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Neutrino Flavor Changing Neutral Currents and Stellar Collapse

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Abstract. Flavor changing neutral current interactions are predicted in some extensions of the Standard Model. We discuss a process by which a neutrino can change flavor by scattering with a quark. We show how the stellar collapse environment is sensitive to neutrino flavor changing scattering on heavy nuclei. In particular, when this interaction is included in the stellar collapse model, the dynamics of the core's evolution and outcome of collapse are drastically changed.

Keywords: non-standard neutrino interactions, core collapse supernovae, neutrino-nucleus scattering

PACS: 97.60.Bw, 13.15.+g, 26.50.+x, 25.30.Pt

INTRODUCTION

Neutrino flavor changing can occur due to the fact that neutrinos have mass and their flavor eigenstates do not coincide with their mass eigenstates. Neutrino flavor changing is a result of the quantum mechanical effect of flavor states oscillating. Another possible way neutrinos could change flavor is by flavor violating interactions. Such interactions are predicted by some extensions of the Standard Model but have yet to be found by experiments. We have investigated the effects of these proposed flavor changing interactions on the core collapse supernova model [1, 2]. We have found that physical effects due to flavor changing scattering processes are qualitatively different from the effects due to flavor oscillations, and furthermore that this type of flavor changing significantly alters the standard core collapse supernova model.

INTERACTIONS AND CROSS SECTIONS

There are several models that predict flavor violating interactions of different types. We will consider a general model for neutrino flavor changing scattering with a quark. A low energy effective Lagrangian describing this theory is

$$\mathcal{L} = G_F \bar{\nu}^i \gamma^\mu (1 - \gamma_5) \nu^j \bar{q} \gamma_\mu (\epsilon_{Vij}^q + \epsilon_{Aij}^q \gamma_5) q. \quad (1)$$

This Lagrangian has the form of a neutral current. The indices on the neutrino fields indicate flavor. Interactions of this form are known as flavor changing neutral currents (FCNCs). The epsilons in the quark currents are dimensionless parameters which quantify the strength of the interaction relative to the Fermi constant.

The Lagrangian describes the interaction of a neutrino and quark. However, the core of a collapsing star contains nuclear matter, not free quarks. We need cross sections for

neutrinos interacting with the matter in the core. It is believed that different phases of nuclear matter arise in the core throughout collapse, but this topic is an area of active research. For our calculations we have considered the simplest opacity source. It is known that nuclei exist in the core for at least some portion of the collapse. We therefore consider neutrino flavor changing elastic scattering with a spin zero nucleus in the $q^2 = 0$ limit. The cross section [1] for this process is

$$\sigma_{ij} \approx \frac{2G_F^2}{\pi} \left| \epsilon_{Vij}^d(2N + Z) + \epsilon_{Vij}^u(2Z + N) \right|^2 E_\nu^2. \quad (2)$$

For comparison, the cross section for Standard Model neutral current elastic scattering with a spin zero nucleus is

$$\sigma \approx \frac{2G_F^2}{\pi} (Z + N)^2 E_\nu^2. \quad (3)$$

Notice that both these cross sections have a coherent amplification: the factors of $(2N + Z)^2$ and $(2Z + N)^2$ in the flavor changing case, and the factor $(Z + N)^2 = A^2$ in the Standard Model case. The core of a collapsing star has nuclei with mass number of order $A = 100$. The coherent scattering cross sections for these nuclei are roughly four orders of magnitude larger than cross sections for neutrino scattering on free nucleons. The FCNCs we are considering are weaker [3] than SM interactions, but because of coherent amplifications the flavor changing cross sections are appreciable and enough neutrino flavor changing occurs in the core to effect the standard stellar collapse model.

EFFECTS OF NEUTRINO FLAVOR CHANGING

After neutrino trapping, when the Fermi sea of electron neutrinos reaches a maximum level, net electron capture becomes blocked. Electron capture and beta decay reactions are still taking place in the core, but they are in equilibrium. Once the neutrino sea reaches its maximum level, the electron fraction Y_e no longer changes. However, if electron neutrinos could change flavor to mu and tau neutrinos, then phase space would open to allow electron capture to occur and cause net reduction in Y_e .

The neutrino FCNCs we are considering are weaker than Standard Model interactions and in particular, the cross sections for neutrino flavor changing coherent scattering with nuclei are smaller than cross sections for electron capture. We therefore restrict our discussion to the following limiting case. When neutrino flavor changing scattering is operating in the core, the number of electron neutrinos remains the same: every time a hole is opened in the electron neutrino sea, it is filled by a neutrino created from electron capture. By means of neutrino flavor changing then, electron fraction is converted to mu and tau neutrino fraction:

$$\Delta Y_e = -(\Delta Y_{\nu_\mu} + \Delta Y_{\nu_\tau}). \quad (4)$$

The change in electron fraction can be used to quantify dynamical changes to the core collapse model.

The homologous core mass and initial shock energy depend on the core's electron fraction at bounce. Lowering the core's electron fraction on infall results in a smaller

homologous core and therefore more outer core material for the shock to photodissociate. The shock therefore loses more energy before reaching the outer envelopes of the star. A lower electron fraction also results in a weaker initial shock. Both of these effects disfavor getting an explosion.

We have performed a one-zone collapse simulation (details can be found in Ref. [2]) to calculate scattering rates and reduction in Y_e due to the neutrino flavor changing. We assumed a maximum trapped neutrino fraction of $Y_\nu^{\text{trap}} = 0.05$ so that according to Eq. (4), the maximum reduction in Y_e possible is $\Delta Y_e = 0.1$. We have found from our simulation that this maximum reduction in Y_e occurs for our neutrino FCNCs up to their current level of experimental constraint. We note here that a change in Y_e as low as 0.02 is dynamically significant [4].

Neutrino FCNCs also have consequences unrelated to the core's electron fraction. Neutrinos may aid the explosion by depositing energy behind the stalled shock. Flavor changing interactions result in many more neutrinos to participate in shock revival, thus positively effecting the explosion. An observable feature of neutrino FCNCs is the existence of mu and tau neutrinos in the supernova spectrum, with the same distribution for each of the flavors. This result is different from what would occur solely due to neutrino oscillations. For example, neutrino oscillations could cause certain portions of the neutrino distributions to be exchanged.

CONCLUSIONS

We have examined the effects of neutrino flavor changing neutral current interactions on the core collapse supernova model. We have seen that neutrino-quark interactions are enhanced because of coherent scattering with nuclear matter, and that these interactions cause qualitatively different flavor transformation than matter enhanced oscillations. In particular, neutrino flavor changing scattering processes during infall have both negative and positive effects regarding the explosion. They cause the dynamics of collapse, and the expected neutrino spectrum to be significantly changed from the predictions of the current supernova model.

If new physics of this type is discovered experimentally, it must be included in the supernova model. Conversely, detection of supernova neutrinos could give evidence for discovery or constraint of this type of interaction. A complete supernova simulation that includes these interactions is needed to quantify how they would effect the explosion mechanism and neutrino spectra, and also determine other effects they would have on the model.

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