Sterile neutrinos and supernova nucleosynthesis

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Abstract

The role of the sterile neutrinos to the r-process nucleosynthesis in supernova explosions is studied. Previously it has been argued that a large part of neutrino mixing can be excluded if the supernovae are the origin of the heavy elements. It is shown that a conversion to sterile neutrinos may evade those limits. The possibility that such conversions can enhance the nucleosynthesis is investigated. The desired mass spectrum is consistent with neutrino masses suggested by other observed phenomena, like the solar neutrino problem, the atmospheric neutrino problem, dark matter and the LSND signals.

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1 Light sterile neutrinos

Many theories beyond the standard model involve sterile neutrinos or similarly behaving objects. Often the new neutral fermions are not called neutrinos, since they may originate from completely different physics, but in many occasions they behave as sterile neutrinos, and may even mix with the known neutrinos. Here generically any fermion without standard model interactions, mixing with the ordinary neutrinos, is called a sterile neutrino.

Typically the sterile neutrinos are very heavy, being hence out of interest in astrophysics. However, there are also several plausible ways to generate light sterile neutrinos. The small mass for the sterile neutrinos could be generated by similar mechanisms as that of the ordinary neutrinos, like see-saw or radiative mechanisms. Since the basic theory does neither predict nor forbid light sterile neutrinos, the existence of them is fundamentally an experimental problem.

Light sterile neutrinos can provide a solution to the solar neutrino deficit, the atmospheric neutrino problem, the missing matter of the universe, the anomalous ionization of interstellar hydrogen, the explosion of a supernova, the crisis of the big bang nucleosynthesis, and the anomalies observed in the Karmen experiment (See [1] and references therein). Most of these problems can also be solved individually without sterile neutrinos, either by ordinary neutrinos or by some other objects. It is also possible that some, if not all, anomalies are due to misconceptions in underlying theory or uncontrolled phenomena in the experimental apparatus.

The standard electroweak model with three massive neutrinos allows only a simultaneous solution of two or three of the above problems, unless excessive fine tuning is applied. By introducing three sterile neutrinos one can solve almost all of the above problems simultaneously, as well as fit the alleged neutrino mixing observed by LSND [2].
2 Supernova nucleosynthesis

It is widely believed that most of the heavy elements observed in the universe, as well as on the earth, have been produced in supernovae. The reactions responsible for this are called the r-process. After the collapse the iron mantle is at heavy pressure and high temperature, and there are lots of free neutrons available. The free neutrons are captured by nuclei which can grow to the edge of stability. Since the neutron capture is faster than beta decay, the reactions can proceed through stability barriers. The process lasts only a few tens of seconds, and the products are ejected in the universe in the explosion of the star.

The success of the r-process relies on the neutron excess. If for some reasons there were more protons than neutrons, no heavy nuclei could be formed since there are no stable nuclear configuration with the proton number exceeding the neutron number for such mass numbers.

Under the immense neutrino radiation the proton to neutron ratio is dictated by the neutrino interactions. Even though the relevant region is far outside the neutrinosphere, the neutrino radiation is so intensive that all the nucleons are continuously bombarded by neutrinos. Hence, to a good approximation the neutron fraction is given by

\[ Y_n = \frac{1}{1 + \frac{F_{\nu_e} \langle E_{\nu_e} \rangle}{F_{\bar{\nu}_e} \langle E_{\bar{\nu}_e} \rangle}}, \]  

where \( F \) is the neutrino energy flux and \( \langle E \rangle \) the average neutrino energy. Assuming the fluxes to be sufficiently equal, and the average energies to be \( \langle E_{\nu_e} \rangle \sim 11 \text{ MeV} \), and \( \langle E_{\bar{\nu}_e} \rangle \sim 16 \text{ MeV} \), one obtains \( Y_n \simeq 0.6 \) which satisfies qualitatively the requirement. More detailed numerical calculations have shown that indeed the standard picture of the supernova neutrinos gives a successful synthesis of the heavy nucleids. However, there still is a small mismatch, the models do not seem to yield enough of some elements.
3 Neutrino oscillations and the r-process

Any change of the neutrino fluxes could upset the nucleosynthesis. A conversion between neutrino flavors would change the neutron fraction by changing the average energies of neutrinos, even when the neutrino fluxes would remain equal. Since muon and tau neutrinos (and antineutrinos) are emitted from a deeper region of the star, due to their lack of charged current reactions, they have higher average energies, above 20 MeV. Hence an interchange $\nu_e \leftrightarrow \nu_\mu$ would lead to $E_{\nu_e} > E_{\bar{\nu}_e}$, and consequently $Y_n < 0.5$. That would be intolerable.

To save the r-process one has to exclude a neutrino flavor conversion between the emission of neutrinos and their passage through the iron rich regions [3]. This leads to a forbidden range in the neutrino mixing plane which covers the neutrino dark matter mass range, and especially excludes the attractive scenario of having a massive muon neutrino as hot dark matter and explaining simultaneously the possible oscillation events in LSND.

It has been proposed that an inverted mass spectrum ($m_{\nu_\mu} < m_{\nu_e}$) would solve the contradiction [4]. In this case there is no conversion between muon neutrinos and electron neutrinos, instead muon antineutrinos would convert to electron antineutrinos. The resulting neutrino spectrum would be less favored by the observations of SN1987A, although not necessarily ruled out. Another unaesthetic feature of this scenario is the fancy shape of the required neutrino mass matrix.

4 Conversions to sterile neutrinos

The sterile neutrinos are not produced significantly in the core [5] unless they have relatively strong non-standard interactions. Hence the neutrino flux emitted from the neutrinosphere consists solely of the standard neutrinos. Consequently, any conversion to sterile neutrinos only reduces the effective neutrino flux.

As is clear from above, a detraction from the electron neutrino flux enhances the r-process, while diminishing the antineutrino flux endangers
its success. The deficit of electron neutrinos may take place directly, 
$\nu_e \rightarrow \nu_S$, or indirectly via other flavors: $\nu_\mu \rightarrow \nu_S$ and then $\nu_e \rightarrow \nu_\mu$. The 
indirect way is not necessarily more complicated.

A conversion from muon neutrinos to electron neutrinos can wash 
out the effects of any previous transmutations between electron neutrinos and 
sterile neutrinos. Hence the possibility for the transition $\nu_e \rightarrow \nu_S$ does 
not evade the limits for the mixing between active neutrinos, unless it 
occurs after the conversion $\nu_\mu \rightarrow \nu_e$.

The matter induced effective potentials for neutrinos are given by

$$V(\nu_e) = V_0(3Y_e - 1 + 4Y_{\nu_e} \alpha), \quad (2)$$

$$V(\nu_\mu) = V_0(Y_e - 1 + 2Y_{\nu_e} \alpha) \quad (3)$$

where $Y$ are the relevant abundances of respective particles in matter, 
and $V_0$ is a linear function of density. The factor $\alpha (0 < \alpha < 1)$ appears 
in the free streaming region since the neutrinos are all going in the same 
direction out of the core, and it is inversely proportional to the square of 
the distance from the center.

In the region outside the core where $0.35 < Y_e < 0.5$, the relevant 
potential differences for the different transitions are related as

$$|\Delta V(\nu_e \rightarrow \nu_\mu)| > |\Delta V(\nu_e \rightarrow \nu_S)| > |\Delta V(\nu_\mu \rightarrow \nu_S)|. \quad (4)$$

However, the mass differences must also fit: for $\nu_e \rightarrow \nu_S$ the mass eigen-
state dominated by the sterile state must be the heaviest state, and for 
$\nu_e \rightarrow \nu_\mu$ and for $\nu_\mu \rightarrow \nu_S$ that by muon neutrinos. For antineutrinos, 
i.e. right-handed Majorana states, the mass differences must be of the 
opposite sign. If all transitions were described by sufficiently equal mass 
differences, the one with the smallest potential difference would cross the 
resonance first (for an outgoing neutrino).

At regions close to the inner core the potentials may behave less 
smoothly. In those regions the electron density drops due to the neutro-
nisation process, and can fall below 1/3. In such a case the potential for 
electron neutrinos would change sign, and a resonance for the transition 
$\nu_e \rightarrow \nu_S$ would occur for arbitrarily small mass differences. Because of
a specific evolution of the star, two level crossings are formed, only one of which may evolve outside the neutrinosphere \[6\]. The adiabaticity requirements are very stringent, and cannot be trivially satisfied by light neutrinos \((m_\nu < 10 \text{ eV})\) for any mixing. However, the adiabaticity condition, as well as the position of the level crossing may depend strongly on the neutrino conversion itself, hence little exact can be said at this stage. Even worse, for an inhomogenous or anisotropic case there may be several resonances more.

To arrange a resonance for the transition \(\nu_e \rightarrow \nu_S\) after the respective conversion between electron and muon neutrinos a specific mass hierarchy is required: \(m_\nu^e < m_\nu^S < m_\nu^\mu (1/2)\). Again, to define the required range more exactly requires a thorough numerical study which is out of the scope of this work. Nevertheless, it can be said safely that the solar neutrino mass scale is definitely too small for this purpose.

In the presence of a conversion between electron and muon neutrinos the transition from muon neutrinos to sterile neutrinos can as well affect the nucleosynthesis \[1\]. This possibility is quite natural because of the above hierarchy \((4)\). Hence, whenever the mass differences are sufficiently equal, the \(\nu_\mu \rightarrow \nu_S\) transition can naturally pass the resonance zone outside the neutrinosphere, but before the resonance between electron and muon neutrinos. This occurs for example in the scheme having two light neutrino mass eigenstates made of the electron neutrino and a sterile neutrino, and a heavier neutrino mass eigenstate made mainly of the muon neutrino. Hence, if the muon neutrino flux has been sufficiently reduced, an interchange between muon and electron neutrinos would not kill the r-process, instead it can even enhance it.

It can be estimated that the transition \(\nu_\mu \rightarrow \nu_S\) is adiabatic, for neutrino masses in the dark matter range, if the mixing angle satisfies

\[
\sin^2 2\theta_\mu > 10^{-4} \ldots 10^{-3}.
\]  

(5)

However, a partial transition is sufficient, so that even lower mixings may be enough.

The resonance zones \((\nu_\mu \rightarrow \nu_S)\) and \((\nu_\mu \rightarrow \nu_e)\) are situated very closely, and if they are too wide they overlap. One can estimate that
the width of the resonances is narrower than the distance between the resonance zones if

\[ \sin^2 2\beta < 0.02, \]

where \( \beta \) is the largest mixing angle. For the relevant mixing angles the overlap of the resonances does not spoil the conversions.

## 5 Discussion

Although our understanding about the origin of the elements has made huge progress in the recent years, the birthplace of the heavy elements has not yet been proven. This work relies on the assumption that the heavy element nucleosynthesis indeed takes place in supernovae. This is a very justified assumption since there are no other good candidates to accommodate that process.

It was found that light sterile neutrinos with a large mixing with the ordinary neutrinos would affect the r-process. Such mixings are not forbidden by either laboratory experiments or astrophysical arguments. A large mixing would, however, violate the previous cosmological limits for the sterile neutrino mixing [7], but since these limits are based on the currently unjustified [8] requirement that there are less than 0.4 new effective neutrinos, there is no reason to abandon these solutions.

The introduction of sterile neutrinos provides a simple way to save the interpretation of the identity of the hot dark matter and the LSND signal as an indication of neutrino mass, without stretching too much the theory. Hence, even though the interpretation of the Los Alamos neutrino experiment is at present premature, it has no imminent contradiction with astrophysics.

The required mass matrices leave the possibility to solve the solar and atmospheric neutrino problems by neutrino oscillations. The simplest solution compatible with everything would be the model with two very light neutrinos, consisting of the electron neutrino and a sterile neutrino, and two heavy neutrinos, made of muon and tau neutrinos in the few eV range. The solar neutrino problem could then be solved by the conversion
from electron neutrinos to sterile neutrinos, the atmospheric neutrino problem by the oscillation between muon and tau neutrinos. These would also form the hot dark matter. The mixing between electron and muon neutrinos would then most naturally be in the region visible to LSND.

It is not yet clear whether the existence of sterile neutrinos could actually improve the fit of the nucleosynthesis model to the observations. Qualitatively this could happen, since a conversion to sterile neutrinos could increase the neutron abundance. However, the full nucleosynthesis is a very complicated network, and modelling it requires a detailed numerical simulation which has not been done yet for this case.

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