Neutrinos from CNO cycle at the present epoch of the solar neutrino research

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The CNO cycle suggested by Hans Bethe [1] and Carl von Weizsacker [2] contributes only a small fraction to the energy generated in the Sun. It is the main source of energy for more massive stars. However, the study of CNO cycle is now very important by several reasons and future experiments will certainly aim at this task. In a way, the unknowns related to CNO cycle constitute the last missing chain to compose the total picture of the energy generation in the Sun. The study of solar neutrinos achieved a great progress during last 40 years. The discovery of neutrino oscillations, the positive sign of $\delta m^2_{12}$ from the observed MSW effect in the solar matter, the measurement of the parameters of the neutrino oscillation in the solar neutrino experiments [3] - [9] plus KamLAND [10] – these are the major milestones of this study. We are approaching the era of precision measurements in the solar neutrino research. But there is a missing chain in this construction. Let’s look at the equation of the balance for the solar energy:

$$0.918 f_{pp} + 0.002 f_{pep} + 0.07 f_7 + 0.01 f_{CNO} = 1$$  \hspace{1cm} (1)

Here the fluxes $f_i$ refer to the ratio of the generated fluxes to the ones calculated by the standard solar model and the coefficients by $f_i$ are the weights of the corresponding nuclear reactions in the total energy generated in the Sun.

This (1) can be rewritten as

$$0.918 f_{pp} + 0.002 f_{pep} = 1 - 0.07 f_7 - 0.01 f_{CNO} \hspace{1cm} (2)$$

The physical meaning of the (2) is simple: the uncertainty of the pp-flux (with the associated flux of pep-neutrinos directly connected with the first one) is determined by two unknowns – the flux of beryllium neutrinos $f_7$ and the flux of CNO-neutrinos (so far we do not differentiate here the flux $f_{13}$ from the decay of $^{13}$N and the flux $f_{15}$ from the decay of $^{15}$O). The flux $f_7$ has been measured recently in Borexino experiment [11] with the uncertainty of about 10%. One can see from the (2) that 10% uncertainty in the determination of $f_7$ can be transferred into 0.7% uncertainty for pp-neutrinos. The aim for the future of the Borexino is 5% uncertainty. This will result in 0.35% uncertainty for pp-neutrinos. To get the same contribution from CNO neutrinos the flux $f_{CNO}$ should be measured with the uncertainty 35%, i.e. 7 times higher than that of Borexino as it follows just from the ratio of the corresponding weights in (2). Only then one can claim that the uncertainty of pp-neutrinos is less than 1%. This can be summarized in the following statement: the contribution of the CNO cycle to the solar luminosity is small but unknown, to get precision in the evaluation of pp-flux one needs to measure $f_{CNO}$ to find out exactly how small this contribution is. Quite appropriate question is – why it
is important to get a very precise value for the flux of pp-neutrinos generated in the Sun? Future precise measurements of the flux of pp-neutrinos can be compared with the value found from (2). If there is no match, i.e. the observed flux turns out to be smaller than one found from (2), this can be interpreted as a presence of still unknown (hidden) source of solar energy. Other possibility – is the existence of sterile neutrinos by which some part of energy is leaked out into the channel which can’t be directly observed in experiment. The only indication will be the observed deficit of pp-neutrinos. Obviously, the sensitivity of these experiments is directly connected with the precision obtained in measurements of $f_7$ and $f_{CNO}$.

In evaluating the contribution of the CNO cycle to the solar energy one should be very cautious with details. Here it is worth to emphasize that when we mention CNO neutrinos we should take into consideration that in CNO cycle two kinds of neutrinos are generated: neutrinos from the decay of $^{13}\text{N}$ and of $^{15}\text{O}$. There are also neutrinos from the decay of $^{17}\text{F}$ but their flux is much lower, so far let’s not take this into consideration. The isotope $^{13}\text{N}$ is generated in $(p,\gamma)$ reaction on $^{12}\text{C}$, and $^{15}\text{O}$ - on $^{14}\text{N}$. These are two branches of the main loop of the CNO cycle (see Fig.1). Usually the conjecture is made that CNO cycle is in a stationary state, i.e. the nuclear rates of left and right branches of the Loop I presented on Fig.1 are nearly equal. But in reality it may turn out to be different. It well may be that due to some instabilities in the interior of the Sun (for example $^3\text{He}$ instability etc well discussed since long time ago) the nuclear rate of the left branch of the Loop I is substantially higher than the one of the right branch. The energy released in the thermonuclear reactions of CNO cycle in this case will be substantially different than SSM suggests. In other words: the contribution of CNO cycle to the total energy produced in the Sun depends not only on the heavy element abundance in the solar matter but also on the degree of the deviation from the stationary state of the very CNO cycle. When we discuss what is really excluded by experimental data we should also take this into consideration. In fact this means that it is necessary to measure both neutrino fluxes: $f_{13}$ and $f_{15}$ and look at what energy is produced in left and right branches of the Loop I.

![Figure 1: CNO-cycle.](image)

The isotopes $^{12}\text{C}$ and $^{14}\text{N}$ are used as the catalysts and are not spent during running of the CNO cycle. But in reality the picture is not quite symmetric. During running of CNO cycle the isotope $^{12}\text{C}$ has been burned in the thermonuclear reaction as a fuel abundant in the material of the initial protostellar cloud. As a result of this process at the initial stage of the formation of the Sun the isotope $^{14}\text{N}$ has been accumulated till the level which corresponds to the stationary level when the reaction rates for the generation of $^{12}\text{C}$ and $^{14}\text{N}$ nearly equal. At this stage the flux $f_{13}$ and the flux $f_{15}$ are nearly equal. There is some region where the temperature is high enough for the $(p,\gamma)$ reaction on $^{12}\text{C}$ but not high enough for the one on $^{14}\text{N}$. This is why the flux $f_{13}$ is always a bit higher than the flux $f_{15}$. But what will be in a non stationary case when two branches of the main loop are a bit “out of order”? Is it possible at all that some non stationary case can be realized? It has been shown in [12], [13] that...
some mild mixing is allowed when there’s a small influx of fresh material from external layers to the core of the Sun which increases substantially the abundance of $^{12}\text{C}$ in the core and, as a consequence, the flux $f_{13}$ and, as a consequence, the energy yield from left branch of the Loop I of the CNO cycle. The calculations show that mixing which will not come in conflict with the results of helioseismology can increase the flux $f_{13}$ by 50% and even more and, consequently, the energy produced by left branch also by 50% and even more. The current experimental program should be ready to this outcome.

What possibilities do we have to measure the neutrino fluxes generated in CNO cycle? Fig.2 shows the energy spectra of recoil electrons from $(\nu e^-)$ scattering for the case of ideal energy resolution.

![Energy Spectra](image.png)

**Figure 2:** The differential energy spectra for recoil electrons for SSM and for the model with the increased flux $f_{13}$.

One can see from this figure that the effect from CNO neutrinos is composed only from small fragments on top of the relatively big areas for $^7\text{Be}$- and pep-neutrinos. The energy resolution of the detectors smears the picture. The background from the internal radioactivity is another factor, making difficult the task of the extraction of the signal from CNO neutrinos from the measured energy spectrum. In the meantime, the very signal from $^7\text{Be}$- and pep-neutrinos is obtained by a certain conjecture about the probable fluxes $f_{\text{CNO}}$. Then how to extract the CNO fluxes? Deconvolution from the shape of the energy spectrum will hardly bring result in view of all complications mentioned earlier. One possibility is to use detectors with different sensitivities to different fluxes. For example, if to use detectors with different thresholds of the detection of solar neutrinos, this principally can solve the problem. This can be both electronic and radiochemical detectors. A good example of the first one is a LENS detector [14], of the second one – a lithium detector [13], [15]. In future it is quite perspective to use detectors with a large volume of liquefied noble gases as scintillators (projects XMASS [16], CLEAN [17]) to study dark matter and solar neutrinos. The interesting possibilities are suggested also by newly developed detector with a $^{100}\text{Mo}$ target [18]. These experimental programs have good prospects for new discoveries. The Sun as a powerful source of neutrinos of different energies will always attract attention of experimentalists. The detectors of new generation in newly developed underground laboratories will provide new possibilities for high precision measurements. These two factors present certain guarantees that study of solar neutrinos will be for quite a long time a very fruitful field for new discoveries.

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