Part IV
The Sun and the Solar System

Solar Physics and Neutrino Problem

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Abstract

The connection between solar physics and neutrino physics is discussed. The so called "Neutrino Problem" and methods of neutrino registrations are presented.

Introduction

What is neutrino?

Neutrino is an elementary particle moving with the speed of light and having spin 1/2. Neutrino is generated in processes of natural radioactivity, nuclear reactions and into accelerators of particles, but the main source of neutrinos are thermonuclear reaction in the core of Sun and stars. There are three types of neutrino - electron neutrino ν_e, muon neutrino - ν_μ and tau neutrino - ν_τ, related, respectively, to the massive leptons.

Why study this?

Because of that neutrinos do not almost interact with the matter, they come to us from places impossible to be observed by traditional methods of astronomy. Using neutrino telescopes we can look at the cores of the stars and explore processes that take part in these regions. Neutrino observations give us the possibility to study the internal structure of the Sun and to verify our theoretical models for this structure. Neutrino observations help us also to understand the explosion of supernovae and mechanisms of faint interactions. If this particle has mass at rest it can modify the evaluation of the dark matter (hidden mass) in the Universe.

What do we expect?

In the days of the beginning of neutrino astronomy it poses a problem which is not solved yet. This is the problem of solar neutrinos. It can be simply formulated: the observed solar neutrino flux does not match with the predicted one by the so called "standard solar model". One of the main goals of neutrino astronomy is to find solution of this problem and to try to answer, is the standard model is not correct or our knowledge of the nature of neutrino is incomplete.

Neutrino astronomy also gives us the possibility to understand in details stellar evolution till the spectacular end of some types of stars.

1 Neutrino generation

1.1 p - p chain

The main source of neutrinos are the star cores. In the case of the Sun the main reaction, responsible for neutrino flows is the so called p-p chain. Below are shown reactions of p-p chain and maximal energy of generated neutrino:

$$p + p \rightarrow {}^2H + e^+ + \nu_e \qquad \leq 0.42 MeV \tag{1}$$

or

$$p + e^- + p \rightarrow {}^2H + \nu_e \qquad 1.442 MeV \tag{2}$$

$${}^2H + p \rightarrow {}^3He + \gamma$$

$${}^3He + {}^3He \rightarrow \alpha + 2p$$

or

$${}^3He + {}^4He \rightarrow {}^7Be + \gamma$$

$${}^7Be + e^- \rightarrow {}^7Li + \nu_e \qquad (90\%)\ 0.861\ MeV \tag{3}$$

$${}^7Li + p \rightarrow 2\alpha$$

or

$${}^7Be + p \rightarrow {}^8B + \gamma$$

$${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e \qquad \leq 15\ MeV \tag{4}$$

$${}^8Be^* \rightarrow 2\alpha$$

or

$${}^3He + p \rightarrow {}^4He + e^+ + \nu_e \qquad \leq 18.77\ MeV \tag{5}$$

The main part of solar neutrinos is due to the first of these reactions. Unfortunately ${}^{37}Cl$ detector and Kamiokande are not enough sensible to register these neutrinos. They will be registered by ${}^{71}Ga$ - detector. The second reaction has probability 0.4% of the first one, but the energy of generated neutrino is higher, so it can be detected in our detectors.

15% of the entire time ${}^3He$ interacts with α - particle and forms ${}^7Be$ and γ quantum. This reaction (3) gives a small quantity of neutrino detection in ${}^{37}Cl$ and ${}^{71}Ga$ detectors. Reaction (4) has probability only 1/5000 of the first reaction, but this reaction is the main reaction, which is registered in ${}^{37}Cl$ - detector and Kamiokande detector. Reaction (5) happens very rarely - only 2 times of 10^7 events of reaction (1).

1.2 CNO chain

This mechanism of energy generation produces only 1.5% of the solar luminosity (standard model) and is not so important for neutrino generation, but may be important in other type of stars whit higher temperatures. The main reactions of CNO - chain (in the case of the Sun) are presented here:

$$\begin{aligned}
{}^{12}C + p \rightarrow\ & {}^{13}N + \gamma \\
{}^{13}N \rightarrow\ & {}^{13}C + e^+ + \nu_e \quad \leq 1.199\ MeV \\
{}^{13}C + p \rightarrow\ & {}^{14}N + \gamma \\
{}^{14}N + p \rightarrow\ & {}^{15}O + \gamma \\
{}^{15}O \rightarrow\ & {}^{15}N + e^+ + \nu_e \quad \leq 1.732\ MeV \\
{}^{15}N + p \rightarrow\ & {}^{12}C + \alpha.
\end{aligned}$$

The neutrinos generated in CNO - chain have energies higher than threshold of our detectors, so they must be taken into account.

1.3 Solar neutrino problem

As it was mentioned above the first detector of solar neutrino surprised the scientists. The predicted frequency of neutrino registration does not coincide with observed one. This is the so called Solar Neutrino Problem.

For measure of solar neutrino is accepted unit . 1 SNU is equal of 10^{-36} interactions in the target matter per second.

The predicted frequency in ${}^{37}Cl$ target is (7.9 ± 2.6) SNU. The observed frequency is (2.1 ± 0.9) SNU, where error is 3σ.

This problem is not solved yet, there are many explanations, but only future experiments can determine the right solution.

The existence of this problem was observed also on the Japan detector Kamiokande. The preliminary result of this detector shows

$$\frac{\phi_{obs}}{\phi_{theor}} = 0.45 \pm 0.15, \tag{6}$$

where ϕ is the flow of ${}^{8}B$ solar neutrinos, and error is 1 σ.

2 Neutrino registration

2.1 Methods of registration

Methods of neutrino registration are based on the classical methods of neutral particles detection in nuclear physics, namely:

- direct methods - These methods use generation of charged particle (non-elastic detectors).

- indirect methods - These methods use momentum transfer between neutrino and a charged particle (momentum detectors).

Non - elastic reactions are always reactions of the type:

$$\nu + A \rightarrow X + A^{'} \ ,$$

where A and $A^{'}$ are nuclei and X is a number of charged particles (ordinary reduced to the leptons related to the neutrino). $A^{'}$ must be in an instable state, which reaches stable state trough β or γ decay.

The sensibility of the detectors based on these reactions strongly depends on the energy of the incident neutrino because the effective cross-sections of the reactions are proportional to the energy E_{ν} of the neutrino.

Indirect methods use reaction:

$$\nu + A \rightarrow \nu + A$$

$$E^{\nu}_{initial} = E^{\nu}_{final} + E^{A} \ ,$$

where $E^{n}_{initial}$ is initial neutrino energy, E^{n}_{final} is the final and E^{A} is absorbed energy from the target nucleus. The absorbed energy makes nucleus to move and this movement can be detected by heating it produces.

For the practical realization of non-elastic reaction detectors are used two methods:

a) radio-chemical, which is based on of the reactions:

$$\nu + A \rightarrow e^{-} + A^{'}$$

$$A^{'} \rightarrow e^{-} + A^{"}$$

or

$$\tilde{\nu_e} + A \rightarrow e^{+} + A^{'}$$

$$A^{'} \rightarrow e^{-} + A^{"}$$

The first detector of this type is proposed and constructed by R. Davis and uses Cl nuclei:

$$\nu + \ ^{37}Cl \rightarrow e^{-} + \ ^{37}S$$

Energy threshold for this reaction is 0.81 MeV. That means that neutrinos with energy below 0.81 MeV can be registered. A more sensitive reaction is:

$$\nu + \ ^{71}Ga \rightarrow e^{-} + \ ^{71}Ge$$

$$^{71}Ge \rightarrow e^{-} + \ ^{71}Zn$$

This reaction has energy threshold of 0.24 MeV. Unfortunately this method has many internal restrictions. It does not permit to determine the direction of incident neutrino flow (zero angular resolution). It is impossible to find the energy spectrum of the neutrino source and exact time of neutrino registration (zero time resolution).

b) cascade method - This method is based on the reaction:

$$\nu + \ ^{115}In \rightarrow e^{-} + \ ^{115}Sn^{*}$$

$$^{115}Sn^* \rightarrow ^{115} Sn^{**} + \gamma(100keV) \quad \tau = 3.25\mu s$$
$$^{115}Sn^{**} \rightarrow ^{115} Sn + \gamma(500keV) \quad \tau = 0.1ns$$

The double γ decay is characteristic signature of this reaction and eliminate background noise. This method permits to know exact time of neutrino detection with a precision of some nanoseconds.

The realization of detectors, based on the elastic reactions, also can be divided into types:

a) super conductive cameras - these cameras use the neutrino scattering on massive nuclei in a superconductive target. The effective cross-section of these elastic reactions is expressed by formula:

$$\sigma = 0.4210^{-44} N^2 E_\nu^2 \ ,$$

where N is the atom number of the target atoms and E_ν is the energy of the incident neutrino expressed in MeV. The average energy absorbed in target nuclei is

$$E = 2E_\nu^2/(3Nm_n) \ ,$$

where m_n is the mass of the nucleon

This absorbed energy leads to a small heating δT of the target matter. If the super-conductor has a temperature very close to the critical temperature of the transition superconductive state - normal state, the additional heat changes the state of the super-conductor, which can be registered.

This type of detectors permits to register energy spectrum of neutrino sources, but the practical realization is very delicate task.

b) neutrino mirror - this method is only theoretical possibility nowadays because it is necessary to determine momentum transfer δp, which is under threshold of sensibility of the systems for detection of gravitational waves.

2.2 Neutrino detectors (Telescopes)

a) ^{37}Cl - experiment

This experiment uses reaction

$$\nu_e + \ ^{37}Cl \rightarrow \ e^- + \ ^{37}Ar$$

and was proposed by Davis et al. (1969). The experimental construction is shown in Fig. 1.

The target is a reservoir, containing $4.10^5 l$ C_2Cl_4 and put deep underground in mine Homestake (USA). The detector is put underground to eliminate the background noise from the cosmic rays. During 15 years R. Davis and his collaborators extracted a small quantity ^{37}Ar, collected during some months of registration. The experiments showed that ^{37}Ar can be extracted with an effectiveness higher than 90%. The average velocity of ^{37}Ar production is equal to 0.462 ± 0.04 atom/day, a small part of this velocity is due to the background noise: $V_{noise} = 0.08 \pm 0.03$ atom/day. The computed velocity of neutrino interaction is therefore (2.05 ± 0.3) SNU. Nine experiments carried out in the

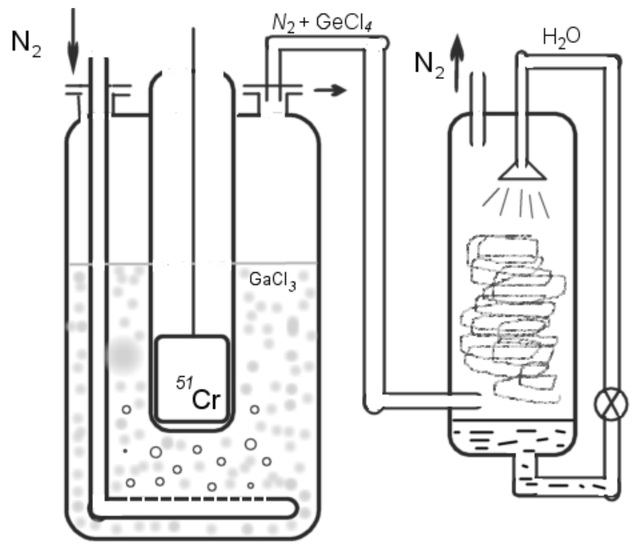

Figure 1: The ^{71}Ga neutrino detector

period 1986 - 1988 showed a higher velocity of interaction than that in the period 1970 - 1986.

This experiment showed that SNO - chain was not so important in the case of the Sun (if CNO - chain dominates the theoretical interaction velocity must be 29 SNU), and probably the Standard Solar Model needs corrections.

b) Kamiokande experiment

Kamiokande experiment is realized in Japan. It uses reaction:

$$\nu + e \rightarrow \nu' + e',$$

where prime means changes in the momentum and energy of the particles. These changes are registered by Cerenkov radiation of the moving electrons. The threshold of the above reaction is > 5 MeV and only ^8B and *hep* - neutrinos can be detected, but this method of registrations have some angular resolution, so the source of neutrinos can be identified.

The detector is a reservoir of 3.10^3t of pure water and produced photons are captured by a big amount of photo-amplifiers. In 1984 the detector was modernized to reduce the threshold of registration. A similar detector (IBM) works in Ohio (USA). Kamiokande and IBM detectors for first time registered neutrinos from an extra-solar source - supernova SN1987A. Kamiokande results also confirm the existence of Solar Neutrino Problem, as it was mentioned in section "Solar neutrino problem".

c) ^{71}Ga - detectors

Nowadays there are two experiments, which use ^{71}Ga as target matter. The first one is GALLEX - experiment of western Europe countries, the second -

SAGE - is a Russian-American collaboration. GALLEX detector is located in the mountains of Italy, and uses 30 t water solution of Ga. SAGE is located in the Caucasus mountains and uses 60 t metallic Ga. These two detectors work on the base of reaction:

$$\nu_e + {}^{71}Ga \rightarrow e^- + {}^{71}Ge$$

Atoms of Ge are extracted by chemical way from the Ga solution, and radioactive decay of these atoms is counted in proportional detectors. The threshold of the above reaction is 0.233 MeV, which permits to register pp - neutrinos.

2.3 SN1987A - First extra-solar neutrino detection

The first registration of extra-solar neutrino source was made by water detectors Kamiokande and IBM (Hirata et al., 1987; Bionta et al., 1987). The American detector IBM registered at 7h 35 min 35s UT (February 23, 1987) 8 events during 6 s. Almost in the same time the Japanese detector Kamiokande registered 11 events. Unfortunately, the time registration of Kamiokande was not enough precise to determine a difference of 0.04s needed neutrinos to cross the Earth.

Russian-Italian detector LSD, located under Mont Blanc also reported neutrino detection - 5 neutrinos during 7s, but at 2h 52min UT or 4 hours before other registrations. This registration is still under discussion because other detectors do not mentioned such event.

3 Explanations of Solar Neutrino Problem

There are two types of "solutions" of this problem: the first ones involve changes into astrophysical model of the Sun, to build a non-standard model, the second ones give new properties to the neutrino for building a non-standard theory of electro-weak interactions.

Typical representative of the first class is the so called model of small Z. Because of that neutrino production strongly depends of the temperature in the core of the star, the decrease of the temperature leads to a decrease in neutrino flux. The temperature gradient inside the Sun is proportional to the radiative opacity and therefore the decrease of the opacity leads to decrease of the temperature in the center of the Sun. In this model this decrease of the opacity is reached by assumption of small contents of heavy elements - Z in the core of the Sun.

Another model of this group is the model of fast rotating solar core. This model assumes that fast rotation in the core decreases the plasma pressure, necessary for keeping balance against the gravity force. Helioseismological explorations, however, do not support such a supposition.

There are models based on strong magnetic field, strong diffusion, black hole in the center of the Sun, weakly interacting massive particles (WIMP) Q-nuclei and so on, but all these models have difficulties to describe all observed characteristics of the Sun.

The theory of Mihaev, Smirnov and Wolfenstein (MSW theory) is the most popular explanation of the neutrino problem, representative of the second type "solutions".

In this theory electron neutrinos ν_e born into core of the Sun, almost completely transform themselves into muon or tau neutrinos - ν_μ, ν_{tau}, when they cross the Sun. This transformation is due to the increased probability of neutrino oscillations in the solar medium. For realization of MSW effect it is necessary neutrino different states $(\nu_e, \nu_\mu, \nu_{tau})$ to have different masses. Nowadays the problem of neutrino mass is under discussion and only new exploration and detectors will answer which is the right explanation.

Conclusion

The solar neutrino problem needs more extensive experiments to determine the real reason for the appearance of this phenomenon. These experiments are very expensive and can be realized only in the frames of large international collaboration.

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