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# Potential for Supernova Neutrino Detection in MiniBooNE

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The MiniBooNE detector at Fermilab is designed to search for $\nu_\mu \to \nu_e$ oscillation appearance at $E_\nu \sim 1$ GeV and to make a decisive test of the LSND signal. The main detector (inside a veto shield) is a spherical volume containing 0.680 ktons of mineral oil. This inner volume, viewed by 1280 phototubes, is primarily a Čerenkov medium, as the scintillation yield is low. The entire detector is under a 3 m earth overburden. Though the detector is not optimized for low-energy (tens of MeV) events, and the cosmic-ray muon rate is high (10 kHz), we show that MiniBooNE can function as a useful supernova neutrino detector. Simple trigger-level cuts can greatly reduce the backgrounds due to cosmic-ray muons. For a canonical Galactic supernova at 10 kpc, about 190 supernova $\bar{\nu}_e + p \to e^+ + n$ events would be detected. By adding MiniBooNE to the international network of supernova detectors, the possibility of a supernova being missed would be reduced. Additionally, the paths of the supernova neutrinos through Earth will be different for MiniBooNE and other detectors, thus allowing tests of matter-affected mixing effects on the neutrino signal.

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## I. INTRODUCTION

As is well-known, about two dozen neutrinos in total were detected from SN1987A in the Kamiokande II, IMB, and Baksan detectors [1]. Even these very limited observations, despite some of their puzzling features, did provide a basic confirmation of the core-collapse supernova mechanism as well as interesting limits on the properties of neutrinos [2]. The Galactic supernova rate is about $(3 \pm 1)$/century (most would be obscured optically by dust) [3], so it is very important that a supernova neutrino signal not be missed because of detectors being down for upgrades or calibrations. This can be accomplished by having as many independent supernova neutrino detectors as possible. Since different detectors use different targets and techniques, having results from several detectors is also very useful for making cross-checks of the data and theory. Additionally, the neutrino paths through Earth will be different, and matter-affected mixing effects on the signal can be significant (see, e.g., Ref. [4]).

The supernova neutrino detection capabilities of various present or near-term detectors are documented elsewhere: Super-Kamiokande (SK) [5], the Sudbury Neutrino Observatory (SNO) [6], Borexino [7], KamLAND [8], the Large Volume Detector (LVD) [9], and AMANDA [10]. SK, once repaired, would expect about $10^4$ identified supernova events. The others would expect between a few and several hundred identified events. (The number of identified events in AMANDA is more difficult to quantify since the supernova is seen only as a statistically significant increase in the noise rate). The yields are expected to be larger than from SN1987A in part because the assumed distance is smaller. SN1987A was at a distance of about 50 kpc, in the Large Magellanic Cloud, a small companion of the Milky Way Galaxy. The next supernova will more likely be in our Galaxy proper, and conventionally, a distance of 10 kpc is assumed, approximately the median distance of Galactic stars from Earth. In the case of SK, it is approximately 16 times larger than its predecessor Kamiokande II.

The MiniBooNE detector at Fermilab is designed to search for $\nu_\mu \to \nu_e$ oscillation appearance, using a beam of $\sim 1$ GeV $\nu_\mu$ produced by $\pi^+/K^+$ decay in flight. These mesons are produced when a proton beam from the Fermilab Booster hits a beryllium target about 500 m away from the detector. The mesons are focused by a magnetic horn system that will allow charge selection and hence running with antineutrinos instead of neutrinos. The beam will operate with the very low duty cycle of 5 Hz of 1.6 $\mu s$ spills, so only modest shielding from cosmic-ray muons is required. This is provided by a 3 m earth overburden, which nearly eliminates the hadronic component of the cosmic rays (the hadronic interaction length is about 1 m water equivalent). The MiniBooNE experiment will decisively confirm or refute the LSND [11] neutrino oscillation signal; full operations begin in Summer 2002.

We briefly review the basic characteristics of the MiniBooNE detector. A more complete description can be found in Ref. [12]. The detector is a 6.1 m radius steel sphere, filled with mineral oil. The oil has density 0.85 g/cm$^3$ and its chemical composition is $C_nH_{2n+2}$, with $n \simeq 30$. At 5.75 m radius, there is a phototube support structure that optically isolates the inner volume from a veto region. The veto region is painted white to maximize light-gathering efficiency (Čerenkov imaging will thus not

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*Present address: Center for Experimental Nuclear Physics and Astrophysics, University of Washington, Seattle, WA 98195, USA be possible); it is viewed by 241 phototubes, and is expected to have greater than 99% efficiency for detecting cosmic-ray muons crossing the veto region once. The inner volume, containing 0.680 ktons of oil, is designed as an imaging Čerenkov detector viewed by 1280 phototubes providing 10% photocathode coverage. For the main oscillation experiment, a fiducial volume will be defined inside 5 m radius, and containing 0.445 ktons of oil. Though no scintillating compounds have been added to the oil, there is still some light from scintillation. We assume 4 photoelectrons per MeV, with a 3 : 1 ratio of Čerenkov to scintillation light. The total cosmic-ray muon rate in the detector is about 10 kHz, with about 8 kHz throughgoing and 2 kHz stopping. These rates were estimated directly using the known sea-level rates [13], and are in agreement with preliminary measurements in the detector. In the very near future, as the detector is commissioned and calibrated, the detector properties will be well-measured, and full Monte Carlo modeling of supernova neutrino detection will be done.

While the detector is clearly not optimized for detecting supernova neutrinos, since $\sim 200$ $\bar{\nu}_e + p \to e^+ + n$ events would be expected, it is worth examining whether it can indeed be used as a supernova neutrino detector. In this paper, we show that with just simple trigger-level cuts, MiniBooNE can efficiently operate as a supernova neutrino detector without interfering with its main task of testing the LSND [11] signal. This is despite the likely skepticism to the idea that a surface-level detector could reduce its cosmic-ray muon backgrounds enough to function as a supernova neutrino detector.

## II. THE SUPERNOVA SIGNAL

In large stars (greater than about $8 M_\odot$), nuclear fusion reactions begin with protons and eventually proceed through heavier nuclei until iron is produced. Since iron is the most tightly-bound nucleus, the energy generation rate in the core falls as the fraction of iron increases. Once the iron core has reached about $1.5 M_\odot$, it can no longer be supported by even electron degeneracy pressure, and it collapses. Once nuclear densities are reached, the core cannot be compressed further, and rebounds, with the subsequent outgoing shock ejecting the stellar envelope. In this paper, we characterize the supernova neutrino signal in a very simple way, though consistently with numerical supernova models [14]. The change in gravitational binding energy from the stellar core and the proto-neutron star is about $3 \times 10^{53}$ ergs, about 99% of which is carried off by all flavors of neutrinos and antineutrinos over about 10 s. The emission time is much longer than the light-crossing time of the proto-neutron star because the neutrinos are trapped and must diffuse out, eventually escaping with approximately Fermi-Dirac spectra characteristic of the surface of last scattering. In the canonical model, $\nu_\mu, \nu_\tau$ and their antiparticles have a temperature $T \simeq 8$ MeV, $\bar{\nu}_e$ has $T \simeq 5$ MeV, and $\nu_e$ has $T \simeq 3.5$ MeV. The temperatures differ from each other because $\bar{\nu}_e$ and $\nu_e$ have charged-current opacities (in addition to the neutral-current opacities common to all flavors), and because the proto-neutron star has more neutrons than protons. It is generally assumed that each of the six types of neutrino and antineutrino carries away about 1/6 of the total binding energy, though this has an uncertainty of at least 50% [15].

In this paper, we will focus on just the $\bar{\nu}_e$ signal. The spectrum shape for the supernova events is given by the product of the cross section and a Fermi-Dirac distribution, i.e.,

$$\frac{dN}{dE_\nu} \propto \sigma(E_\nu) \frac{E_\nu^2}{1 + \exp(E_\nu/T)} \,. \tag{2.1}$$

This is the spectrum of neutrinos which interact. The detection reaction in MiniBooNE is $\bar{\nu}_e + p \to e^+ + n$, and the corresponding positron spectrum is immediately obtained if we assume that $E_e = E_\nu - 1.3$ MeV (i.e., if neutron recoil is neglected). The cross section in this approximation [16] is

$$\sigma(E_\nu) = 0.0952 \times (E_\nu - 1.3)^2 \,, \tag{2.2}$$

where energies are in MeV and and the cross section is in units of $10^{-42}$ cm$^2$. The full cross section, including the recoil, weak magnetism, and radiative corrections is given by Vogel and Beacom [16]. For a temperature $T$, the positron spectrum peaks at about $4T$ [6] (for comparison, the average neutrino energy before weighting by the cross section is $3.15T$).

The expected number of events (assuming a hydrogen to carbon ratio in the detector of 2 : 1) is

$$\begin{aligned} N &= 11.8 \left[\frac{E_B}{10^{53}\ \mathrm{erg}}\right] \left[\frac{1\ \mathrm{MeV}}{T}\right] \\ &\times \left[\frac{10\ \mathrm{kpc}}{D}\right]^2 \left[\frac{M_D}{1\ \mathrm{kton}}\right] \left[\frac{\langle\sigma\rangle}{10^{-42}\ \mathrm{cm}^2}\right] \,. \end{aligned} \tag{2.3}$$

As noted, we will assume $E_B = 3 \times 10^{53}$ ergs, $T = 5$ MeV, and $D = 10$ kpc. We assume that all events within a radius of 5.5 m can be used, corresponding to 0.595 ktons. Though the optical barrier is at 5.75 m radius, the phototubes faces are at 5.5 m radius. The positrons have very short range (they lose about 2 MeV/g/cm$^2$) and are nearly isotropically directed. For the thermally-averaged cross section per $CH_2$ "molecule" (2 protons) we use $\langle\sigma\rangle = 54 \times 10^{-42}$ cm$^2$ at $T = 5$ MeV. Including the corrections of Ref. [16] would reduce the thermally-averaged cross section by about 20%; in the present study, these corrections may be neglected.

Thus the total yield from $\bar{\nu}_e + p \to e^+ + n$ is expected to be $N \simeq 230$. The positrons will be detected in MiniBooNE by their Čerenkov (and scintillation) light. The neutrons will be radiatively captured on protons, but we assume that the resulting 2.2 MeV gamma rays will not be visible, due to low-energy radioactivity backgrounds.

For $\bar{\nu}_e + p \to e^+ + n$, the yield is nearly proportional to $T$ (since $\langle\sigma\rangle \sim T^2$), and as noted, the peak of the positron spectrum is about $4T$. The true temperature may be somewhat different (see, e.g., Ref. [15, 17]), and it may be effectively increased by mixing with $\bar{\nu}_\mu/\bar{\nu}_\tau$ (see, e.g., Ref. [18]). We neglect possible distortions in the tail characterized by a chemical potential, as their effects are minimal for this cross section [6].

The next-most important reaction in the detector will be the neutral-current nuclear excitation of $^{12}$C, which yields a 15.11 MeV gamma, with $\simeq 30$ events expected (see, e.g., [7]). These gammas will Compton-scatter multiple electrons to a variety of energies. In the present study, we neglect these events. We also neglect the smaller numbers of events from neutrino-electron scattering and charged-current reactions on $^{12}$C.

To simulate the energy resolution of the detector, we first consider the minimum energy resolution that occurs because of the Poisson statistics of the number of photoelectrons. For a detector with $\alpha$ *detected* photoelectrons per MeV, the minimum energy resolution is

$$\delta(E) = \frac{\sqrt{E}}{\sqrt{\alpha}}, \tag{2.4}$$

where all energies are in MeV. Note that $\alpha$ varies from detector to detector and depends on the number and efficiency of the phototubes, their distance from the fiducial volume, light absorption, the fraction of tubes that are multiply hit, etc. It is therefore generally a function of position and direction. In other Čerenkov detectors, e.g., SK and SNO, all of these effects and more are modeled in the Monte Carlo, and energy resolution close to the Poisson limit can be obtained (only about 25% worse). We assume $\alpha = 4$ for MiniBooNE (SK and SNO have $\alpha = 6$ and 9, respectively), and that similar event reconstruction techniques can be employed. At the energies of interest, the detector efficiency is taken to be unity.

We conservatively assume that the energy resolution in MiniBooNE will be about 1.5 times the minimum given by Poisson statistics above. In LSND, the energy resolution was about 2.5 times worse than Poisson for reasons that had to do with the very high light yield due the scintillating compounds added to their mineral oil. Because of the large number of multiply-hit phototubes, energy was estimated by integrated charge, rather than simply by the number of hit phototubes. In those phototubes, the charge distribution per photoelectron is very broad, and has a long tail at high charge. Though the same phototubes are being used in MiniBooNE, we do not expect to have these problems. MiniBooNE will not have such a high light yield (the ratio of Čerenkov light to scintillation light should be 3 : 1 instead of 1 : 4, and $\alpha = 4$ instead of 30), and approximately 300 new phototubes with better charge resolution have been added. Therefore, the energy resolution at low energies in MiniBooNE should be rather good.

## III. BACKGROUNDS

We have shown that about 230 $\bar{\nu}_e + p \to e^+ + n$ events are expected in MiniBooNE from a canonical Galactic supernova at 10 kpc, and that the positron spectrum peaks at about 20 MeV. If these events can be separated from backgrounds, then this is a respectable yield of events, approximately 10 times more than were observed in total from SN1987A. As we show below, the spectrum shape should be well-measured too.

The key question, of course, is whether these signal events can be separated from the large cosmic-ray related backgrounds expected in a surface-level detector (for comparison, SK and SNO are under about 1 and 2 km of rock, respectively). As noted above, hadronic cosmic rays will be reduced to a negligible rate by the 3 m earth overburden. All of the backgrounds that we consider are related to cosmic-ray muons, and their total rate through the detector is about 10 kHz (8 kHz throughgoing, 2 kHz stopping). How then can we see the 230/10 s $\simeq$ 20 Hz supernova signal underneath the 10 kHz muon rate? In this Section, we study the background rates in detail and show how they can be greatly reduced with simple trigger-level cuts.

### A. Muon Energy Loss

We first consider direct energy deposition by muons. If the veto shield were perfectly efficient, then any muon in the main detector volume would be identified by its signal(s) in the veto. If throughgoing and stopping muons can be easily distinguished by their signals in the veto and main detector, then we would only have to consider possible Michel electrons from muon decays for the 2 kHz of stopping muons, and not the full muon rate of 10 kHz, thus minimizing the detector deadtime (this is discussed below).

However, since the muon rate is so high, an appreciable rate (2 kHz $\times$ 0.01 $\simeq$ 20 Hz) of muons can evade one veto layer and then stop in the detector. Sea-level muons have average energies of about 4 GeV, and will lose about 1.6 GeV in the 3 m earth overburden (assuming 2 MeV/g/cm$^2$ for a minimum-ionizing muon, and that the 3 m earth overburden is about 8 m water equivalent). Therefore, a typical muon might travel about 14 m in oil (density 0.85 g/cm$^3$). The spectrum of muon energies is falling only slowly in this energy range, so a broad distribution of path lengths in the detector is expected. Therefore, very few muons will lose less than 100 MeV or so, which would correspond to about 60 cm for a minimum-ionizing muon. Therefore, direct energy deposits by unvetoed stopped muons will always be so large as to be easily distinguishable from the supernova signal. One might also consider corner-clipping throughgoing muons, to which similar considerations apply; such muons will also have two chances to trigger the veto.

Therefore, we will define a muon event as any event in which the number of hit phototubes in the veto **OR** the main detector is large. This is easy to implement as a trigger-level cut, and it solves the problem of the veto inefficiency.

### B. Muon Decays

Most of the stopped muons in the detector will decay, and the Michel electrons and positrons from muon decay have an energy spectrum

$$\frac{dN}{dE_e} \propto E_e^2\,(1 - 0.013 E_e)\,, \tag{3.1}$$

where all energies are in MeV and the kinematic endpoint of the spectrum is 52.8 MeV. The normalization of the spectrum is set by the rate of stopped muons, namely 2 kHz. This is a potentially very important background, since the event energies are similar to those of supernova events.

We can dramatically reduce the Michel background by imposing a holdoff of 15.2 $\mu$s after every muon (the muon lifetime is 2.2 $\mu s$). During this holdoff period, no data will be taken, which creates a detector deadtime fraction. In the ideal case, the holdoff would only be applied for stopping muons, so that the deadtime fraction would be 2 kHz $\times$ 15.2 $\mu$s $= 0.03$, which would be negligible. However, because the veto is not perfect, we have to apply this holdoff after any muon event, as defined above, so the deadtime fraction will be 10 kHz $\times$ 15.2 $\mu$s $= 0.15$, which is still small. Most muon events are throughgoing, and so will not actually have a Michel decay electron. If true throughgoing events can be flagged at the trigger level, then the deadtime fraction can be reduced. Similarly, if the positions of true stopping muons could be determined, then only events nearby in distance and time would be excluded, instead of making the whole detector dead (for example, SK uses this technique to avoid large deadtime). With the long holdoff of 15.2 $\mu$s, we will cut all but a fraction $10^{-3}$ of Michel decays, so that the true rate of surviving Michels will be an extremely small 2 Hz in the main detector volume. Note that if the holdoff time is reduced, the deadtime fraction decreases linearly, but the surviving Michel rate increases exponentially.

### C. Beta Decays of $^{12}$B

Of the 2 kHz of stopped muons, about 44% are $\mu^-$ [19], of which about 8% will be captured instead of decaying [20]. Almost all of these captures are on $^{12}$C nuclei, rather than free protons, and all but about 16% will go to particle-unbound excited states of $^{12}$B [21]. Note that low-energy protons and alpha particles will be invisible in MiniBooNE because of the low scintillation yield and the effects of light quenching. The rate of captures to the ground state of $^{12}$B is thus about 11 Hz. This isotope is unstable to $\beta^-$ decay, with mean lifetime 20 ms and electron total energy endpoint 13.9 MeV. The shape of the electron total energy spectrum is

$$\frac{dN}{dE_e} \propto (13.9 - E_e)^2\, E_e \sqrt{E_e^2 - m_e^2}\,, \tag{3.2}$$

where all energies are in MeV and the normalization is set by the rate of 11 Hz. We have neglected the Fermi function, since it causes very little distortion at these high electron energies. With the above considerations for the trigger design, the $^{12}$B lifetime is so long that a holdoff time cannot be used. However, most of the $^{12}$B beta decays will produce events well below the typical supernova event energies (about 80% of the $^{12}$B beta-decay electrons have energies below 10 MeV).

The LSND collaboration observed about twice as many low-energy events that appeared to be $^{12}$B beta decay as expected [20]. These events were identified by their energy, not their lifetime, so other muon-induced radioactivities could also contribute. The origin of this discrepancy is unknown, but will be investigated further in MiniBooNE.

### D. Other Backgrounds

At energies below about 5 MeV, the background rates from a wide variety of radioactive contaminants will rise very quickly. These events do not overlap our supernova signal region, and can easily be removed at the trigger level by requiring a minimum number of hit phototubes. The possibility of large backgrounds not considered here can be excluded empirically by the results from the LSND detector [20], which was also located at very shallow depth and used a similar trigger.

## IV. RESULTS

In Fig. 1 we show the theoretical shapes of the supernova neutrino events, as well as the $^{12}$B decay and surviving muon decay backgrounds, over a 10 s interval assumed to contain the full supernova signal. All three classes of events are nearly isotropic, and will be nearly uniformly distributed in position.

The supernova signal is well above most radioactive backgrounds in energy, and reasonably above that from $^{12}$B. It is also well below the large energy depositions from muons. Michel decays from stopped muons do lie in the same energy range as supernova neutrino events, and their rate is about 2 kHz. However, we have shown that these background events can easily be reduced to a rate of about 2 Hz.

In Fig. 2 we have taken the estimated energy resolution (see above) of the detector into account. It is shown that this has a relatively minor effect on the spectra.

We have assumed that muons can be identified with very high efficiency by requiring either a large number of

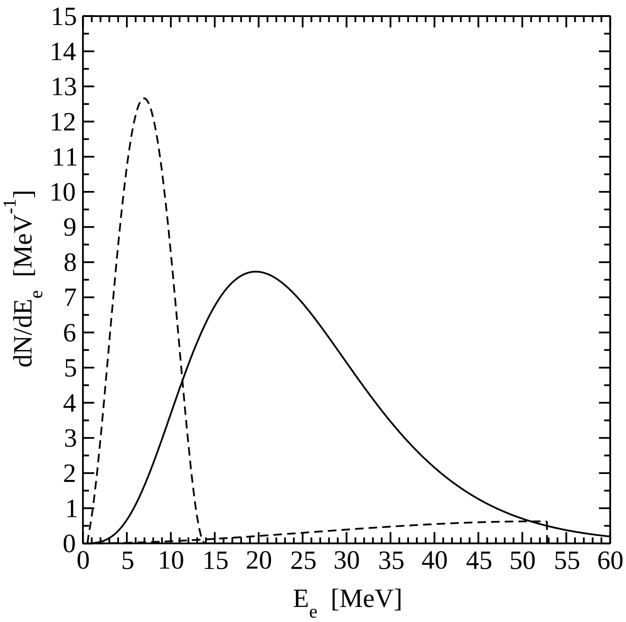


FIG. 1: Spectra of the supernova signal (solid line), $^{12}$B decay background (dashed line peaking at low energy), and surviving muon decay background (dashed line peaking at high energy) versus the true electron total energy, over a 10 s interval assumed to contain the full supernova signal. A volume of 0.595 ktons is assumed, though all rates are reduced by 15% to account for the detector deadtime fraction imposed by applying a 15.2 $\mu$s holdoff after any muon event. Energy resolution is not included. Below about 5 MeV, backgrounds from ambient radioactivities will dominate over the spectra shown.

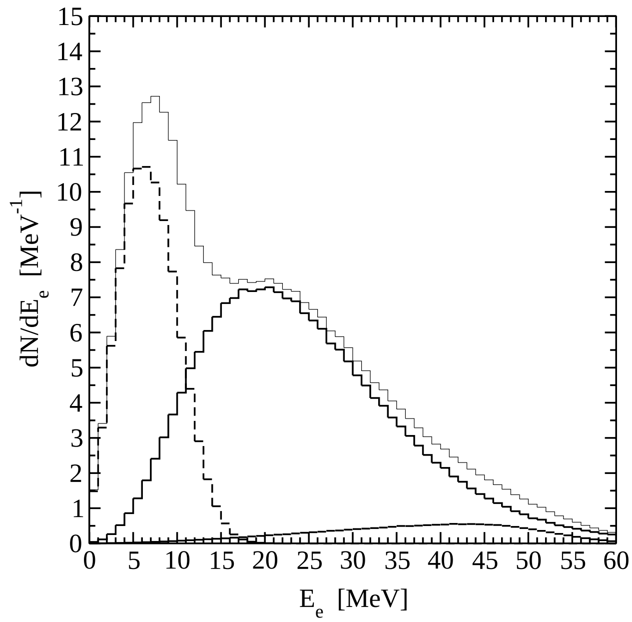


FIG. 2: The same as Fig. 1, except that energy resolution is now implemented as described in the text. The thin solid line indicates the sum spectrum. The curves shown indicate the true spectral shapes. For an actual supernova, there will be Poisson fluctuations on the numbers of events shown in each of the (1 MeV wide) bins.

hit phototubes in the veto region **OR** the main detector volume. We can then impose a 15.2 $\mu$s holdoff after any such event. This is over-conservative in the sense that most of these muons will not actually stop and decay in the detector, but the penalty is minor, just a 15% deadtime. With a modest cut at low energies, i.e., requiring a minimum number of hit phototubes, the low-energy radioactivities and a good deal of the $^{12}$B beta decays can be cut. In sum, the steady-state rate should be about 4 Hz, easily manageable by the data acquisition electronics.

A candidate supernova can be flagged by a large increase in the data rate, as shown in Fig. 3. A circular buffer can store data for offline evaluation, where it can be examined to see if it has reasonable characteristics (energy spectrum, duration, event positions and directions, etc.). Detailed discussions of supernova trigger for offline evaluation systems were published for Kamiokande [22] and MACRO [23].

## V. DISCUSSION AND CONCLUSIONS

The MiniBooNE experiment [12] will decisively test the neutrino oscillation signal reported by LSND [11]. If the signal is confirmed, it will have a big impact on all of neutrino physics, since simple models with three active neutrinos appear to be inadequate to explain all the data. In addition, several authors have shown that the required mixing parameters would have interesting implications for various aspects of core-collapse supernovae, including the explosion mechanism, $r$-process production of the heavy elements, and the detected neutrino signal [24].

Our results show that MiniBooNE could be quite useful as a supernova neutrino detector, despite being optimized for much higher energies and being at a shallow depth of only 3 m. With very simple trigger-level cuts, the backgrounds associated with the 10 kHz cosmic-ray muon rate can easily be reduced to a manageable level, as shown in Figs. 1 and 2. The approximately 230 events from a canonical Galactic supernova at 10 kpc can thus be easily identified, with only minimal background contamination. Only about 15% of these events will be lost to detector deadtime as a result of cuts to reduce the muon decay background. This leaves about 190 supernova events, and their spectrum should be well-measured. The steady-state data rate of about 4 Hz in the data acquisition electronics is also easy to handle. The details of implementing a supernova trigger into the MiniBooNE data acquisition system are now being studied. Further, in the very near future, direct measurements of the detector performance and backgrounds will be measured in detail.

What can MiniBooNE add to the worldwide effort to detect supernova neutrinos? *First*, it is highly desirable to have as many different detectors as possible. This will

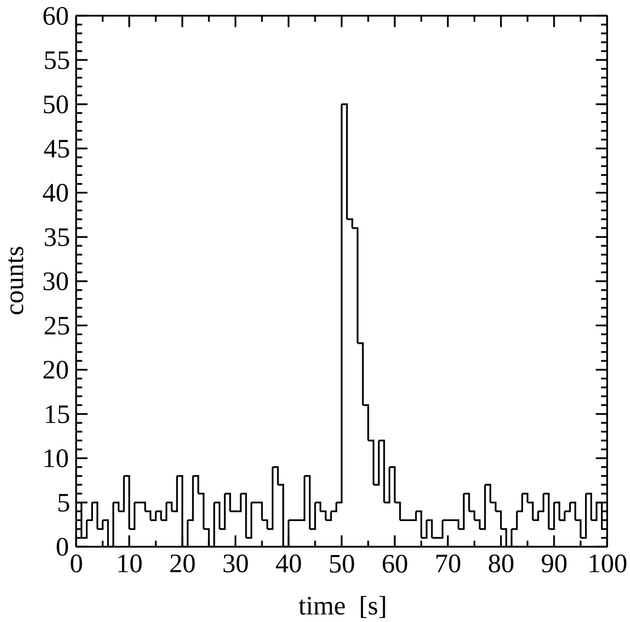


FIG. 3: Total number of signal and background events, in 1 s bins over 100 s, showing the Poisson fluctuations for one random simulated experiment with a supernova at $t = 50$ s. The background rates above 10 MeV from $^{12}$B beta decays and muon decays are each about 2 Hz. All rates have been multiplied by 0.85 to account for detector deadtime, as discussed in the text. The supernova signal was modeled as a sharp rise followed by an exponential decay with time constant 3 s.

allow important cross checks of the results, both from a theoretical and an experimental point of view. *Second*, MiniBooNE may be able to act as a node in the Supernova Early Warning System (SNEWS) [25]. While triangulation of the supernova direction by arrival-time differences in several detectors likely remains very difficult [26], having many independent nodes in the network greatly reduces the false alarm rate. Also, since neutrinos leave the proto-neutron star hours before light leaves the stellar envelope, detection of supernova neutrinos may allow for astronomical observations of the earliest stages of the supernova. *Third*, not all detectors are live all the time, due to upgrades and calibrations. Until SK is repaired, the $\bar{\nu}_e + p \to e^+ + n$ yield in MiniBooNE would be comparable to that from other detectors with hydrogen targets. *Fourth*, the signal in MiniBooNE may be useful for studying matter-affected mixing effects on neutrino propagation in Earth, especially when compared to other $\bar{\nu}_e + p \to e^+ + n$ detectors at different locations. These matter effects can significantly distort the spectrum of detected positrons (see, e.g., Ref. [4]).

We have shown that MiniBooNE can function as a useful supernova neutrino detector, despite its high cosmic-ray related background rates. One immediate application of this technique is that other surface-level neutrino detectors may be also be useful for detecting supernova neutrinos.

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