Possible tests for sterile neutrinos

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Abstract

It is shown that the future SNO and Super-Kamiokande experiments, in which high energy $^8$B neutrinos will be detected through the observation of CC, NC and $\nu-e$ elastic scattering processes, could allow to reveal in a model independent way the presence of sterile neutrinos in the flux of solar neutrinos on the earth.

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We discuss here some possibilities to reveal transitions of solar $\nu_e$’s into sterile states in the future SNO and Super-Kamiokande (S-K) experiments. According to the hypothesis of neutrino mixing, the flavor neutrino fields $\nu_{\ell L}$ are linear combinations of the left-handed components of neutrino fields $\nu_i L$ with masses $m_i$:

$$\nu_{\ell L} = \sum_i U_{\ell i} \nu_i L,$$

(1)

where $U$ is a unitary mixing matrix.

From the data of LEP experiments it follows that the number of flavor neutrinos is equal to three. If the total lepton number is conserved, massive neutrinos are Dirac particles and the number of massive neutrinos is equal to three. On the other hand, in the Majorana case the number of light neutrinos with definite mass can vary from three to six (see [5]). If this number is more than three, in addition to Eq.(1) we have

$$\left(\nu_{\ell R}\right)^c = \sum_i U_{\ell i} \nu_i L,$$

(2)

where $\left(\nu_{\ell R}\right)^c = C\nu_{\ell R}^T$ is the charge-conjugated field. Due to the mixings (1) and (2), not only transitions between active neutrinos $\nu_{\ell L} \rightarrow \nu_{\ell' L}$ are possible, but also transitions between active and sterile neutrinos $\nu_{\ell L} \rightarrow \bar{\nu}_{\ell' L}$ ($\nu_{\ell R}$ and $\bar{\nu}_{\ell L}$ are the quanta of the right-handed fields $\nu_{\ell R}$). The quanta of the right-handed fields are called sterile because they do not enter in the Lagrangian of the standard weak interactions.

Transitions of active neutrinos into sterile states can exist only in models beyond the Standard Model. Thus, the discovery of transitions of active neutrinos into sterile states would have a fundamental importance for the theory. The existing data do not exclude such transitions. The data of all solar neutrino experiments can be explained if $\nu_e$ is mixed with a sterile neutrino $\nu_s$. Assuming the correctness of the Standard Solar Model (see [6]), the following values of the mixing parameters were obtained [7]:

$$\Delta m^2 \simeq 5 \times 10^{-6} \text{eV}^2 \quad \text{and} \quad \sin^2 2\theta \simeq 7 \times 10^{-3}.$$

(3)

Let us remark that these values of the mixing parameters are compatible with the constraints on $\nu_e$-$\nu_s$ mixing obtained [8] from big-bang nucleosynthesis.

Information about the transitions of active neutrinos into sterile states can be obtained only through the measurement of the total transition probability of an active neutrino $\nu_{\ell}$ into all possible active neutrino states, $\sum_{\ell' = e, \mu, \tau} P_{\nu_{\ell} \rightarrow \nu_{\ell'}}$, or any average of this quantity. If it occurs that this total transition probability is less than one, it would mean that transitions of active neutrinos into sterile states take place.

It is obvious that we can obtain information about the total transition probability only through the investigation of neutral-current (NC) neutrino processes. In 1996 two new solar neutrino experiments will start. In the SNO experiment solar neutrinos will be detected through the observation of the following charged-current (CC), elastic (CC and
NC) and NC processes:

\[ \nu_e + d \rightarrow e^- + p + p \quad \text{(CC)} \]  \hspace{1cm} (4)

\[ \nu + e^- \rightarrow \nu + e^- \quad \text{(ES)} \]  \hspace{1cm} (5)

\[ \nu + d \rightarrow \nu + p + n \quad \text{(NC)} \]  \hspace{1cm} (6)

In the CC process (4), the electron spectrum will be measured and the flux of solar \( \nu_e \)'s on the earth as a function of neutrino energy \( E, \phi_{\nu_e}(E) \), will be determined [2].

In the S-K experiment [3] solar neutrinos will be detected through the observation of the ES process (5). The event rate is expected to be about 100 times larger than in the current Kamiokande experiment and the spectrum of the recoil electrons will be measured with high accuracy.

In both the SNO and S-K experiments, due to the high energy thresholds (\( \simeq 6 \text{ MeV} \) for the CC process, \( 2.2 \text{ MeV} \) for the NC process and \( \simeq 5 \text{ MeV} \) for the ES process), only neutrinos coming from \(^{8}\text{B}\) decay will be detected. The energy spectrum of the initial \(^{8}\text{B}\) \( \nu_e \)'s can be written as

\[ \phi_{\nu_e}(E) = \Phi_B X(E) . \]  \hspace{1cm} (7)

Here \( X(E) \) is a known [4] normalized function determined by the phase space factor of the decay \(^{8}\text{B}\rightarrow^{8}\text{Be} + e^+ + \nu_e\), and \( \Phi_B \) is the total flux of initial \(^{8}\text{B}\) solar \( \nu_e \)'s.

Let us consider first the NC process (6). The total NC event rate, \( N^{\text{NC}} \), is given by

\[ N^{\text{NC}} = \int_{E_{\text{th}}} \sigma^{\text{NC}}_{\nu d}(E) \sum_{\ell=e,\mu,\tau} P_{\nu_e \rightarrow \nu_{\ell}}(E) X(E) dE \Phi_B \]

\[ = \left< \sum_{\ell=e,\mu,\tau} P_{\nu_e \rightarrow \nu_{\ell}} \right>_{\text{NC}} X^{\text{NC}}_{\nu d} \Phi_B . \]  \hspace{1cm} (8)

Here \( \sigma^{\text{NC}}_{\nu d}(E) \) is the cross section of the NC process (6), \( E_{\text{th}} \) is the threshold neutrino energy and

\[ X^{\text{NC}}_{\nu d} \equiv \int_{E_{\text{th}}} \sigma^{\text{NC}}_{\nu d}(E) X(E) dE \simeq 4.7 \times 10^{-43} \text{ cm}^2 . \]

If \( \left< \sum_{\ell=e,\mu,\tau} P_{\nu_e \rightarrow \nu_{\ell}} \right>_{\text{NC}} < 1 \) it would mean that there are transitions of solar \( \nu_e \)'s into sterile states. However, from Eq.(8) it is clear that we cannot reach any conclusion on the value of \( \left< \sum_{\ell=e,\mu,\tau} P_{\nu_e \rightarrow \nu_{\ell}} \right>_{\text{NC}} \) without assumptions about the value of the total \(^{8}\text{B}\) neutrino flux \( \Phi_B \).

Let us now consider the ES process (5). In order to separate the NC contribution to the ES event rate we must use the information on the flux of solar \( \nu_e \)'s on the earth \( \phi_{\nu_e}(E) \) that can be obtained from the CC process in SNO. We have

\[ \left< \sum_{\ell=e,\mu,\tau} P_{\nu_e \rightarrow \nu_{\ell}} \right>_{\text{ES}} X_{\nu_e} \Phi_B = \sum_{\text{ES}} \]  \hspace{1cm} (9)
with
\[
\left\langle \sum_{\ell=e,\mu,\tau} P_{\nu_e \to \nu_\ell} \right\rangle_{\text{ES}} = \int_{E_{\text{th}}} \sigma_{\nu_\ell e}(E) X(E) \sum_{\ell=e,\mu,\tau} P_{\nu_\ell e}(E) dE
\]
\[
= \frac{X_{\nu_\ell e}}{\Sigma_{\text{ES}}}
\]
and
\[
\Sigma_{\text{ES}} \equiv N_{\text{ES}} - \int_{E_{\text{th}}} \left( \sigma_{\nu_\ell e}(E) - \sigma_{\nu_\mu e}(E) \right) \phi_{\nu_e}(E) dE
\]
Here \(N_{\text{ES}}\) is the total ES event rate, \(\sigma_{\nu_\ell e}(E)\) is the cross section of the process \(\nu_\ell e \to \nu_\ell e\) (with \(\ell = e, \mu\)) and
\[
X_{\nu_\ell e} \equiv \int_{E_{\text{th}}} \sigma_{\nu_\ell e}(E) X(E) dE \simeq 2 \times 10^{-45} \text{ cm}^2
\]
for \(E_{\text{th}} \simeq 6\text{ MeV}\) (which corresponds to a kinetic energy threshold \(T_{\text{th}} = 4.5\text{ MeV}\) for the electrons in the CC process).

Combining the relations (8) and (9), we obtain
\[
\frac{1 - \left\langle P_{\nu_\ell e \to \nu_\ell e} \right\rangle_{\text{ES}}}{1 - \left\langle P_{\nu_\ell e \to \nu_\ell e} \right\rangle_{\text{NC}}} = \frac{\Sigma_{\text{ES}} X_{\nu_\mu e}}{N_{\text{NC}} X_{\nu_\ell e}} \equiv R_{\text{ES}}^{\text{NC}}
\]

(10)

The ratio \(R_{\text{ES}}^{\text{NC}}\) is a measurable quantity. It does not depend on the flux \(\Phi_B\). If it will occur that \(R_{\text{ES}}^{\text{NC}} \neq 1\) it would mean that there are transitions of solar \(\nu_e\)’s into sterile states. Of course, if \(R_{\text{ES}}^{\text{NC}} = 1\) it is not possible to reach any conclusion about the presence of \(\nu_e \to \nu_s\) transitions (\(R_{\text{ES}}^{\text{NC}} = 1\) if \(P_{\nu_\ell e \to \nu_\ell e}(E) = 0\), but also if \(P_{\nu_\ell e \to \nu_\ell e}(E) = \text{constant}\).

In the S-K experiment the energy spectrum of the recoil electron will be investigated in detail. This measurement will allow to perform other test of the existence of sterile neutrinos. We have
\[
\left\langle \sum_{\ell=e,\mu,\tau} P_{\nu_\ell e \to \nu_\ell e} \right\rangle_{\text{ES};T} = \frac{\Sigma_{\text{ES}}(T)}{X_{\nu_\ell e}(T) \Phi_B}.
\]
(11)

Here
\[
\Sigma_{\text{ES}}(T) \equiv n_{\text{ES}}(T) - \int_{E_{\text{th}}(T)} \left[ \frac{d\sigma_{\nu_\ell e}}{dT}(E, T) - \frac{d\sigma_{\nu_\mu e}}{dT}(E, T) \right] \phi_{\nu_e}(E) dE
\]
\[
\equiv n_{\text{ES}}(T) - \int_{E_{\text{th}}(T)} \left[ \frac{d\sigma_{\nu_\ell e}}{dT}(E, T) - \frac{d\sigma_{\nu_\mu e}}{dT}(E, T) \right] \phi_{\nu_e}(E) dE,
\]
(12)
is a measurable quantity (\(n_{\text{ES}}(T)\) is the spectrum of the recoil electrons, \(T\) is the electron kinetic energy, \(\frac{d\sigma_{\nu_\ell e}}{dT}(E, T)\) is the differential cross section of the process \(\nu_\ell e \to \nu_\ell e\), with
\[ \ell = e, \mu, \tau, \quad E_m(T) = \frac{1}{2} T \left( 1 + \sqrt{1 + 2 m_e/T} \right), \text{and} \]

\[ X_{\nu_e}(T) \equiv \int_{E_m(T)} \frac{d\sigma_{\nu_e}(E,T)}{dT} X(E) \, dE \]

is a known function.

From Eq. (11) it follows that

\[ \langle \sum_{\ell=e,\mu,\tau} P^{P_{\nu_e \rightarrow \nu_{\ell}}} \rangle_{ES,T} \leq R^{ES}(T) \tag{13} \]

with

\[ R^{ES}(T) \equiv \frac{\Sigma^{ES}(T)}{X_{\nu_e}(T)} \left/ \left( \frac{\Sigma^{ES}(T)}{X_{\nu_e}(T)} \right)_{\text{max}} \right. \]

Thus, if the quantity \( \Sigma^{ES}(T)/X_{\nu_e}(T) \) depends on the energy \( T \) it would mean that solar \( \nu_e \)'s transform into sterile states.

We have calculated the ratio \( R^{ES}(T) \) in a model with \( \nu_e-\nu_s \) mixing and the values of the mixing parameters that were obtained by the fit of the solar neutrino data [4]. The results of this calculation, presented in Fig.1, illustrate the rather strong \( T \)-dependence of the ratio \( R^{ES}(T) \) in the model.

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Figure 1