OMNIS, The Observatory for Multiflavor NeutrInos from Supernovae

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ABSTRACT

OMNIS, the Observatory for Multiflavor NeutrInos from Supernovae, is being planned for siting in the Center for Applied Repository and Underground Research, CARUS, in New Mexico. OMNIS will consist of 14 kT of lead and iron which, when radiated by neutrinos from a supernova, will produce secondary neutrons. Detection of the neutrons then signals the arrival of the supernova neutrinos. A supernova at the center of the Galaxy, will produce about 2000 events in OMNIS, mostly from neutral current interactions. OMNIS' combination of lead and iron modules gives it particular sensitivity to neutrino oscillations of the type $\nu_\mu \rightarrow \nu_e$ or $\nu_\tau \rightarrow \nu_e$. Its intrinsic timing capability, better than 1 ms, gives it the capability to measure neutrino mass from the time-of-flight shifts in the luminosity curves of the neutrinos of different flavors to around 2 eV/c^2. OMNIS will also be able to detect differences in the luminosity cutoffs of the different flavors in the event of the prompt collapse to a black hole, which might allow diagnostics on that collapse process.

1. Introduction

The final state of evolution of a massive star results in a collapse which ultimately produces a few times 10^{53} ergs of neutrinos (Burrows 1990). The standard model of this process suggests that ν_e's have a mean energy of around 11 MeV, $\bar{\nu}_e$'s around 16 MeV, and all others, ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's, and $\bar{\nu}_\tau$'s, around 25 MeV. This is a result of the fact that the ν_e's and $\bar{\nu}_e$'s interact with matter through both the charged- and neutral-current interactions, whereas all the other neutrinos, at least at the energies at which they are produced in supernovae, interact only through the neutral-current interaction. Since the ν_e's and $\bar{\nu}_e$'s therefore have more options for sharing their energy, they will emerge with a lower energy than will the neutrinos of the other flavors.

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Detection of the neutrinos from a supernova can provide diagnostics of the environment from which they ar produced and by which they are trapped, at least for a time span of a second or so. Indeed, the observation of the $\bar{\nu}_e$ signal from SN 1987a produced a qualitative confirmation of the theoretical description of the trapping process, as the neutrinos are thought to be produced on a time scale of milliseconds (Burrows 1990). However, much more can be learned both by observation of a much larger statistical sample of SN neutrinos and by observation of the luminosities of neutrinos other than $\bar{\nu}_e$'s.

2. Technical Characteristics of OMNIS

With this latter point in mind, we are designing OMNIS, the Observatory for Multiflavor NeutrInos from Supernovae. OMNIS involves collaborators from Ohio State University, the Universities of California at Los Angeles, San Diego, and Irvine, the University of Texas, the University of Wisconsin, and Lawrence Livermore and Oak Ridge National Laboratories. OMNIS was originally conceived (Cline et al. 1990) as utilizing the nuclei in the walls of an underground facility to convert the neutrinos into neutrons, which would then be detected in neutron detectors. However, the conversion efficiency of possible types of rock was found to be much less than that of iron or lead. Thus the present version of OMNIS consists of 4 kT of lead and 10 kT or iron. Slabs of the metal are alternated with vertical racks of neutron detectors. The neutrinos will be detected when they interact with the iron or lead to emit secondary neutrons, which in turn will be observed in the neutron detectors.

Lead is a particularly efficient converter of the neutrinos to neutrons, as its threshold for neutron emission via neutral current interactions is only 7.37 MeV. In addition, it can interact through the charged current interaction to produce ^{208}Bi, a process which has a slightly higher threshold for neutron emission of 9.77 MeV, but a considerably larger cross section (Fuller, Haxton, and McLaughlin, 1998; hereafter denoted FHM98). Indeed, it has been calculated (FHM98) that lead will produce about 800 neutrons per kT for the standard model neutrino spectrum for all flavors, but primarily from neutral current interactions induced by ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's and $\bar{\nu}_\tau$'s. Lead has an additional interesting feature: it also can produce events in which two neutrons are emitted. The threshold for that process is 14.98 MeV. OMNIS has the capability to detect such events with fairly high efficiency. Although the yield of events from the charged current process is a small fraction of the total, xx events per kT, that yield is extremely dependent on the energy of the ν_e's and $\bar{\nu}_e$'s, a point to which I return below.

Iron, by contrast, has a high threshold for neutron emission via neutral current interactions, 11.20 MeV, and a sufficiently high threshold for charged current processes that its production will be negligible. This is both a positive and a negative characteristic; its results in a lower efficiency, but calculation of its yield is simpler than for lead. Iron has been calculated (Woosley et al., Langanke) to produce xx events per kT for the Standard Model neutrino spectrum, with virtually all coming from ν_μ's, $\bar{\nu}_\mu$, ν_τ's and $\bar{\nu}_\tau$'s.

Thus the two types of converters will provide three spectra: one from the single-neutron events from lead, another from the two-neutron events from lead, and the third from the events from iron.

3. Sensitivity to Oscillations

The yield from the lead is particularly sensitive to some types of oscillations. Specifically, either $\nu_\mu \rightarrow \nu_e$ or $\nu_\tau \rightarrow \nu_e$ oscillations would produce much more energetic ν_e's than would be expected from the SN. This would produce dramatic effects in the lead detector; if maximal mixing occurred the yield from the lead detector would be enhanced (FHM98) by about a factor of four, and the two-neutron event yield would be enhanced by a factor of about 40. Thus the ratio of one- to two-neutron events from the lead would produce a clear signature of oscillations of this type.

4. Fast Timing Capability of OMNIS

Another important feature of OMNIS is its fast timing capability. Once the neutrons are produced they lose little energy until they reach the scintillator. There they lose most of their energy in their first few scatterings from the protons in the scintillator, a time (as indicated by extensive Monte-Carlo simulations) of less than 200 ns, and a time since their production that is even shorter. The subsequent thermalization of the neutrons requires about 30 μs, at which point they are captured by a Gd nucleus, a 0.1% additive to the scintillator. This capture produces four γ-rays with a total energy of 8 MeV. The combination of these fast-slow signals provides a signature for the neutron-induced events, but also produces a remarkably fast timing capability for OMNIS.

4.1. Measuring Neutrino Mass

Because of OMNIS' intrinsic timing capability, the timing of the onset of any neutrino luminosity curve will depend on statistics: this limit will be roughly a few ms for a SN at the galactic center (Beacom 1999. This level of timing could produce a measurement of neutrino mass from the effect of the time-of-flight of the neutrinos on their distributions. If one neutrino is very light, the arrival time difference between that neutrino and more massive neutrinos (denoted by ν_τ) is

$$\Delta t = 0.515(m/E)^2 D, \tag{1}$$

where m is the mass of the heavy neutrino in units of eV/C^2, E is its energy in MeV, and D is the distance to the SN in units of 10 kpc. This level of accuracy would be difficult to attain in any other way. It should be noted that a closer supernova might produce many more events (Betelgeuse would produce several million events in OMNIS!), which could determine the onset of the distributions better, but would also reduce the intrinsic time lag. A SN at the galactic center would be expected to determine the onset of the distributions to a few ms, which would determine the mass of the heavier neutrino to a few eV/d^2 (Beacom 1999).

4.2. Diagnosing Collapse to a Black Hole

Perhaps the most dramatic manifestation of such fast timing, though would occur if collapse went fairly promptly to a black hole. If this did occur, some neutrinos would probably be emitted before the infalling matter first traped the neutrinos near the black hole, then swallowed both matter and neutrinos. However, because the ν_e's and $\bar{\nu}_e$'s interact more strongly with the infalling matter (because they interact with both neutral and charged current interactions) than do neutrinos of other flavors, they would be trapped farther from the hole than would the ν_μ's and ν_τ's and their respective antineutrinos. This would suggest that the ν_e and $\bar{\nu}_e$ luminosities would be terminated before those of the ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's and $\bar{\nu}_\tau$'s. This difference, estimated (Mezzacappa) to be of the order of 10 ms, might be expected to depend on the details of collapse, e.g., angular momentum. Thus the timing properties of OMNIS, together with the statistics associated with 2000 events (Beacom and Boyd), would allow for diagnosis of the process of collapse to a black hole!

5. Additional Aspects of OMNIS

We are planning on siting OMNIS in the Center for Applied Repository and Underground Science, CARUS, in southeastern New Mexico. The lead modules will occupy about 30 linear meters of the site, while the iron modules will occupy slightly over 100 meters. The height of the modules is restricted by the "back" (height) of the drifts to be about 4.5 meters, while the width of the drifts restricts the module width to about 4.0 meters. The detectors will consist of alternating slabs of lead or iron and of racks of scintillators with photomultiplier tubes at both ends. The ends of the modules would also be covered by doors of lead or iron, which will slide on rails. This will allow access to photomultiplier tubes or to the ends of the scintillators should maintenance be required.

At present we are testing two types of neutron detectors, one of plastic scintillator and the other of liquid scintillator. The individual detectors will either be 20 cm diameter by 2 m long cylindrical tubes of liquid scintillator or plastic scintillators of comparable size. Either type of scintillator would be loaded with a small amount of Gd, Li, or B to produce the signatures of neutron induced events.

6. Conclusions

The unique physics and astrophysics that could be obtained from a statistically meaningful sample of events from the next Galactic supernova, including luminosities of all neutrino flavors, argue strongly for building an observatory to provide those data. We are planning OMNIS to fulfill that need. Furthermore, the fast timing characteristics of OMNIS give it the capability to measure neutrino masses at levels that would be difficult to achieve with any other technique, as well as possibly diagnose the collapse to a black hole.

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