The Observatory for Multiflavor NeutrInos from Supernovae

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OMNIS, the Observatory for Multiflavor NeutrInos from Supernovae, will consist of 12 kT of lead and iron. When irradiated by neutrinos from a supernova, it will produce secondary neutrons which will be detected. A supernova at the Galactic center will produce about 2000 events in OMNIS, mostly from μ- and τ-induced neutral current interactions, creating an unprecedented opportunity to understand the processes that govern stellar collapse. OMNIS' lead component gives it particular sensitivity to oscillations of the type ν_μ or $\nu_\tau \rightarrow \nu_e$. Its intrinsic timing capability, better than 0.1 ms, would allow it to measure neutrino mass from time-of-flight shifts in the luminosity curves of the neutrinos of different flavors to 20–30 eV/c^2. In the event of collapse to a black hole, OMNIS may be able to determine the mechanism that caused the collapse, and determine neutron masses to a few eV/c^2.

1. Introduction

A massive star passes through its successive stages of stellar evolution, and ultimately produces a core collapse supernova (SN). The collapse probably produces a neutron star, which cools by emitting about 10^{53} ergs of neutrinos [1] in a few seconds. About 1% of that energy goes into the shock wave that explodes the star, and about 0.01% into the light that might be observed by astronomers. The energy in the neutrinos is 1000 times the energy that our Sun will emit over its entire lifetime.

The standard model [2] of this process suggests that the resulting ν_e's have a mean energy of 11 MeV, $\bar{\nu}_e$'s of 16 MeV, and ν_μ's, $\bar{\nu}_\mu$'s, ν_τ's, and $\bar{\nu}_\tau$'s (= ν_x's) of 25 MeV. The ν_e's and $\bar{\nu}_e$'s interact with matter through both charged-current (CC) and neutral-current (NC) interactions and ν_x's through NC interactions only. This results in trapping of the ν_e's and $\bar{\nu}_e$'s farther from the star's core, so they emerge (from a cooler region) with less energy than do the ν_x's.

The neutrino luminosities are thought to first exhibit a "neutronization spike" that would signal the beginning of the stellar collapse, primarily from

$$p + e^- \rightarrow n + \nu_e. \tag{1}$$

Subsequent broad distributions lasting for several seconds would then be expected from neutrinos of all flavors being produced in the hot core of the star by

$$e^+ + e^- \rightarrow \nu_i + \bar{\nu}_i \tag{2}$$

where i = e, μ, or τ. Although this process occurs only once in 10^{19} positron annihilations, it cools the star's core in a few seconds.

Detection of the neutrinos from a SN can provide diagnostics of the environment from which they are produced. Indeed, the observation of the $\bar{\nu}_e$ signal [3], [4] from SN1987a qualitatively confirmed at least some of the features of the standard model [1], [2] of stellar collapse. However, much more can be learned by observing both a larger statistical sample of SN neutrinos and neutrinos other than $\bar{\nu}_e$'s.

2. Characteristics of OMNIS

Thus we are designing OMNIS, the Observatory for Multiflavor NeutrInos from Supernovae. It involves collaborators from a dozen institutions. It is designed [5], [6], [7] to utilize 6 kT of lead and 6 kT of iron "converters" which, when

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hit by the SN neutrinos, would of produce neutrons. These would then be detected in conventional neutron detectors.

Lead is a relatively efficient converter of neutrinos to neutrons. Its threshold for neutron emission via NC interactions is only 7.37 MeV. In addition, ν_e's can produce ^{208}Bi, via the CC interaction, with a neutron emission threshold of 9.77 MeV. A SN at a distance of 8 kpc should produce [8] about 780 neutrons per kT of lead for all flavors for standard model SN neutrino spectra, primarily from NC interactions induced by ν_x's. In addition, higher-energy neutrinos can produce events in which two neutrons are emitted in lead (threshold = 14.98 MeV). The yield of events from the CC process is expected to be only ~ 47 events per kT in the lead, but that yield depends very sensitively on some types of neutrino oscillations, as discussed below.

Iron, by contrast, has a high threshold for neutrino produced neutron emission via NC interactions, 11.20 MeV, and negligible production for CC processes. This results in a lower efficiency than that for lead, but a yield that is independent of neutrino oscillations. Iron should produce [9] around 140 neutrons per kT for the standard model neutrino spectrum for a SN at 8 kpc, with virtually all events coming from ν_x's.

OMNIS' detector modules will consist of alternating slabs of lead or iron and racks of scintillators with photomultiplier tubes at both ends. The lead and iron modules will have additional slabs of lead and iron, respectively, on the top and bottom, and sliding doors on the sides to provide access to the individual detectors should maintenance be required. The scintillator, either liquid or solid, will contain 0.1% of Gd to produce the signatures of the neutron capture events. Plastic scintillator detectors will span the surfaces just above OMNIS' lead and iron modules to identify high energy muons, which might themselves produce background neutrons. These scintillators will be used to veto such events.

OMNIS will be sited in the Center for Applied Repository and Underground Science, CARUS, 655 m underground ([10]), near Carlsbad, New Mexico.

2.1. OMNIS' Yields and Comparisons to Other SN Neutrino Observatories

The OMNIS converters thus provide two time dependent spectra from the one- and two-neutron events from lead and a third from iron. For a SN at the Galactic center, *i.e.*, at 8 kpc from earth, OMNIS' lead will produce about 1600 events, and its iron about 300 events, assuming that there are no oscillations (see below). These predictions assume a neutron detection efficiency determined [11] from extensive Monte-Carlo simulations.

OMNIS' events will nearly all be induced by ν_x's. Super-Kamiokande, by contrast, will produce 8000 events from a SN at the Galactic center, but they will nearly all be $\bar{\nu}_e$ induced. Thus OMNIS is intended to complement the yield from Super-Kamiokande. The Sudbury Neutrino Observatory will produce about 300 neutral current induced events for a SN at the Galactic center, but this will not be sufficient to produce the scientific information that we hope to obtain from OMNIS. Furthermore, SNO will not have OMNIS' timing capability (see below) in all of its operating modes.

2.2. OMNIS' Fast Timing Capability

An important feature of OMNIS is its fast timing capability. Once neutrons are produced they lose little energy until they reach the scintillator, where they lose most of their energy in a few scatterings from the protons therein. Monte-Carlo simulations [11] have shown that these occur in less than 200 ns. The subsequent thermalization of the neutrons requires ~ 30 μs, after which they are captured by a Gd nucleus, producing ~ 8 MeV of γ-rays. This predicted timing was confirmed by tests done with a prototype detector ([12]). The combination of these fast and slow signals produces both the signature for the neutron-induced events, and OMNIS' fast timing capability.

3. Astrophysics and Physics from OMNIS

3.1. Astrophysics of Stellar Collapse

The neutrino spectrum in the standard model of stellar collapse is Fermi-Dirac, but neutrino bremsstrahlung [13] can affect both the numbers and energies of the neutrinos emitted, while inelastic scattering [13], [14] and convection can affect their energies. In addition, the energy distributions may be "pinched" at both the high- and low-energy ends in dense stellar cores [15]. These effects could be studied with a high-statistics observation of SN neutrinos. The details of the neutrino spectra are also important for, *e.g.*, neutrino mass measurements and black hole collapse diagnostics, in addition to understanding the processes of stellar collapse and cooling.

3.2. Measuring Neutrino Masses

Because of OMNIS' fast intrinsic timing capability, the onset of any neutrino luminosity curve will probably be limited by statistics. This would be $\sim$ a few ms for a SN at the Galactic center [16]. This could produce a measurement of neutrino mass from the time-of-flight differences observed in the neutrino distributions. The arrival time difference between light neutrinos and those of larger mass m and energy E, for a SN at distance D, is

$$\Delta t = 0.515[(m/eV)/(E/MeV)]^2(D/10kpc), \quad (3)$$

For a SN at the center of the Galaxy, this would produce a time separation of $\sim$ 2 s between a light neutrino and one of mass 50 eV/c^2 (after traveling 33,000 years!). The onset of the distributions from an 8 kpc distant SN would be defined to a few ms, which in turn would determine [16] the mass of the heavier neutrino to 20–30 eV. This level of accuracy is an improvement of many orders of magnitude over existing limits for μ and τ neutrinos.

3.3. Observing Neutrino Oscillations

The yields from the lead modules are especially sensitive to ν_μ or $\nu_\tau \rightarrow \nu_e$ oscillations; either would transfer the energy of the ν_x's to ν_e's to produce much more energetic ν_e's than is predicted in the standard model. This would enhance the yield in lead [8] by up to a factor of 4, and the two-neutron yield by up to a factor of 40. Thus the ratio of these two yields would provide an extremely accurate measure of the extent to which such oscillations occur. Note that the yield from iron serves to confirm that the level of oscillations can be measured from the ratio of the yields in lead, i.e., that some unexpected physics that has nothing to do with neutrino oscillations has not occurred to change the ratio of the one- to two-neutron yields in the lead.

3.4. Diagnosing Collapse to a Black Hole

OMNIS' fast timing would indicate an abrupt termination of the neutrino luminosities if the stellar collapse went fairly promptly to a black hole. Because the ν_e's and $\bar{\nu}_e$'s would be trapped farther from the center of the star than would the ν_x's, the ν_e and $\bar{\nu}_e$ luminosities would terminate after those of the ν_x's, since the black hole would grow outward from the center of the star (although this is complex [17]; it could be inverted by the differences in the energies of the neutrinos of different flavors, hence in the magnitudes of their cross sections). This difference has been estimated [18] to be $\sim$ 1 ms. The neutrinos might also determine [19] the mechanism of the collapse to a black hole, as their relative luminosities would be different if the collapse was triggered by a softening of the nuclear equation of state resulting from deleptonization [18] from that expected if infall in excess of the Chandrasekar mass [20] was the cause.

4. Frequency of Galactic Supernovae and Black Hole Formation

The historical record identifies one or two Galactic SNe per century. However, a more careful examination of those events shows that they all occurred in the 10% of the Galaxy nearest our solar system (see discussion in Beacom et al. [19]). This suggests that most SNe were obscured from observation in optical photons by intervening dust, so that a more realistic rate may be one every 10 to 20 years.

The fraction of the instances in which core collapse SNe form black holes has also been estimated in several studies (see discussion in [19]). The different approaches suggest that black holes are formed 25% of the time at one extreme to 90% of the time in the other. While the actual fraction is highly uncertain, these studies do suggest that black holes are formed in at least a significant fraction of core collapse SNe.

5. OMNISita, a Test Module

A small test module, called OMNISita, will be built using borrowed or surplus components from other experiments ([21], [22]). This will contain about 300 gallons of liquid scintillator and 50 to 100 T of lead. It will allow initial studies of backgrounds from the CARUS rock, from cosmic rays, and from the lead and iron impurities, of importance to determining the purity requirements of the materials to be used in OMNIS. It will also permit studies of data acquisition and coincidence requirements in the face of high background event rates, as well as the optimization of customized electronics.

Since OMNISita will be located in the CARUS, it can be used to study possible solutions to insulating electronics and computers from the (salty dust) environment. It will also serve as a test setup for studying the effects of salt creep on structural designs that will ultimately be used in OMNIS. OMNISita's assembly will begin in Autumn, 2000.

6. Conclusions

The unique astrophysics and physics that could be obtained from a statistically large sample of neutrinos from the next Galactic SN, including luminosities of all neutrino flavors, argue strongly for building an observatory such as OMNIS to provide those data. Furthermore, the fast timing characteristics of OMNIS give it the capability to measure some extraordinary scientific observables.

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