NEUTRONIZATION NEUTRINO PULSES FROM SUPERNOVAE AND THE TRIPLET MAJORON MODEL

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We address a possible implication of the triplet majoron (TM) model for neutrino pulses from supernovae. If the $\nu_e\nu_e$–majoron coupling is $\cong 0.7\times10^{-3}$, suggested by one of the recent ββ-decay experiments, equilibration of ν-species via $\nu_e\nu_e\to\nu_\mu\nu_\mu(\nu_\tau\nu_\tau)$, occurs on a time scale $\sim10^{-4}$ s. Rapid equilibration followed by decay in flight via $\nu(\nu_\tau)\to\bar\nu_e+\chi^0$, could dramatically enhance the probability of observing neutronization neutrinos, even for $g^2_{\mu e}\cong g^2_{\tau e}\cong10^{-18}$. This effect would make nearby supernovae sensitive tests of TM models.

A millisecond "neutronization" pulse of ν_e is predicted by most stellar collapse calculations [1–3]. Unfortunately this pulse is virtually undetectable in the present water Čerenkov counters. Thus the eleven and eight neutrinos from SN 1987A detected by the Kamioka II [4] and IMB [5] detectors respectively, are believed to originate from the thermal $\bar\nu_e$, emitted with approximately equal numbers and energies as the other five species ν_e, $\bar\nu_\mu$, ν_μ, $\bar\nu_\tau$, ν_τ, over a 1–10 s interval, rather than from the neutronization pulse [6–8].

The reason for this is that the $\bar\nu_e$ are strongly absorbed on free protons with a cross section

$$\sigma(\bar\nu_e p\to e^+ n)\approx E^2_{\bar\nu}\ (\mathrm{MeV})\times10^{-43}\ \mathrm{cm}^2, \tag{1}$$

whereas electron neutrinos can be detected only via electron recoil in elastic collisions with a hundred time smaller cross section at typical energies ($E=E_\nu=E_{\bar\nu}=10$ MeV). This scattering cross section is

$$\sigma(\nu_e e\to\nu_e e)\approx E_\nu\ (\mathrm{MeV})\times10^{-44}\ \mathrm{cm}^2.$$

Considering the five-to-one ratio of electrons to protons in water, and the fact that at the source, the ν_e from the neutronization pulse carry < 5% of the total energy while they are three to four times less numerous than the $\bar\nu_e$, we expect that between 60 and 80 $\bar\nu_e$ should be detected for each detected neutronization ν_e.

This picture is considerably modified if the triplet majoron (TM) model [9,10] and in particular, the value $g_{ee}=0.7\times10^{-3}$ for majoron–ν_e couplings suggested by the recent PNL–USC experiment [11], are indeed correct. The simplest minimal version of this model, designed to spontaneously generate Majorana ν masses, introduces one new Higgs triplet, $(\chi^0\chi^-\chi^{--})$, each carrying two units of lepton number. Assuming that the χ multiplet couples roughly equally to the various leptonic flavors (i.e. $g_{\mu\mu}\approx g_{\tau\tau}\approx g_{ee}\simeq0.7\times10^{-3}$), the interconversion reaction, $\nu_e\nu_e\to(\text{virtual }\chi^0)\to\nu_i\nu_i$, has a large cross section,

$$\sigma(\nu_e\nu_e\to\nu_i\nu_i)\approx(1/32\pi)\ g^2_{ee}g^2_{ii}E^{-2}$$
$$\approx10^{-38}/[E(10\ \mathrm{MeV})]^2\ \mathrm{cm}^2. \tag{2}$$

This guarantees almost instantaneous ($t\leqslant10^{-4}$ s) equilibration of all neutrino species. Since ν_μ and ν_τ have approximately six times smaller cross sections for scattering on electrons, this appears to make the neutronization signal even more elusive. However, in the TM model, neutrinos can also change into the much more readily detected $\bar\nu_e$. Direct $\nu_e\to\bar\nu_e$ vacuum oscillations are suppressed by the helicity factor $(M_{\nu e}/E)^2$.

The model also allows for significant flavor mixing via the terms

$$g_{\nu e}\nu_e\nu_\mu\chi^{0+}+g_{\tau e}\nu_e\nu_\tau\chi^{0+}+g_{\mu\tau}\nu_\mu\nu_\tau\chi^{0+}.$$

The bounds on rare μ-decay only mildly restrict $g_{\mu e}$ [10]. The decay $\bar{\mu}\to e^-e^-e^+$ could proceed via a virtual χ^{--} with a rate

$$\Gamma(\mu\to 3e)\approx M_\mu^5(M_\chi^{--})^{-4}g_{ee}^2g_{e\mu}^2.$$

Demanding $\Gamma(\mu\to 3e)\leqslant 10^{-12}\ \Gamma(\mu\to e\nu\bar{\nu})$ implies then that $g_{\mu e}\leqslant 4\times 10^{-5}$. Here we have utilized the values [9,10] $m_{\chi^{--}}=\sqrt{2}m_{\chi^-}$ and $M_{\chi^-}\gtrsim 20$ GeV, the lower bound from experiments at PETRA. For $m_{\nu_\mu}\simeq 1$ eV, a value of $g_{\mu e}$ at this upper limit could generate a very fast decay

$$\nu_\mu\to\bar{\nu}_e+\chi^0,$$

where the $\nu\to\bar{\nu}$ flip is forced by the requirement that the interaction lagrangian of the TM model conserves overall lepton number, $L=L_e+L_{\nu_e}+...+L_\chi$.

It is important to note that much weaker dimensionless couplings, even at the level $\simeq 10^{-10}$, may suffice to ensure that the decay $\nu_\mu\to\bar{\nu}_e+\chi^0$ proceeds with rate $\Gamma\simeq(g^2/8\pi)m_{\nu_\mu}$, which is fast enough so that: (a) the decay lifetime in the laboratory

$$\tau_{\rm lab}=8\pi E/g^2m_{\nu_\mu}^2\approx\frac{2\cdot(E/20\ \mathrm{MeV})}{g^2(m_{\nu_\mu}/\mathrm{eV})^2}\cdot 10^{-7}\ \mathrm{s}$$
$$\ll 5\times 10^{12}\ \mathrm{s},$$

corresponding to the distance to SN 1987A ($\approx 1.5\times 10^{23}$ cm), so that the decay occurs en route, and (b) the delay in arrival time of the small mass $\bar{\nu}_e$, due to the early phase of propagation as heavier ν_μ,

$$\Delta t=t_{\rm lab}M_{\nu_\mu}^2/2E^2=4\pi/g^2E\approx\frac{1}{g^2}\frac{10^{-22}}{(E/10\ \mathrm{MeV})}\ \mathrm{s},$$

will not exceed $\delta t=10^{-3}$ s, the width of the neutronization pulse. A similar delay occurs when the initial ν_μ emerges at a small angle θ with respect to the supernova–earth axis, and the $\bar{\nu}_e$ resulting from the decay is then redirected to earth as shown in fig. 1. Since the decay angle is kinematically limited by m/E, the extra path length is likewise bound:

$$c\Delta t=\Delta L=c\tau_{\rm lab}(1-\cos\theta)\approx c\tau_{\rm lab}\tfrac{1}{2}\theta^2\leqslant c\tau_{\rm lab}(m^2/2E^2).$$

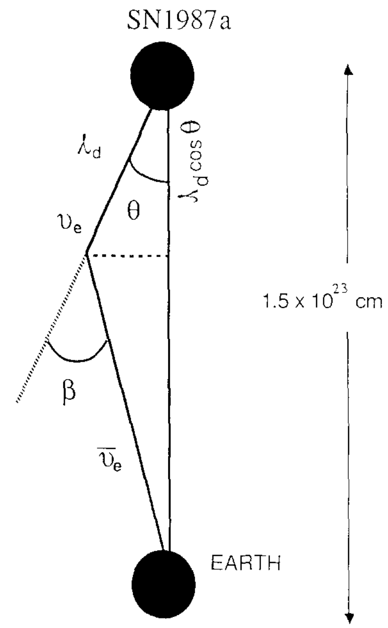

Fig. 1.

Here we have assumed $m_{\nu_\mu}\equiv m\gg m_{\nu_e}$.

Strictly speaking, in the minimal triplet majoron model, in which $\langle\chi^0\rangle=v\neq 0$ is the only source for the (pure Majorana) neutrino masses, there are no interspecies decays in vacuum. Since in this case

$$m_{ij}=g_{ij}\langle\chi^0\rangle=g_{ij}v, \tag{3}$$

and the physical basis $|\nu_a\rangle$, of the (vacuum) neutrino state diagonalizes the mass matrix m_{ij}, and simultaneously the couplings g_{ij}. No $\nu_\alpha\to\bar{\nu}_\beta+\chi^0$ decay could then occur, and this feature survives standard GSW radiative corrections. We need, however, to envision only a tiny correction to eq. (3) i.e. a term δm_{ij}, due to some other source which is *not* proportional to g_{ij}, to generate none vanishing off-diagonal $g_{\alpha\beta}$ in the physical basis [#1]. It has been speculated [12] that the decay $\nu_e\to\nu_i+M^0$ en route from the sun may resolve the solar neutrino puzzle. The $\bar{\nu}_e$ events seen at Kamioka and IMB exclude this possibility. We adopt therefore the "natural" mass hierarchy $m_{\nu_\tau}\geqslant m_{\nu_\mu}\geqslant m_{\nu_e}$, where, following common usage, ν_τ denotes the mass eigenstate $|\nu_\alpha\rangle=|\nu_3\rangle$, with a

[#1] For example, a Dirac δm is readily generated via a $W_L\to W_R$ loop, and a charged lepton mass insertion in L–R models.

dominant admixture of τ flavor etc. The decays [#2] $\nu_\mu \to \bar{\nu}_e + \chi^0$ will yield then $\bar{\nu}_e$. (The cascade $\nu_\tau \to \bar{\nu}_\mu + \chi^0$, $\bar{\nu}_\mu \to \nu_e + \chi^0$ yields ν_e) [#3]. Thus between 1/3 and 2/3 of the neutrinos in the initial neutronization pulse will be transformed into $\bar{\nu}_e$, with a twenty-fold enhanced detection cross section. We note that the energies of the neutronization neutrinos are in the present scenario higher than normally expected since the ν_μ and ν_τ components are more weakly scattered in the core, and hence the ν are emitted from an inner "hotter" region. This may compensate for the energy decrease in the two-body decay.

In a sample of 20 neutrinos, we could expect 1–2 neutronization induced *anti*-neutrinos. This is consistent, but cannot be meaningfully tested, with the data from SN 1987A. In future detections of nearer collapses in our own galaxy, 20–100 times larger fluxes are expected. The above scenario would predict then between 10–200 $\bar{\nu}_e$ detections, distinguished experimentally by the (almost) spherically symmetric distribution of Čerenkov light, within the first millisecond. If such a phenomenon were observed, it will be very difficult to explain without appeal to a (slightly generalized) TM model.

The majoron model could have many additional manifestations in the supernova collapse [13–16]. None of these seem as striking as that discussed here, and none can presently rule out the majoron model, even for the tentative value of the coupling constant $g_{ee} \simeq 0.7 \times 10^{-3}$ [#4].

[#2] Strictly speaking, the final physical bosonic states are the massless, pseudoscalar Goldstone majoron $M^0 = i(\chi^0 - \bar{\chi}^0)/\sqrt{2}$ and the corresponding scalar $\rho^0 = (\chi^0 + \bar{\chi}^0)/\sqrt{2}$ which obtains a small mass, $m_\rho \simeq v(\lambda\chi^4)$, with $\lambda\chi^4$ the quartic χ coupling. Depending on whether $m_{\nu_\alpha}, m_{\nu_\beta} \gtrless m_\rho$, we have both $\nu_\alpha \to \bar{\nu}_\beta M^0$ and $\nu_\alpha \to \nu_\beta \rho^0$ (or only $\nu_\alpha \to \bar{\nu}_\beta M^0$). In the latter case the decay rate is reduced by a factor 2.

[#3] Such $\bar{\nu}_e$ are undetected in the Davis experiment and hence a compound solar-ν scenario with a regular strong $\nu_e \to \nu_\mu$ MSW rotation, followed by $\nu_\mu \to \bar{\nu}_e + \chi_0$ will not reproduce neutrinos of either the requisite energy or type.

[#4] It should be pointed out that other searches in ^{76}Ge by Caldwell et al. [17] and Fisher et al. [18] suggest bounds on g_{ee} which are somewhat smaller than the value used above. None of our above conclusions will be modified by such a small change.

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