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Possible violation of the spin-statistics relation for neutrinos: checking through future galactic supernova

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Abstract

We use the detection of neutrinos from a future galactic type-II supernova event in a water Cerenkov detector like Super-Kamiokande to constrain the possible violation of spin-statistics by neutrinos resulting in their obeying a mixed statistics instead of Fermi–Dirac.

Keywords: Supernova neutrinos; Neutrino properties

Recently there was a suggestion of neutrinos violating the spin-statistics relation and thereby becoming a good candidate for all (or part) of the dark matter in the universe [1]. There are a number of papers which discuss the possible violation of spin-statistics relation by neutrino though no consistent satisfactory model exists [2–6]. On the other hand the experimental verification of neutrinos with half spin following a mixed statistics was not thoroughly studied earlier. For nucleons however such studies exist [2]. The recent paper on the possibility of neutrinos violating the Pauli Exclusion Principle [1] however has renewed interest in the subject [7]. The Doglov–Smirnov work [1] points out that if neutrinos do obey Bose–Einstein (BE) statistics instead of Fermi–Dirac (FD), then they may form large cosmological Bose condensates and account for the dark matter. This also opens up the possibility of large lepton asymmetry in the universe. As double beta decay disallows purely bosonic neutrinos, one will be interested in mixed statistics in terms of a continuous "Fermi–Bose" parameter, κ ($\kappa = -1$ is purely fermionic and $\kappa = 1$ is purely bosonic) [8]. This on the other hand has astrophysical consequences as well. For example this will have impact on the type II supernova (SN) dynamics and will change the energy spectrum of neutrinos coming out of the supernova. In this report we shall not be concerned with the justification of the Dolgov–Smirnov suggestion but concentrate on the question: given the scenario of neutrinos of all three flavors obeying the mixed statistics, how would future observation of galactic neutrinos in large terrestrial detectors put limits on the mixed statistics parameter κ. We assume that apart from (possibly) violating the spin-statistics theorem, the massive neutrinos do not have any other non-standard property. We shall see that with detectors like Super-Kamiokande (SK) one indeed can test this hypothesis at a significant level of accuracy.

Massive stars at the end of their normal lifespan, collapse due to the gravitational pull once the silicon burning in the core stops and the core has a mass greater than the Chandrasekhar mass. The neutrinos that are produced by electron capture on nuclei and free protons during the initial collapse phase escape. However, as the density of the core exceeds densities of 10^{11}–10^{12} gm/cc during collapse, neutrinos get trapped. At densities higher than the nuclear matter density a shock wave forms inside the core and travels outward. Whether the shock wave can reach the edge of the core with enough energy to cause the explosion with the observed energies is the central question of supernova physics today.

At the high densities and temperatures of the SN core during the post-bounce phase, neutrinos and antineutrinos of all

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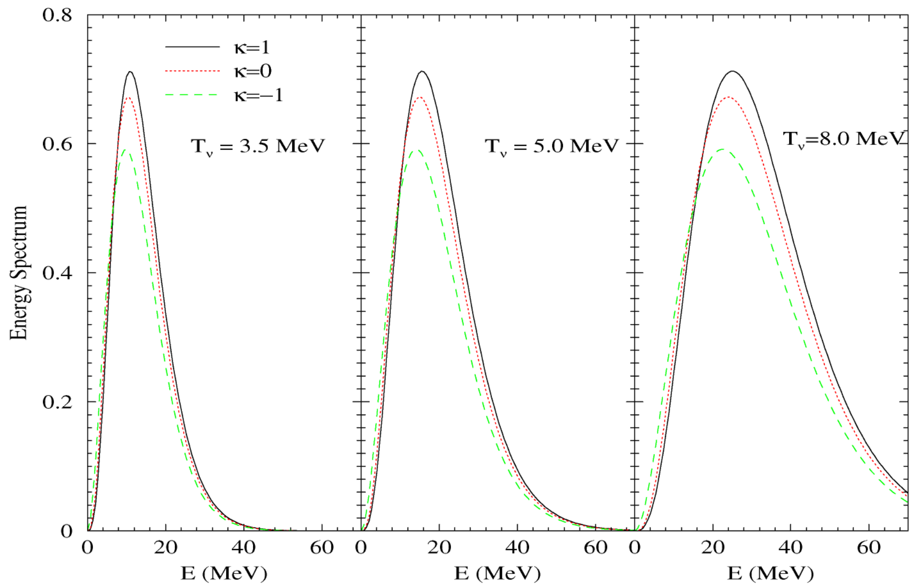

Fig. 1. (Colour online.) The thermal energy spectrum for the FD, MB and BE distribution of SN neutrinos with typical temperature of 3.5 MeV (left panel), 5 MeV (middle panel) and 8 MeV (right panel).

three flavors are produced. Almost $\sim 99\%$ of the gravitational energy produced through the huge contraction of the star ($\sim$ a few times 10^{53} ergs) is released in the form of the six species of neutrinos (ν_e, ν_μ, ν_τ and their antiparticles). In the high density central part of the core, neutrinos of each flavor have high opacity and hence cannot come out. But at larger radius due to a strong density gradient, neutrinos can diffuse out and eventually escape. Therefore, we expect almost thermal spectra for all the neutrino species, with temperatures characteristic of their radius of last scattering in the SN, usually called the neutrino sphere radius. Since ν_e and $\bar{\nu}_e$ have charged current interactions with the SN matter in addition to neutral current interactions and since SN matter is neutron rich, ν_e, $\bar{\nu}_e$ and ν_x ('x' stands for μ, τ, $\bar{\mu}$ and $\bar{\tau}$) decouple at different radii. Hence the neutrino spheres of the three different types, ν_e, $\bar{\nu}_e$ and ν_x, have different radii and hence different equilibrium temperatures (T_ν), with $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}(T_x)$. For our purpose we shall take $T_{\nu_e} = 3.5$ MeV, $T_{\bar{\nu}_e} = 5$ MeV and $T_{\nu_x} = 8$ MeV [9], used in most simulations and calculations as the standard values. As there are arguments which claim that $T_{\bar{\nu}_e}$ and T_{ν_x} should be closer [10], we vary these temperatures over a range as detailed later in this report. These temperatures are obtained by using FD equilibrium energy distributions and may change somewhat had the simulations been carried out with BE distributions or distributions with mixed statistics. However the qualitative results of our investigation here will not change if they are done with equilibrium BE temperatures for ν_e, $\bar{\nu}_e$ and ν_x. Again realistic simulations indicate small departures from equilibrium distribution of energies of the neutrino, with the high energy tail lower or "pinched". The pinching factor[1] is expected to range between $\eta_e \sim 0$–3, $\eta_{\bar{e}} \sim 0$–3 and $\eta_x \sim 0$–2 for the ν_e, $\bar{\nu}_e$ and ν_x flux respectively [11]. We further assume that the total luminosity E_B is equipartitioned among the six neutrino and antineutrino species. We remind readers here that the electron type antineutrinos (with at most one neutrino scattering event) were detected along with the SN 1987A explosion. But with 11 and 8 events at Kamioka and IMB, fitting of energy spectrum and determination of temperature had large errors [12].

Following [1] we parametrize the equilibrium distribution of the neutrinos with a mixed statistics as

$$f_\nu^{(\mathrm{eq})} = \left(\exp(E/T) + \kappa\right)^{-1}, \tag{1}$$

where E is the energy of the neutrinos, T the temperature of the distribution and κ is the Fermi–Bose parameter for the mixed statistics, as mentioned earlier. Fig. 1 shows the energy spectrum of the neutrinos corresponding to FD ($\kappa = +1$), Maxwell–Boltzmann MB ($\kappa = 0$) and BE ($\kappa = -1$) distributions, with typical temperatures of 3.5 (left panel), 5 (middle panel) and 8 MeV (right panel). The area under each of the curves gives the average energy expected for the corresponding values of T_ν and κ. It is clear from the figure that for the same T_ν, at small values of E the predicted spectrum for the BE distribution is higher than for the FD distribution. However for large E, the trend is reversed and the spectrum predicted for FD is higher than that for the BE distribution and has a longer high energy tail. This trend reflects the fact that for the same T_ν, the predicted average energy for the neutrinos is larger for the FD distribution. We also stress from Fig. 1 the fact that the spectral shape for the FD and BE distributions are different. We want to use the signature of this difference in predicted average energy and spectral shape of the SN neutrinos in terrestrial detectors, to disfavor the "wrong" neutrino statistical distribution and put limits on the Fermi–Bose parameter κ.

In Fig. 2 we show the effect of introducing the pinching in the FD distribution. We plot the galactic SN neutrino flux spec-

[1] The definition of η is given in Eq. (2).