# Energetic (> 1 GeV) Neutrinos as a Probe of Acceleration in the New Supernova

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If an accelerator of energetic ions turns on inside a new type II supernova while the shell is sufficiently thick, energetic secondary mesons will be produced by collisions in the expanding shell. These will decay to give rise to neutrinos of energies much larger than the deleptonization and thermal neutrinos emitted during the collapse itself. If the power in accelerated protons is comparable to the optical luminosity, there may be enough neutrinos to be detectable in existing underground detectors within the next few months.

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It is well known that the energy available for production of high-energy particles in supernovae is sufficient to supply the galactic cosmic rays. Several specific acceleration mechanisms have been suggested from time to time. These use either the rotational energy of a strongly magnetized neutron star[1-4] or the energy of the shock wave emanating from the collapse to accelerate particles.[5,6] Each of the models has theoretical problems of various kinds which are difficult to evaluate because of the complexity of the system.[7] The purpose of this Letter is to draw attention to the potential importance of high-energy neutrinos from the supernova Shelton 1987 for the study of the problem experimentally.

A general analysis of cosmic-ray acceleration and interactions in an expanding supernova remnant has been given by Berezinsky and Prilutsky.[8] They considered the production of neutrinos from the decay of charged pions and associated gamma rays from the decay of neutral pions. They focused on the question of whether the power required to supply the observed cosmic rays in the face of adiabatic losses in the expanding remnant was so great that experimental limits on the isotropic flux of gamma rays would be violated. Motivated by the existence of a nearby new supernova, we use recent results on neutrino production[9] and neutrino-induced signals[10] to obtain quantitative predictions for signals in existing underground detectors that might be expected in the next few months and years from this supernova. The purpose is to provide a quantitative tool for interpretation of searches for neutrino-induced upward muons and for contained energetic-neutrino interactions from this supernova.

After the first few months the shell should become transparent to high-energy photons.[8] Then air-shower and air Cherenkov detectors in the southern hemisphere may also be able to see signals from the supernova if particles are accelerated to sufficiently high energies to produce the gamma rays. (Proton energies of about 10 PeV and 10 TeV, respectively, would be required for air showers visible in a particle array at the surface and for showers visible through their Cherenkov light produced high in the atmosphere.) We will not analyze photon production here but will return to it in a more detailed paper.

Two ingredients are required to produce energetic, nonthermal neutrinos: (1) acceleration of protons (or heavier ions) inside the expanding supernova (or possibly at the shell) and (2) a sufficiently thick gas target so that collisions of the accelerated protons will occur in the shell to produce pions and kaons which will give rise to neutrinos when they decay. The shell itself may be significantly less than an interaction length thick if, as expected, the protons are contained in the shell by diffusion in the turbulent magnetic fields.

In order to calculate the energy spectrum of neutrinos produced we need to know the spectrum of parent protons, their luminosity, and the thickness and density of the target. Some models characteristically accelerate particles to a fixed energy at each instant.[1] Others[6] give a distribution of energies. In the absence of *a priori* knowledge of how the accelerator works, we have calculated neutrino spectra for monoenergetic proton beams of various energies and for power-law proton spectra with various spectral indices. In each case we normalize to an instantaneous total power in accelerated protons of $L_{cr} = 10^{43}$ ergs/sec at an assumed distance of 50 kpc (kiloparsecs).[11] All results simply scale linearly with $L_{cr}$.

The neutrino spectra are calculated as in Ref. 9 by a Monte Carlo cascade program that follows the hadronic cascade through a medium of a given density profile and calculates meson production and decay to neutrinos. In this Letter we have considered a simple, uniformly low density in which all pions decay. A simple estimate[8] of the time dependence of the density in an expanding spherical shell shows that the pion's decay length is shorter than its interaction length for times longer than a few days even for pions with Lorentz factors up to $10^9$. Therefore, the low-density limit is applicable.

What is measured in the large, underground detectors is the upward fluxes of neutrino-induced muons produced by interactions of the neutrinos in the rock below the detector. Thus, the neutrino fluxes must be folded with the cross section for muon production in the Earth by muon-type neutrinos and antineutrinos. Rates of contained events (that is, neutrino interactions inside the fiducial volume of a detector) are obtained by our folding the neutrino cross sections with the fluxes of both muon- and electron-type neutrinos. These rates are generally much smaller than the rates of external events for energetic spectra of neutrinos because the effective volume for interactions external to the detector is enhanced by the muon range, which increases with energy.

In Fig. 1 we show the number of external events per week in a detector of 100-$m^2$ area for monoenergetic proton beams of various energies and for power-law spectra of protons with various spectral indices, $dN_p/dE_p = \text{const} \times E^{-\gamma}$. In each case, curves are shown for three accumulated thicknesses of target material, 1000, 100, and 10 g/$cm^2$. Note that the rate saturates for thicknesses $X$ only a factor of 2 or so higher than the nucleon interaction length in hydrogen, which is 56 g/$cm^2$. Since the protons are expected to be trapped by magnetic fields in the expanding shell, it is likely that the saturated result will be applicable.

Any acceleration mechanism should have some time dependence. Pulsar mechanisms would be expected to rise to maximum power quickly and then decay with some characteristic time. A stochastic mechanism might turn on more slowly. An interesting example is the specific model of Kulsrud, Ostriker, and Gunn,[12] for which we calculate the signal as an illustration. In their model, particles are accelerated to a time-dependent fixed energy that is high at first (some $10^6$ GeV), and gradually decreases. The accelerating field is that of the low-frequency, magnetic dipole radiation of a rapidly rotating neutron star with a nonaligned magnetic field.

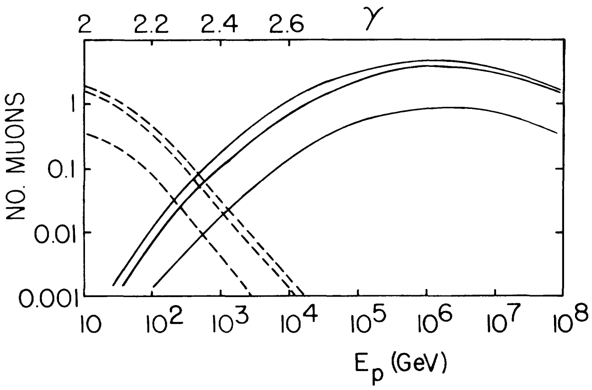


FIG. 1. Number of neutrino-induced muons per week in a detector of 100-$m^2$ area as a function of the parent proton spectrum. Solid lines and bottom axis refer to monoenergetic proton beams. Dashed lines and top axis refer to power-law spectra with differential index $\gamma$. In both cases the top curve is for a path length of 1000 g/$cm^2$, the middle curve for 100 g/$cm^2$, and the bottom one for 10 g/$cm^2$. All proton spectra are normalized to $10^{43}$ ergs/sec at 50 kpc.

Figure 2 shows the accumulated event rate for their model with an initial period of a millisecond, a surface magnetic field of $2 \times 10^{12}$ G, and hence a luminosity of $6 \times 10^{43}$ ergs/sec. The luminosity in the model is constant for about a year in this example, but the neutrino-induced rate flattens off after about three weeks. This is because after that time most of the power goes into electrons rather than protons, and electrons produce essentially no neutrinos. For comparison we also show the accumulated rate for the spectrum with spectral index 2.2, which is approximately linear with time.

We have shown the Kulsrud, Ostriker, and Gunn example here—despite the fact that the plasma near the neutron star is probably too dense to allow the wave to propagate[13] and accelerate particles—because it illustrates how a study of the time dependence of any high-energy, neutrino-induced signal can distinguish between models.

Any acceleration mechanism that occurs inside an expanding supernova remnant will suffer from adiabatic energy losses.[14] If one tries to supply all observed cosmic rays from such a mechanism, there is a danger that the power requirement will be too high. Berezinsky and Prilutsky[8] have shown, for example, that it is likely that the observed isotropic flux of gamma rays from the decay of neutral pions would be greater than observed. This argument does not, however, prevent such an acceleration mechanism from producing an observable neutrino signal even if the accelerated nuclei never get out of the shell. However, one would expect the production of secondaries in the shell to decrease when the energy loss due to expansion becomes important (of the order of a year or somewhat less[8]).

A favored candidate for producing the bulk of cosmic rays (up to perhaps 10–100 TeV) is first-order Fermi acceleration as the shock wave from the supernova remnant expands into the interstellar medium.[6] The accelerated particles in this case would presumably not

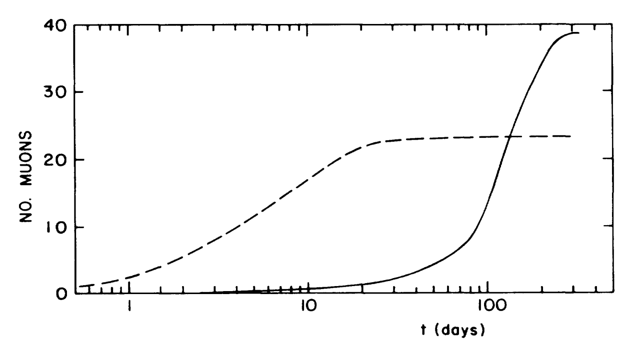


FIG. 2. Accumulated signal of neutrino-induced muons per 100 $m^2$ as a function of time. Dashed line, the model of Ref. 12; solid line, a proton spectrum with $\gamma = 2.2$ and constant power. Time dependence of other proton spectra for constant luminosity can be obtained by use of Fig. 1 to scale the time dependence shown by the solid line here.

penetrate far enough inside the shock to have a significant probability of interacting with the bulk of the shell and so would not produce significant fluxes of neutrinos. As discussed above, however, both internal and external mechanisms might coexist. Evidently, the pulsar in the Crab Nebula is powering an accelerator of electrons to produce the observed synchrotron radiation.[7] Observations of energetic neutrinos from supernova 1987A might show whether such a mechanism can also accelerate ions.

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