Supernova Bounds on Neutrino Properties: a mini-review

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This talk summarizes our recent work which studied the impact of resonant neutrino conversion induced by some non-standard neutrino properties beyond mass and mixing, such as neutrino magnetic moment, lepton-flavor non-universality as well as flavor changing neutral current interactions in SUSY models with broken $R$ parity, on supernova physics.

1 Introduction

Neutrino flavor conversion could cause some significant influence on supernova physics. In this talk we discuss the effect of such conversion induced by non-standard properties of neutrinos, not just by mass and mixing, on supernova physics. In particular, we consider the effect on neutrino shock-reheating, supernova heavy elements nucleosynthesis as well as $\bar{\nu}_e$ signal, and show that in some case rather stringent limits on model parameters can be obtained.

1.1 Some basic features of supernova neutrinos

A type-II supernova occurs when a massive star ($M \gtrsim 8M_\odot$) has reached the last stage of its life. Almost all of the gravitational binding energy of the final neutron star (about $\sim 10^{53}$ erg) is radiated away in form of neutrinos. The individual neutrino luminosities in supernovae are approximately the same but the individual neutrino energy distributions are very different because they interact differently with the star material, as following reactions show,

\[ \nu_e + n \rightarrow p + e^-, \quad (1) \]
\[ \bar{\nu}_e + p \rightarrow n + e^+, \quad (2) \]
\[ \nu + N \rightarrow \nu + N, \quad (N = p, n). \quad (3) \]

Since the cross sections of the charged-current reaction is larger than that of the neutral-current one and there are more neutrons than protons, the $\nu_e$’s have the largest interaction rates with the matter and hence thermally decouple at the lowest temperature. On the other hand, $\nu_{\tau(\mu)}$ and $\bar{\nu}_{\tau(\mu)}$’s lack the the charged-current absorption reactions on the free nucleons inside the neutron

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star and hence thermally decouple at the highest temperature. As a result, the average neutrino energies satisfy the following hierarchy:

\[ \langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\tau (\mu)}} \rangle \approx \langle E_{\bar{\nu}_{\tau (\mu)}} \rangle. \]  

Typically, the average supernova neutrino energies are, \( \langle E_{\nu_e} \rangle \approx 11 \text{ MeV}, \langle E_{\bar{\nu}_e} \rangle \approx 16 \text{ MeV}, \langle E_{\nu_{\tau (\mu)}} \rangle \approx \langle E_{\bar{\nu}_{\tau (\mu)}} \rangle \approx 25 \text{ MeV}. \)

1.2 Impact of neutrino oscillation on supernova physics

Here we very briefly review some significant effects of neutrino oscillation, which occurs if neutrinos are massive and mixed, on supernova physics, studied in some previous work. First issue is concerned with the neutrino conversion effect on shock re-heating in the delayed explosion scenario. If neutrinos are massive and mixed and follow the mass hierarchy as observed in the quark sector, one expects MSW resonant conversion between \( \nu_e \) and \( \nu_\mu \) or \( \nu_\tau \) inside supernova. If the conversion occurs between the neutrinosphere and the stalled shock this can help the explosion. Due to the conversion the energy spectra of \( \nu_e \) and \( \nu_\mu \) or \( \nu_\tau \) can be swapped and hence \( \nu_e \) would have larger average energy leading to a larger energy deposition by reactions in eqs. (1) and (2) so that the stalled shock would be re-energized.

Second issue is the impact on heavy elements nucleosynthesis in supernova. To have successful \( r \)-process the site must be neutron rich, i.e. \( Y_e < 0.5 \) where \( Y_e \) is number of electron per baryon. The \( Y_e \) value is mainly determined by the competition between the two absorption reactions in eqs. (1) and (2). In the standard supernova model the latter process is favoured due to the higher average energy of \( \bar{\nu}_e \) which guarantees the neutron richness. If the neutrino oscillations do occur between the neutrinosphere and the region relevant for \( r \)-process the site can be driven to proton-rich due to the reaction (1) and therefore, \( r \)-process could be prevented.

Third argument is the effect of neutrino oscillation on \( \bar{\nu}_e \) signal in the terrestrial detector. It is discussed that from SN1987A data the large oscillation between \( \bar{\nu}_e \) and \( \bar{\nu}_\mu \) or \( \bar{\nu}_\tau \) is disfavoured since the oscillation can induce harder \( \bar{\nu}_e \) spectra than the observed one.

Finally, although we will not discuss this further in this talk, we also mention that neutrino oscillation in the presence of polarization of the medium in the star due to the strong magnetic field could lead to some interesting consequences.

2 Neutrino oscillation induced by non-standard neutrino properties

Here we discuss our main interest, the effect of neutrino oscillation induced by some non-standard properties of neutrinos other than mass and mixing.
2.1 Resonant Spin-Flavor Precession

First discussion is devoted to the impact of the resonant spin-flavor precession (RSFP) on supernova nucleosynthesis and dynamics. Transition magnetic moment of neutrinos can cause simultaneous change of helicity and flavor of neutrinos. Moreover, in matter, for the case of Majorana neutrinos, $\nu_\tau$ (or $\nu_\mu$) can resonantly convert into $\bar{\nu}_e$ and vice versa.

Contrary to the case of MSW effect, RSFP can decrease the electron fraction in the $r$-process region even if the MSW effect co-exist. This is because RSFP can swap the energy spectra of $\bar{\nu}_e$ and $\nu_\tau$ (or $\nu_\mu$), leading to the larger $\bar{\nu}_e$ energy and increasing the neutron richness due to the reaction (2).

In Fig. 1 we plot the expected electron fraction in the presence of RSFP with flavor mixing. We see that for weaker magnetic field, the result agrees with Qian et al. but for stronger magnetic field $Y_e$ can be lower than the expected value in the absence of oscillation ($\sim 0.4$), which implies the enhancement of $r$-process.

Figure 1: Contour plots for the electron fraction $Y_e$ in the $\sin^2 2\theta - \delta m^2$ plane in the $r$-process site, for the magnetic field profile $B(r) = B_0 (r_0/r)^2 \times 10^{12}$ G ($r_0 = 10$ km) with $B_0 = (a) 0.01$, (b) 0.1 (c) 1.0 and (d) 10.0. The transition magnetic moment of neutrino is assumed to be $10^{-12} \mu_B$ where $\mu_B$ is Bohr magneton. (From ref. 11.)

RSFP can help the shock reheating by neutrino since the energy of $\bar{\nu}_e$ is increased. We estimate the neutrino energy deposition rate at the stalled shock, which is normalized to 1 in the absence of any kind neutrino conversion. We present our results in Fig. 2. We see that for some range of parameter, the total reheating rate can be increased as large as 40%. We note, however,
that RSFP conversion could be in conflict with SN1987A data since the energy spectra of $\bar{\nu}_e$ get harder.

2.2 Massless neutrino conversion induced by flavor non-universality

In some cases, neutrinos can mix and even resonantly convert into another flavor in matter even if they are strictly massless. Here we focus on a particular scenario of massless-neutrino conversion suggested in ref. It is possible with extra gauge singlet neutrinos and requiring lepton number conservation to keep the standard neutrinos massless but mixed. It is, however, very difficult to observe this mixing through conventional neutrino oscillation experiments because the phase cannot be developed in vacuum since neutrinos are massless. However, in matter neutrinos can acquire non-trivial phase due to flavor non-universality. Here, we consider the $\nu_e - \nu_\tau$ system and define the measure of non-universality as $\eta \equiv \frac{1}{2} (h_\tau^2 - h_e^2)$, where $h_\tau$ and $h_e$ denote the deviation from the standard coupling which are assumed to be as large as a few % especially for $h_\tau$. It has been shown that for nonzero $\eta$, the resonant neutrino conversion between $\nu_e - \nu_\tau$ and $\bar{\nu}_e - \bar{\nu}_\tau$ can occur. Such massless neutrino conversion is different from the usual MSW conversion in that the conversion probability is energy independent and it occurs for both neutrino and antineutrino channels simultaneously.

Here we argue that such conversion can be in conflict with SN1987A $\bar{\nu}_e$ signal and $r$-process scenario and hence we can constrain the relevant parameters. We show our results in Fig. 2 (see the caption).

2.3 FCNC induced neutrino conversion in SUSY models with broken $R$ parity

It has been discussed that neutrino conversion can be induced by flavor-changing neutral current (FCNC) interaction even if neutrinos are unmixed. Here,
Figure 3: Left panel shows the constraints on massless-neutrino mixing from the detected SN1987A $\bar{\nu}_e$ energy spectra. The region to the right of the dashed (solid) lines are excluded by the detection data for an allowed conversion probability of $P < 0.35$ (0.5). Right panel is similar to the left one but from the supernova $r$-process nucleosynthesis. The region to the right of the dotted, dashed and solid lines are excluded for the required values of $Y_e < 0.43$, 0.45, and 0.49, respectively, in the $r$-process. (From ref. 16.)

we focus on a particular conversion mechanism induced by some new interactions between neutrinos and matter mediated by the scalar partners of quarks and leptons in supersymmetric extension of the standard model with explicitly broken $R$-parity. In Fig. 4 we show the parameter region excluded by

Figure 4: Similar plots as in Fig. 3 but for different conversion mechanism induced by FCNC interaction in SUSY models with broken $R$ parity. (From ref. 18.)

SN1987A signal and by $r$-process assuming the vanishing neutrino masses. We note that some features of neutrino conversion in this case is similar to the one we discussed in sec. 2.2, i.e., the energy independence and simultaneous conversion of neutrinos and anti-neutrinos.

We also consider the case where neutrino masses are not negligible because neutrino masses are naturally induced in this model at one loop level. We present in Fig. 5 our results for this case.
Figure 5: Similar plot as Fig. 4 but for non-zero neutrino masses. We note, however, that if $\delta m^2 \equiv m_2^2 - m_1^2$ is negative only the constraints from SN1987A $\bar{\nu}_e$ energy spectra (left panel) is obtained whereas $\delta m^2$ is positive only the constraints from r-process is obtained (right panel) is obtained. (From ref. 18.)

2.4 Neutrino conversion into sterile state

Finally we discussed the case where neutrinos are mixed with some sterile state. We have reanalysed the impact of resonant conversion of electron neutrinos into some sterile state on supernova physics assuming the mass of the sterile state to be in the cosmologically significant range, i.e. 1-100 eV, the range relevant as dark matter component in the universe. Here we consider the system of $\nu_e$ and $\nu_s$ (and their anti-partners) with non-zero masses and mixings and neglect the mixing among other flavors. Due to non-monotonic behaviour of the potential above the neutrinosphere not only neutrinos but also anti-neutrinos can convert into sterile state.

We present our results in Fig. 6. We can conclude from the first plot (upper panel) that if the neutrino re-heating is essential for successful supernova explosion the parameter region right to the curve, say $R = 0.5$, is disfavoured. From the second plot (lower left) we conclude that the successful observation of the $\bar{\nu}_e$ signal from supernova SN1987A in Kamiokande and IMB detectors implies the absence of significant conversion of $\bar{\nu}_e \to \bar{\nu}_s$, disfavouring the parameter region right to the curve, say $P = 0.5$. In the third plot (lower right panel) in the region right to the curve $Y_e = 0.5$ the value of $Y_e$ is larger than 0.5 and hence the r-process is forbidden whereas in the region delimited by the curve $Y_e = 0.4$ the value of $Y_e$ could be decreased compared to the standard case, leading to the enhancement of r-process.

3 Conclusion

We have discussed the impact of the resonant conversion induced by some non-standard properties of neutrinos. In particular we focussed on the conversion induced by neutrino transition magnetic moment, flavor non-universality, FCNC interaction in SUSY models with broken $R$ parity, and mixing with
some sterile state. We have shown that some significant effects on supernova physics are expected and in some case we can derive bounds on neutrino parameters from the shock re-heating, $r$-process as well as SN1987A $\bar{\nu}_e$ signal arguments. We note that these bounds are first of all supernova model dependent, but complementary to the ones we obtain in the laboratory experiments and sometimes they are happen to be more stringent.

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