PROCEEDINGS OF SCIENCE

Neutrino flavor transformation in supernova as a probe for nonstandard neutrino-scalar interactions

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We consider a nonstandard interaction between the neutrino and a hypothetical massive scalar or pseudoscalar. In the ultrarelativistic limit, the new effective interaction between the neutrinos vanishes if neutrinos are Dirac fermions but not if they are Majorana fermions. Using a multi-angle "neutrino bulb model" we calculate the flavor transformation above the neutrinosphere in a core collapse supernova and find that the addition of the nonstandard neutrino self-interaction (NSSI) to the ordinary V-A self-interaction between neutrinos is capable of dramatically altering the collective oscillations. If our understanding of the neutrino signal from a Galactic supernova is sufficiently well understood, supernova neutrinos provide complimentary constraints on scalar/pseudoscalar interactions of neutrinos.

The 20th International Workshop on Neutrinos (NuFact2018)
12-18 August 2018
Blacksburg, Virginia

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PoS(NuFACT2018)147

1. Introduction

The extreme conditions found in the centers of core-collapse supernovae (CCSN) are wonderful laboratories for probing the properties of neutrinos. Beyond the neutrinosphere - the surface of last scattering for the neutrinos - the neutrinos are free streaming and can undergo flavor oscillations. The oscillations are governed by a Hamilton H and at a radial coordinate r the Hamiltonian for a neutrino with momentum $\mathbf{q}$ ($E = |\mathbf{q}|$) is composed of three terms, $H(r,\mathbf{q}) = H_{\rm V}(E) + H_{\rm M}(r) + H_{\rm SI}(r,\hat{\mathbf{q}})$, where $H_{\rm V}(E)$ is the vacuum contribution and $H_{\rm M}(r)$ the effect of matter. In addition to these two terms, the number density of neutrinos in a CCSN is so large that neutrinos feel the presence of all the other neutrinos trying to escape. This leads to the third term $H_{\rm SI}(r,\hat{\mathbf{q}})$ known as the neutrino self interaction. In the Standard Model the self-interaction term has a form which arises from the V-A nature of the weak interaction given by

$$H_{\rm V-A}(r,\hat{\mathbf{q}}) = \sqrt{2}G_{\rm F}\int (1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})\left[\rho(r,\mathbf{p})\,dn_{\nu}(r,\mathbf{p}) - \bar{\rho}^{*}(r,\mathbf{p})\,dn_{\bar{\nu}}(r,\mathbf{p})\right]dE_{\mathbf{p}} \tag{1.1}$$

where ρ and $\bar{\rho}$ are the density matrices of the neutrinos and antineutrinos respectively and dn_{ν} and $dn_{\bar{\nu}}$ are their respective differential number densities. But if we consider non-standard self-interactions (NSSI) for Majorana neutrinos e.g. a scalar or pseudoscalar interaction via a massive boson, there are additional contributions to H_{SI} which are found to be of the form

$$H_{\rm S/P}(r,\hat{\mathbf{q}}) = 4\int (1-\hat{\mathbf{p}}\cdot\hat{\mathbf{q}})\left\{\tilde{\mathbf{g}}\left[\rho^{*}(r,\mathbf{p})\,dn_{\nu}(r,\mathbf{p}) - \bar{\rho}(r,\mathbf{p})\,dn_{\bar{\nu}}(r,\mathbf{p})\right]\tilde{\mathbf{g}}\right\}dE_{\mathbf{p}}. \tag{1.2}$$

In this equation $\tilde{\mathbf{g}}$ is arbitrary Hermitian coupling matrix. The diagonal elements of $\tilde{\mathbf{g}}$ are flavor preserving, the off-diagonal elements are flavor violating. The difference is the very subtle change from the density matrix ρ to its conjugate ρ^{*}. Nevertheless this change has the potential to greatly modify the flavor evolution of the neutrinos in CCSN.

2. Our study

We study the effects of NSSI upon the flavor evolution by solving the Schrodinger equation for the neutrino evolution matrix S above the neutrinosphere i.e.

$$i\frac{dS_{\mathbf{q}}}{d\tau} = H(\tau,\mathbf{q})\,S_{\mathbf{q}}, \tag{2.1}$$

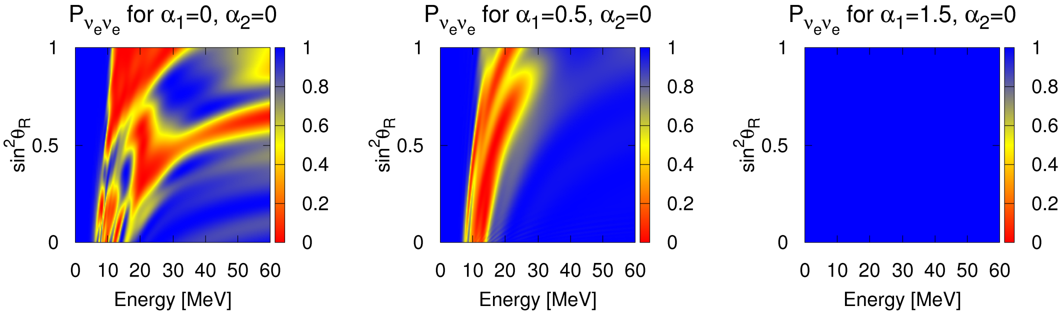

Figure 1: Heatmaps of survival probability of electron neutrinos at a postbounce time of $t_{pb} = 1.0$ s and at $r = 400$ km as a function of energy and emission angle when there is only flavor-preserving NSSI.

where τ is the affine parameter for the neutrino trajectory and we use $H_{\rm SI} = H_{\rm V-A} + H_{\rm S/P}$. We refer the reader to Yang & Kneller [1] for further details. Three results from these calculations are shown in figure (1) which were for cases where the coupling matrix $\tilde{\mathbf{g}}$ was parameterized as $\tilde{\mathbf{g}} = \left[\sqrt{2}G_F/4\right]^{1/2} \alpha_1 1_3$. In the leftmost panel we see the electron neutrino survival probability at $r = 400$ km as a function of the neutrino energy and the quantity $\sin^2\theta_R$ where θ_R is the emission angle of the neutrino at the neutrinosphere relative to the radial direction. As we increase α_1 the range of energies and emission angles which are affected by self-interactions is reduced (middle panel) until at $\alpha_1 = 1.5$ we find the flavor transformation has been completely switched off. From this and many other calculations like it, we are able to build up a flowchart for the consequences of non-standard neutrino self-interactions which is shown in (2).

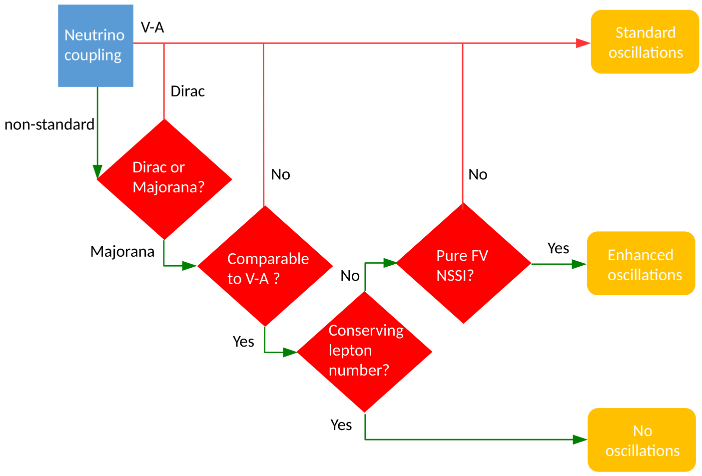

Figure 2: A flowchart indicating the consequences of the non-standard neutrino self-interactions.

3. Conclusion

The neutrino flavor transformations in the supernova environment are sensitive to new interactions between neutrinos if the neutrino are Majorana particles. The exact effect of the NSSI depends upon the magnitude and structure of the coupling matrix $\tilde{\mathbf{g}}$. If the strength of the NSSI are of order the weak interaction then pure flavor-preserving couplings suppress flavor mixing. If flavor-violating NSSI are allowed then the resulting flavor transformations can look almost identical to those from the Standard Model alone. In the case of pure flavor-violating NSSI, the neutrino flavor transformation in the CCSN environment may actually be enhanced. CCSN are a unique laboratory for testing the nature of the neutrino and its interactions.

References

[1] Yang, Y., & Kneller, J. P., Phys. Rev D **97** 103018 (2018)