical models predict production of electron and muon neutrinos with energies up to few tens of MeV during solar flares. In 1980s the Homestake experiment reported excess of detected neutrino events possibly correlated with large solar flares. Since then the interest to similar studies by other neutrino detectors has increased. In this report we summarize the status of experimental searches and describe the methodology for the study of neutrinos from solar flares in Borexino liquid scintillator detector.

1. Introduction
Solar flares are one of the brightest events occur in solar system. Flare is a short flash near the Sun’s surface, it takes place in the active regions near the sunspots and involves all layers of solar atmosphere (photosphere, chromosphere and corona). Therefore, the average frequency of solar flares is connected with the phase of solar activity cycle.

There is no one unified model of solar flare mechanism, several models were proposed [1, 2], though the most popular among them is reconnection model [3]. In this model it is assumed that the engine of solar flare is the restructuring magnetic field which penetrate the solar atmosphere. The reconnection of two magnetic lines with opposite polarity produces the electric field that gives particle acceleration.

Great fluxes of particles (such as electrons, protons and ions) are emitted and accelerated in solar flares. These ejections are followed by radiation in a wide range of electromagnetic spectrum from radio to gamma-rays. Photons with different energies are born in the different mechanisms. X-rays produced through bremsstrahlung of accelerated electrons in chromosphere and transit region and give the starting time of the flare. γ-rays are produced by nuclear deexcitation, neutron capture, positron annihilation and pion decay and may be delayed with respect to X-rays and then give the end time of the flare. This variety made solar flare visible in different parts of spectrum and in different moments of time. Therefore, it is important to have instruments for solar flare registration for different ranges.

There are a great number of satellites in different points of Earth’s and Sun’s orbits that are able to detect solar flares in different energy ranges. For example, GOES satellite [4] detects X-ray from flares, and such satellites as RHESSI [5], Fermi [6] can also detect γ-rays.

There is also an assumption that neutrinos can be born in solar flares due to collisions of accelerated protons [7, 8]. Thus, detection of neutrinos correlated in time with flares can give us
more precise information about this event and will help to extend knowledge of Sun’s physics. In this report we consider the possibility of registration of solar flare neutrinos by detectors on Earth, review the history of previous studies of this kind and also describe methodology of solar flare neutrinos search that is now on-going in Borexino collaboration.

2. Solar flare neutrinos
Possible source of neutrinos in solar flare can be decay of pions and muons that were born after collision of accelerated protons:

\[
p + p \rightarrow \begin{cases} 
\Delta^{++} + n \rightarrow p + n + \pi^+ \\
\Delta^+ + p \rightarrow \begin{cases} 
p + p + \pi^0 \\
 p + n + \pi^+
\end{cases}
\end{cases}
\]

\[
\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{2}
\]

\[
\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{3}
\]

Neutrinos also can be born in the following collision, these reactions have lower probability than the first ones [8]:

\[
p + n \rightarrow \begin{cases} 
\Delta^+ + n \rightarrow n + n + \pi^+ \\
\Delta^0 + p \rightarrow \begin{cases} 
p + p + \pi^- \\
p + n + \pi^0
\end{cases}
\end{cases}
\]

\[
\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \tag{5}
\]

\[
\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{6}
\]

These interactions can take place both in Sun’s and Earth’s atmosphere. Neutrinos that were born on Sun give the prompt and short signal in detector. But neutrinos that appeared on Earth when solar flare particles had reached its atmosphere give the signal that can be delayed by undefined time interval (it depends on solar flare duration) and distributed in longer period. It makes terrestrial solar flare neutrinos hard to distinguish from the background, therefore, this flux is not of interest.

The spectrum of solar flare electron and muon neutrinos is shown in figure 1 [9].

3. History of solar flare neutrinos searches
3.1. The Homestake
The first experiment to search for the signal from solar flare neutrinos was the Homestake detector [10]. It contained 380 m³ of perchloroethylene and took place in the Homestake Gold Mine in South Dakota, USA about 30 years ago, main goal of experiment was to measure total flux of solar neutrinos with energies above 0.8 MeV. The results of this experiment gave huge motivation for solar flare neutrinos studies because it was reported that there was excess of signal in data in time correlation with several large solar flares.

To approve or reject the hypothesis it was important to perform similar search for another experiment.
3.2. Kamiokande
The Kamiokande was the second experiment that have studied this problem [11]. It is the water Cherenkov detector that contained 3000 tons of pure water and was located in the Kamioka Mine near the city of Hida, Gifu Prefecture, Japan, it was designed for the search for proton decay.

There was no significant neutrino signal possibly connected with solar flares in 5 year period.

3.3. SNO
The most recent search for solar flare neutrinos so far was performed by SNO collaboration [12]. It was the experiment located in Creighton Mine in Sudbury, Canada, it contained 1 kiloton of pure heavy water. The main goal was to detect neutrinos from the Sun.

No excess of neutrino events in time windows connected with solar flares was found, fluence upper limits for neutrinos from solar flares were obtained, this result can be seen in figure 2 in comparison with result of the other experiments mentioned above. It can be seen that the best result was obtained by SNO collaboration for energies higher than 3 MeV.

4. The search for solar flare neutrinos in Borexino
Similar studies of solar flare neutrinos is now in progress in Borexino collaboration.

4.1. The Borexino detector
Borexino is a liquid organic scintillator detector located in underground laboratory Gran Sasso in central Italy. It is filled with 278 tons of PC (pseudocumene, $C_9H_{12}$) doped with PPO (2,5-diphenyloxazole, $C_{15}H_{11}NO$) as a scintillator. The very high level of detector radiopurity was reached, because the primary goal of Borexino experiment is spectroscopy of solar neutrinos below 1 MeV. Borexino is also able to detect atmospheric and geo-neutrinos, as well as neutrinos from different astrophysical sources. Detailed description of the detector can be found in [13].
Since Borexino was designed to measure low energy neutrinos we have opportunity to improve results in solar flare neutrinos studies for low energy region. Moreover, there is the secondary DAQ system in Borexino based on fast wave form digitizers which allows to extend energy region of detected events up to 100 MeV, this energies are consistent with the spectrum in figure 1.

Borexino data taking period is about 9 years for now, it covers more than a half of 11-year solar activity cycle including its maximum, this fact increases the probability to observe neutrinos emitted in solar flares in case of its existence.

4.2. Detection of solar flare neutrinos in Borexino
Thanks to its high radiopurity Borexino detector provides unique possibility to study neutrinos from solar flares through different detection channels.

• Neutrino-electron elastic scattering.

\[ \nu_x + e^- \rightarrow \nu_x + e^- \]  \hspace{1cm} (7)

This reaction allows to detect all flavour neutrinos. The signature of this process in detector is single point-like event.

• Bursts of events.
Since the rate of point-like events in data is high it is reasonable to look for groups of such events registered in short time intervals, so called bursts of events. There could be several strategies to define bursts of events. The simplest is just to split all data taking period into equal intervals and count number of event (multiplicity) in each of them. Groups with the highest multiplicities can be defined as bursts and included in the list for the further analysis.

• Reactions on carbon.
The next method to detect neutrinos is through reactions on carbon. For example:

\[ \nu_x + ^{12}C \rightarrow \nu_x + ^{12}C^* \]  \hspace{1cm} (8)

\[ ^{12}C^* \rightarrow ^{12}C + \gamma , \]  \hspace{1cm} (9)

Energy of \( \gamma \)-quanta \( E_\gamma = 15.1 \) MeV.
Signal in detector for this reaction is single event with energy above the threshold. High energy threshold of this reaction allows to decrease the amount of candidate events and therefore to find any connection with solar flares easier since the rate of low energy single events in Borexino is very high.
Another possible reaction on carbon in Borexino:

\[ \nu_e + ^{12}C \rightarrow ^{12}N + e^- \]  \hspace{1cm} (10)

\[ ^{12}N \rightarrow ^{12}C + e^+ + \nu_e \]  \hspace{1cm} (11)

Energy threshold \( E_{thr} = 17.8 \) MeV. The signature of this reaction is two events: prompt and delayed.

• Upward-going muons.
In this method we are going to search for signal from muons that go from bottom of detector to its top. Such muons can be born after interaction of muon neutrinos (possibly emitted in solar flares) with rocks surrounding the detector.

After performing analyses using each of methods described above, we will have four lists of events of different kind. The next step is the same for every method: we need to find out if there is any time correlation between these lists and detected solar flares.
4.3. Time windows and analysis

Important step is the choice of time window for the search of correlation between solar flares and neutrino signal in Borexino. We open the window connected with each flare in analysis to study the Borexino data. Time window duration depends on duration of connected solar flare (solar flare can last from several minutes to several hours). Time window includes the whole period of flare and also some intervals before and after the moment of flare registration to make analysis more model independent.

List of solar flares used in analysis is based on the combined data from several satellites such as RHESSI, GOES, Hinode and Fermi. Since there can occur up to ten solar flares per day only the most powerful flares (M and X classes) are used in analysis.

In case of no correlation to be found fluence upper limits for electron and muon neutrinos from solar flares will be obtained.

5. Conclusion

Searches for neutrinos emitted in solar flares have a long history and were performed by several detectors. Result obtained in the Homestake experiment was not yet approved. Fluence upper limits for solar flare neutrinos were set, this helps to understand better the nature of solar flare events. The similar study is now in progress in Borexino detector which has advantage for this analysis due to its high radiopurity and ability to detect neutrinos through different reactions. The general points of analysis were described.

Acknowledgments

The work was supported by RFBR grant 16-32-00355.

References

[1] Chupp E L and Ryan J M 2009 Research in Astron. Astrophys 9(1) 11
[2] Zharkova V V et al. 2011 Space Sci Rev 159 357
[3] Drake J F et al. 2006 Nature 443 553
[4] http://www.goes.noaa.gov/
[5] http://hesperia.gsfc.nasa.gov/rhessi3/
[6] http://fermi.gsfc.nasa.gov/
[7] Bahcall J N 1988 Physical Review Letters 61(23) 2650
[8] Fargion D 2004 Journal of High Energy Physics 2004(06)
[9] Fargion D 2006 Phys. Scr. T127 22
[10] Cleveland B T et al. 1998 Astrophys. J. 496 505
[11] Hirata K S et al. 1988 Physical Review Letters 61(23) 2653
[12] Aharmim B et al. 2014 Astropart. Phys. 55 1
[13] Alimonti G et al. 2009 Nucl. Instr. and Methods A 600 568