Lithium Experiment on Solar Neutrinos to Weight the CNO Cycle.

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Abstract

The measurement of the flux of beryllium neutrinos with the accuracy of about 10% and CNO neutrinos with the accuracy 30% will enable to find the flux of pp-neutrinos in the source with the accuracy better than 1% using the luminosity constraint. The future experiments on $\nu e^-$ scattering will enable to measure with very good accuracy the flux of beryllium and pp-neutrinos on the Earth. The ratio of the flux of pp-neutrinos on the Earth and in the source will enable to find with very good accuracy a mixing angle theta solar. Lithium detector has high sensitivity to CNO neutrinos and can find the contribution of CNO cycle to the energy generated in the Sun. This will be a stringent test of the theory of stellar evolution and combined with other experiments will provide a precise determination of the flux of pp-neutrinos in the source and a mixing angle theta solar. The work on the development of the technology of lithium experiment is now in progress.

The remarkable progress achieved in a number of experiments with solar neutrinos [1] with a culmination of KamLAND [2] has shown unambiguously that solar neutrinos do oscillate and the parameters of neutrino oscillations belong to the MSW LMA region [3], which is now split into two sub-regions so that at 3$\sigma$ we have $^1$

$$5.1 \times 10^{-5} eV^2 < \Delta m^2 < 9.7 \times 10^{-5} eV^2$$

$$1.2 \times 10^{-4} eV^2 < \Delta m^2 < 1.9 \times 10^{-4} eV^2$$

$^1$The new results in SNO experiment (SNO collaboration nucl-ex/0309004) have shown (at 1$\sigma$) that $\Delta m^2 = 7.1^{+1.2}_{-0.6} eV^2$ and $\theta = 32.5^{+2.1}_{-2.3}$ degrees
for a mixing angle $\theta_{\odot}$

$$0.29 < \tan^2\theta_{\odot} < 0.86$$

The further progress can be achieved by increasing the accuracy of measurements of neutrino fluxes. Here some new aspect has arisen connected with the possibility to increase drastically the accuracy in the evaluation of the contribution of pp chain to the total luminosity of the Sun. The luminosity constrained was first suggested on a quantitative basis by M.Spiro and D.Vignaud [4]. As it is known, there are basically two sources of solar energy: the pp-chain of reactions and CNO-cycle, the latter is presented on Fig.1. Each neutrino source contributes to the solar luminosity a definite value, so that the energy balance can be written:

$$0.913 f_{pp} + 0.002 f_{pep} + 0.07 f_{Be} + 0.0071 f_{N} + 0.0079 f_{O} = 1 \quad (1)$$

for all neutrino sources with the coefficient by the reduced neutrino flux greater 0.0001. Here the neutrino fluxes $f_x$ are given in a reduced (relative to the predicted ones by standard solar model (SSM) BP2000 [5]) and the solar luminosity is normalized to 1. The coefficients by $f_{pp}$, $f_{pep}$ and $f_{Be}$ were obtained from numbers of Table 1 presented in [6], the coefficients by $f_{N}$ and $f_{O}$ were calculated by us accounting that the energy produced for each $^{13}\text{N}$ neutrino in a first half-cycle CNO

$$\alpha^{(13}\text{N}) = M^{(12}\text{C}) + 2M^{(1}\text{H}) - M^{(14}\text{N}) - \langle E_\nu \rangle^{(13}\text{N})$$

$$= 11.00 \text{MeV} \quad (2)$$

and for each $^{15}\text{O}$ neutrino for the second half-cycle CNO

$$\alpha^{(15}\text{O}) = M^{(14}\text{N}) + 2M^{(1}\text{H}) - M^{(4}\text{He}) - M^{(12}\text{C}) - \langle E_\nu \rangle^{(15}\text{O})$$

$$= 14.01 \text{MeV} \quad (3)$$

At the present epoch of the evolution of the Sun the CNO cycle is closed, i.e. the concentration of $^{14}\text{N}$ is close to the equilibrium one as one can see from Fig.2 drawn by the numbers presented in Table 4.4 of [7]. On the early stage of solar evolution the abundance of $^{14}\text{N}$ in the interior of the Sun is still low, consequently, the CNO cycle is not yet closed. From the expression (1) it follows that beryllium neutrinos contribute to the solar luminosity 7% while CNO cycle (neutrinos from $^{13}\text{N}$ and $^{15}\text{O}$) - only 1.5% . Thus, according
to SSM the contribution of CNO cycle to the total energy generated in the Sun is small but nevertheless, at a certain phase of experiment this will be the principal limitation in evaluating the physical quantities. For example, if the flux of beryllium neutrinos is evaluated with the accuracy better than 10%, the beryllium uncertainty to the solar luminosity will be less than 1%, so that major uncertainty to the luminosity in this case will come from CNO cycle. Then the measurement of the flux of neutrinos from CNO cycle will the accuracy of about 30% will enable to find the flux of pp neutrinos in the source with the accuracy better than 1% [8]. At the present time a new generation of solar neutrinos is under development. Some of these detectors are oriented to measure precisely the flux of pp-neutrinos on the Earth by means of $\nu e^-$ scattering [9]. The cross-section of this reaction is calculated with high accuracy so principally they can do the high precision measurements. The effect in $\nu e^-$ scattering experiment is determined mainly by electron neutrinos, the contribution of neutrinos of other flavors is small and well calculable. The ratio of these two values: the flux of electron pp-neutrinos on the Earth and the flux of pp-neutrinos in the source, i.e. in the Sun, will give the survival probability and consequently, a mixing angle. This is a very good approach. In some way it is similar to charged current – neutral current strategy in SNO experiment. But here one value – the flux of pp-neutrinos in the source - is found by measuring the flux of beryllium and CNO neutrinos while other value – the flux of electron pp-neutrinos on the Earth is found by measuring the effect in a $\nu e^-$ scattering detector.

Figure 1: The CNO cycle of thermonuclear reactions.
This strategy becomes possible only because the contribution to the solar luminosity of beryllium and CNO neutrino generated reactions is relatively small, so that modest accuracy in the evaluation of the flux of these neutrinos produces with high accuracy the flux of pp-neutrinos in the source.

Figure 2: The abundances of $^{12}C$ and $^{14}N$ in the interior of the Sun. The solid lines - with diffusion in the matter of the Sun, the dashed lines - without diffusion.

The present limit for the contribution of the CNO cycle is 7.3% \cite{10}. In a next few years even in the optimistic scenario of the progress with the solar neutrino experiments it will be hardly possible to decrease this limit lower than 5% . So, future experiments will not be able to exclude the weight of the CNO cycle in the solar energy as much as 4.5% . But in this case the weight of a pp-chain may be not 98.5% as is estimated now, but only 95.5% . The difference is 3% and this is a principal limitation. The accuracy in the evaluation of the flux of pp-neutrinos generated in the Sun will be limited by this uncertainty. So to go further one should measure the real weight of CNO cycle. This can be done by a lithium detector because it has high sensitivity to neutrinos generated in CNO cycle which contribute 30% to the expected rate. If the accuracy in a lithium experiment is on the level of 10% , then the weight of CNO neutrinos will be determined with the uncertainty of about 0.5% in the absolute value of the contribution to the solar luminosity. This result will be important for two reasons. First – it will provide a direct proof of the theory of stellar evolution. So far we have no
Experimental evidence that the CNO cycle does exist. These data will show how correct is our understanding of the evolution of the stars. For main sequence stars with higher temperature than the Sun the CNO cycle is a major source of energy. In fact, the fate of the Sun is also a CNO cycle star. Figure 2 shows the expected concentrations of $^{12}$C and $^{14}$N in the interior of the Sun.

One can see a peculiar distribution of these isotopes across the radius of the Sun. Carbon is burned in nuclear reactions while nitrogen is accumulated till the equilibrium concentration. To test experimentally whether the real picture corresponds to our understanding is very important. The second reason is that these data combined with the results of other experiments will enable to find with unprecedented accuracy the flux of pp neutrinos in the source and from the ratio of the flux of electron neutrinos on Earth to the one in the source - a mixing angle $\theta_{\text{sol}}$.

Table 1. Standard Model Predictions (BP2000): solar neutrino fluxes and neutrino capture rates, with $1\sigma$ uncertainties from all sources (combined quadratically).

| Source | Flux ($10^{10}$cm$^{-2}$s$^{-1}$) | Cl (SNU) | Ga (SNU) | Li (SNU) |
|--------|-----------------------------------|----------|----------|----------|
| pp     | $5.95 \pm 0.01$                  | 0.0      | 69.7     | 0.0      |
| pep    | $1.40 \times 10^{-2} \pm 0.015$ | 0.22     | 2.8      | 9.2      |
| hep    | $9.3 \times 10^{-7} \pm 0.04$   | 0.04     | 0.1      | 0.1      |
| $^7$Be | $4.77 \times 10^{-1} \pm 0.10$  | 1.15     | 34.2     | 9.1      |
| $^8$B  | $5.05 \times 10^{-4} \pm 0.04$  | 5.76     | 12.1     | 19.7     |
| $^{13}$N | $5.48 \times 10^{-2} \pm 0.20$ | 0.09     | 3.9      | 2.3      |
| $^{15}$O | $4.80 \times 10^{-2} \pm 0.20$ | 0.33     | 5.5      | 11.8     |
| $^{17}$F | $5.63 \times 10^{-4} \pm 0.05$ | 0.0      | 0.1      | 0.1      |
| Total  | $7.6^{+1.4}_{-1.1}$             | 128^{+9}_{-7} | 52.3^{+6.0}_{-6.0} |

The rates in a lithium detector from different neutrino sources are presented in Table 1. If to take the mixing angle $\tan^2\theta=0.41$ the total rate will be 25 SNU, and the contribution of CNO cycle is 30%. To find the flux of CNO neutrinos one should subtract the rates from pep, $^7$Be and $^8$B neutrinos. Even the current accuracies in the evaluation of these fluxes and of mixing angle $\theta_{\text{sol}}$ enable to do it taking into consideration that the accuracy of 30% in the evaluation of the fluxes from CNO cycle are adequate for the task as it was explained earlier. The flux of pep-neutrinos
is found from the flux of pp-neutrinos because the ratio of these fluxes is well known. More accurate measurement of the flux of beryllium neutrinos will help in a further correction of data. This will be done in Borexino and KamLAND experiments. Thus for a further progress in the study of solar neutrinos it is vital to measure the capture rate by a lithium target. There is some ambiguity due to the unknown factor: what is contribution of $^{13}$N and $^{15}$O neutrinos? In fact, the situation in this aspect is quite good for a lithium target because due to a relatively high threshold of this detector the rate from $^{13}$N neutrinos is much less than the one from $^{15}$O neutrinos: the ratio is approximately 1/5, see Table 1 taken from ref.6. This helps in the interpretation of the data because the uncertainty of the rate from CNO neutrinos depends mainly upon the uncertainty of the $^{15}$O neutrino flux.

To find the contribution of beryllium neutrinos one should know not only the flux of beryllium neutrinos but also the shape of the energy spectrum of these neutrinos due to thermal broadening. The details of this were discussed in [1]. The point is that in the laboratory conditions the $^7$Be line will not produce $^7$Be on lithium since the reaction of $^7$Be production is reverse to electron capture by $^7$Be. If to consider electron screening in terrestrial atoms, the energy of beryllium line is even lower than a threshold for $^7$Be production. But in the Sun high temperature produces the thermal broadening of the $^7$Be line, as it was discussed in [12] and later was computed with high accuracy by Bahcall [13]. Because of this some fraction of the line with the energy higher than the threshold will produce $^7$Be. The effect is model dependent. The fact that the measured flux of boron neutrinos is in a good agreement with the one predicted by BP2000 shows that the model gives the correct temperature map of the interior of the Sun, hence there is good reasoning to believe that the thermal broadening of the beryllium line is described by the model correctly.

The substantial issue is that while the contribution of CNO cycle to the solar energy is only 1.5%, the weight of neutrinos from CNO cycle in the production rate of $^7$Be on $^7$Li is about 30%, so that for the total capture rate expected for a lithium target 25 SNU, neutrinos from CNO cycle contribute 8 SNU. If we take the parameters of neutrino oscillations from the allowed region, make the estimates for a detector with 10 tons of lithium and take pure statistical uncertainties, then the capture rate on a lithium target can be measured with the accuracy of approximately 1 SNU for 16 Runs total performed during 4 years of measurements. Here the efficiency of counting of $^7$Be was taken about 90% what is principally possible to do by means of the
cryogenic detectors \cite{14}. After subtracting the rate from these three sources of a pp-chain one gets the rate from neutrinos of CNO cycle. Now we have two possibilities: first, we can take the ratio of $^{13}N$ to $^{15}O$ neutrinos as a given one by a SSM, or we can find separately the contribution of these two neutrino sources to the total capture rate solving the system of two equations:

$$\begin{align*}
L_H + L_{CN} + L_{NO} &= L_\odot \\
R_H + R_{CN} + R_{NO} &= R_{Li}
\end{align*}$$  \hspace{1cm} (4)

Here $L_H$, $L_{CN}$ and $L_{NO}$ are the contributions to the solar luminosity of pp-chain and two half-cycles of CNO cycle, $R_{Li}$, $R_H$ - the measured and estimated for the hydrogen sequence rates in a lithium detector, $R_{CN}$ and $R_{NO}$ means the rates from neutrinos born in $^{13}N$- and $^{15}O$-decays, $R = yL/4\pi r_{\odot}^2\varepsilon$, where $r_{\odot}$ – the distance from Sun to Earth, $\varepsilon$ is the energy contributed to the Sun per one neutrino emitted in each half-cycle of CNO-cycle and $y$ – the capture rate per one neutrino of $^{13}N$- or $^{15}O$-spectra. One can see from these equations that principally it is possible to find separately the fluxes of $^{13}N$ and $^{15}O$ neutrinos. The contributions of the energies associated with $^{13}N$ and $^{15}O$ neutrinos are close as one can see from the expressions (2) and (3). What concerns the rate of a lithium detector, the situation here is very different. The contribution of the $^{15}O$-neutrino is 5 times bigger than the one of $^{13}N$-neutrinos. In other words, the straight lines corresponding to equations of the system (4) are not parallel and the system of equations has a solution.

The idea to use a lithium target for the detection of solar neutrinos was expressed on the eve of a solar neutrino research \cite{15} and this subject was investigated in a number of papers \cite{16}. Lithium experiment is a radiochemical experiment and as a target metallic lithium is planned to be used. The solar neutrinos are captured by $^{7}Li$ (the abundance is 93\% ) and $^{7}Be$ is produced in a reaction:

$$^{7}Li + \nu \rightarrow Be + e^-$$

The isotope $^{7}Be$ has a half life 53 days and is decayed to $^{7}Li$ by means of electron capture. The aim is to extract $^{7}Be$ from lithium and to count the number of extracted atoms. The measured capture rate is converted in a neutrino flux. The main advantage of a lithium detector is that transition $^{7}Be$-$^{7}Li$ is super allowed hence the cross-section can be calculated with a very
good accuracy what was done in [13]. How to extract beryllium from metallic lithium? The basic principle is the following. The chemical compounds of beryllium with nitrogen (Be$_3$N$_2$) and oxygen (BeO) have extremely low solubility in lithium, on the level of 10$^{-13}$ mole percents. At the beginning of the exposure some beryllium sample (about 10 mg) is introduced in the target (10 tons of lithium). This concentration of beryllium is by far exceeding the equilibrium quantity. Beryllium is capturing nitrogen or oxygen atoms which are always present in lithium as impurities and is converted in a beryllium nitride or beryllium oxide. The same happens with the beryllium atom produced by solar neutrinos. These compounds of beryllium are ready to precipitate on any surface provided they have the contact with it. This condition is rarely realized in a bulk of lithium because the ratio of the surface to the volume is negligible. But if the stream of lithium is passed through a fine mesh filter with a very large surface, this contact is guaranteed. So the extraction procedure consists in pumping lithium through a filter and then by collecting the beryllium atoms by means of extraction from an aqueous phase where all beryllium present on a lithium film from the filter gets dissolved. The optimization of the technology consists in finding the conditions by which the extraction process is efficient. Initially the work was done with the samples of $^7$Be produced in lithium by protons with the energy of about 10-100 MeV. This is not very good technology because $^7$Be is produced mainly on the surface of the sample, not inside of a lithium samples and the extraction of $^7$Be produced by this method was far from the real experimental conditions. Now we use 14 MeV neutrons of D-T neutron source as a $^7$Be generator. By this method one can guarantee that $^7$Be was really produced inside of a lithium sample. Another problem is how to count the extracted atoms of $^7$Be? By the decay of $^7$Be the Auger electron is released with the energy 55 eV. This energy is too small for counting by the traditional counting technique. Principally it is possible to use a cryogenic detector as it was demonstrated in [14]. This method is the only possibility to get the high precision measurements because of high efficiency of counting $^7$Be atoms. But as it was shown earlier, it is not absolutely necessary to have the accuracy of measurements on the level of 1 SNU. The good physical result will be obtained even with the modest accuracy of about 2.5 SNU (10% ). In this case one can use the counting by a low background gamma spectrometer with the efficiency of counting of only 8%. Here the accuracy of 10% will be achieved with 10 tons of lithium and 4 years of running the experiment. In 10% $^7$Be decays to the excited level of $^7$Li which emits the
gamma with the energy 478 keV. This energy is very convenient for counting. In the background spectrum there is a very populated line 511 keV, so to discriminate the background from this line one should use a gamma spectrometer with a very good energy resolution. This can be realized by means of a low background gamma spectrometer using high purity germanium detectors [17]. The assembly of the detectors which can be used in this case is similar to one module planned to be used in a Majorana project [18]. The work on the development of the technique of a lithium detector is now in progress at the Institute of Nuclear Research RAS in Moscow, and in the Institute of Physics and Power Engineering in Obninsk.

To summarize we should note that a lithium experiment is the only way to find with unprecedented accuracy the flux of pp-neutrinos generated in the interior of the Sun (in the source) by means of measuring the fluxes of neutrinos generated in a CNO cycle. This information is vital for further study of the thermonuclear processes in the interior of the Sun and can be effectively used for precise measurement of the mixing angle $\theta_{\odot}$. The study of CNO is very important also as a precise test of the theory of stellar evolution. This work was supported in part by the Russian Fund of Basic Research, contract N 01-02-16167-A and by the grant of Russia “Leading Scientific Schools” LSS-1782.2003.2. The authors deeply appreciate the very stimulating discussions with G.Zatsepin, L.Bezrukov, V.Kuzmin, V.Rubakov, S.Mikheev.

References

[1] B.T.Cleveland et al., 1998, *Astrophys. J.* **496**, 505
J.N.Abdurashitov et al., 2002, *J. Exp. Theor. Phys.* **95**, 181
W.Hampel et al. (GALLEX collaboration), 1999, *Phys. Lett.* **B447**, 127
T.Kirsten, 2002, *talk at the XXth Int. Conf. On Neutrino Physics and Astrophysics (NU2002)*, Munich, May 25-30
M.Altmann et al., 2000, *Phys. Lett.* **B490**, 16
E.Bellotti et al. (GNO collaboration), 2000, in *Neutrino 2000, Proc. of the XIXth Int. Conf. On Neutrino Physics and Astrophysics*, 16-21 June, eds. J.Law
R.W.Ollerhead, J.J.Simpson, 2001, *Nucl. Phys. B (Proc. Suppl.)* **91**, 44
Y.Fukuda et. al., 1996, *Phys. Rev. Lett.* **77**, 1638
S. Fukuda et al., 2001, *Phys. Rev. Lett.* **86**, 5651
Q.R. Ahmad et al., 2001, Phys. Rev. Lett. 87, 71301
Q.R. Ahmad et al., 2002, Phys. Rev. Lett. 89, 11301

[2] K. Eguchi et al. (KamLAND collaboration), hep-ex/0212021

[3] V. Barger, D. Marfatia, hep-ph/0212126
   G. L. Fogli, E. Lisi, A. Marrone, D. Montanino, hep-ph/0212127
   M. Maltoni, T. Schwetz, J. W. F. Valle, hep-ph/0212129
   A. Bandyopadhyay, S. Choubey, R. Gandi, S. Goswami, hep-ph/0212146
   J. N. Bahcall, M. C. Gonzalez-Garchia, C. Peña-Garay, hep-ph/0212147
   P. C. de Hollanda and A. Yu. Smirnov, hep-ph/0212270

[4] M. Spiro and D. Vignaud, 1990, Physics Letters B, 242 279-284

[5] J. N. Bahcall, M. N. Pinsonneault, S. Basu, astro-ph/0010346

[6] J. N. Bahcall astro-ph/0108145

[7] J. N. Bahcall, 1989, Neutrino Astrophysics Cambridge University Press, Cambridge

[8] A. Kopylov, 2003, Lithium Project, Report at LowNU2003 Conference
   Paris, France
   A. Kopylov and V. Petukhov, hep-ph/0301016, hep-ph/0306148

[9] M. Nakahata, 2003, XMASS Project, Report at LowNU2003 Conference
   Paris, France

[10] J. N. Bahcall, M. C. Gonzalez-Garcia, and C. Peña-Garay, hep-ph/0212331

[11] J. N. Bahcall, 1994, The $^7$Be Solar Neutrino Line: A Reflection of the
    Central Temperature Distribution of the Sun, Preprint IASSNS-AST 93/40

[12] G. V. Domogatsky, 1969, Preprint of Lebedev Phys. Inst., Moscow, no.153

[13] J. N. Bahcall, Rev. Mod. Phys. 50 (1978) 881

[14] M. Galeazzi, G. Gallinaro, F. Gatti et al., 1997,
    Physics Letters B 398, 187
[15] J.N.Bahcall, 1964, *Physics Letters* **3**, 332  
G.T.Zatsepin, V.A.Kuzmin, 1965, *On the neutrino spectroscopy of the Sun*, in *Proceedings of the 9th International Cosmic Ray Conference, London*, 1024

[16] J.K.Rowly, 1978, *Proc.Conf.on Status and Future of Solar Neutrino Research, BNL*, Jan., 5-7, p.265  
E.Veretenkin, V.Gavrin, E.Yanovich, 1985, *Russian Journal “Atomic Energy”* **88**, N1, 65  
A.V.Kopylov, A.N.Likhovid, E.A.Yanovich, G.T.Zatsepin, 1993, *Proc. Intern. School “Particles and Cosmology”, Baksan Valley, Russia, 22-27 April 1993. Editors: E.N.Alekseev, V.A.Matveev, Kh.S.Nirov, V.A.Rubakov, World Scientific, Singapore-New Jersey-London-Hong Kong*, p.63  
S.Danshin, G.Zatsepin, A.Kopylov et al., 1997, *Part. Nucl.*, **28**, 5  
M.Galeazzi, G.Gallinaro, F.Gatti et al., 1997, *Physics Letters B* **398**, 187  
A.V.Kopylov, 2000, *in Proc.Intern.Conf. on Nonaccelerator New Physics, Dubna, Russia, June 28 – July 3, 1999, Russian Journal “Nuclear Physics”, 2000, 63, N7*, p.p.1345-1348

[17] R.L.Brodzinski et al., 1990, *NIM A292*, p.337

[18] F.Avignone, 2003, *MAJORANA Project, Report at NANP2003 Conference, Dubna, Russia*