NEUTRINO MASS AND THE CORE COLLAPSE SUPERNOVA MECHANISM

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Core collapse supernovae result when the iron core of a massive star becomes unstable late in the star's life, collapses gravitationally, at supernuclear densities becomes incompressible, rebounds, and generates a shock wave that ultimately propagates out through the core and the outer layers of the star to disrupt it in a core collapse supernova explosion. Unfortunately, because of dissociation and neutrino losses, the shock stalls to form an accretion shock, to be revived by a "delayed shock mechanism" first discovered by Wilson[5] and fully developed by Bethe and Wilson.[2] In this mechanism, the stalled shock is revived by neutrino heating, i.e., by the absorption of electron neutrinos and antineutrinos by the dissociation-liberated protons and neutrons behind it.

The muon and tau neutrinos interact only via neutral currents and, therefore, decouple at higher density and temperature in the proto-neutron star. As a result, they have harder spectra. If oscillations between tau and electron neutrinos occur, the shock heating rate would be boosted by converting tau neutrinos, which are not absorbed by nucleons, to electron neutrinos, which are, while at the same time converting the softer-spectra electron neutrinos to tau neutrinos. Because the absorption cross section depends on the square of the neutrino energy, both the probability of absorption as well as the energy absorbed are increased when the neutrino spectra are hardened. Of course, this is beneficial only when the oscillations occur below the gain radius, otherwise the transformation occurs farther out where it becomes useless for shock revival.

For comparison, we follow Fuller et al.[3] and assume a neutrino mass hierarchy that follows the lepton mass hierarchy, i.e., where $m_{\nu_\tau} >> m_{\nu_\mu} > m_{\nu_{\rm e}}$. In particular, we chose the tau neutrino mass to be 25 eV, the electron neutrino mass to be 0 eV, $m^2_{\nu_\tau} - m^2_{\nu_\mu} = 625$ eV^2, and $m^2_{\nu_\mu} - m^2_{\nu_{\rm e}} = 6 \times 10^{-6}$ eV^2. We also chose the vacuum mixing angles to be $\theta_{\rm V} = 10^{-3}$ for ν_τ–$\nu_{\rm e}$ oscillations (within the range considered by Fuller et al.) and $\sin^2 2\theta_{\rm V} = 6 \times 10^{-3}$ for ν_μ–$\nu_{\rm e}$ oscillations. The latter choices for the mass difference and vacuum mixing angle were motivated by the small-mixing-angle solution to the solar neutrino problem. The ν_μ–$\nu_{\rm e}$ oscillations would occur in the low-density outer layers of the star and would not have an impact on generating the explosion.

Because our stalled supernova shock reaches a maximum radius only between 100–200 km, m_τ would have to be of order 150 eV before the resonance region is interior to the gain region. For our $m_\tau = 25$ eV neutrinos, the oscillations occur well outside the heating region and therefore have no impact on initiating an explosion, although their effects on the neutrino signatures are significant, as we have shown in Ref. 4.

In contrast, the Fuller et al. calculations, which used an exploding model, estimated that neutrino oscillations were important for the explosion energetics. The difference arises because in their analysis the shock is already at 500 km and the resonance regions are within the shock heating region. This raises an important point: In order for neutrino oscillations to aid in *initiating* an explosion, the oscillations would have to occur deep within the core, as we have shown, which, for MSW oscillations, would imply that there must be a large mass difference between the tau and the muon neutrinos. Of course, other oscillation scenarios are possible, and one cannot conclude that this must be the case. In any event, even if oscillations do not play a role in initiating the explosion, they may play a role in ensuring that the explosion *energy* is sufficiently high.[3]

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[1] Florida Atlantic University, Boca Raton, FL.

[2] H. Bethe and J. R. Wilson, *Ap. J.* **295**, 14 (1985).

[3] G. Fuller, R. Mayle, B. S. Meyer, and J. R. Wilson, *Ap. J.* **389**, 517 (1992).

[4] A. Mezzacappa and S. W. Bruenn, to be submitted to *Astrophysical Journal* (1998).

[5] J. R. Wilson, p. 422 in *Numerical Astrophysics*, eds. J. M. Centrella, J. M. LeBlanc, and R. L. Bowers (Jones and Bartlett Publishers, Inc., Boston, 1985).