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Supernova neutrinos: a summary

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The detection of neutrinos from the supernova explosion SN1987A, and its significance for models of stellar evolution and for elementary particle physics are reviewed. Consideration is also given to the physics that could be learnt from such an explosion occurring closer than that of the Large Magellanic Cloud, the site of the 1987 explosion.

1. Introduction

The observation of neutrinos from the supernova explosion SN1987A was epochal because it marked the beginning of extra solar system neutrino astronomy. Perhaps of even greater importance was the confirmation of the understanding of stellar evolution in its final catastrophic stages. Supernova of type II are thought to occur at the end of the evolution of massive stars ($M_{\text{star}} \geqslant 8\,M_{\odot}$) after successive nuclear burning results in an iron core whose mass is greater than the Chandrasekhar limit ($M_{\text{core}} \geqslant 1.5\,M_{\odot}$), and is surrounded by an onion-like structure of burning layers of silicon, oxygen, neon, carbon, helium and hydrogen. The Iron core is expected to collapse into a neutron star (or even a black hole if $M_{\text{core}} > 2.0\,M_{\odot}$) releasing $2\text{–}4 \times 10^{53}$ ergs of energy, 99% of which is expected to be converted into neutrinos. Type II supernova explosions have been authoritatively reviewed by Bethe (1990).

2. Neutrino detection reactions

Since in large underground experiments, capable of detecting supernova neutrinos, the detector medium is either light or heavy water, or scintillator, the relevant cross sections are those on free protons, protons and neutrons bound in the deuteron, those on oxygen and carbon nuclei and finally the cross sections for scattering off the atomic electrons.

The first class of cross sections involve semi leptonic processes initiated by the weak charged current where an incoming electron anti-neutrino (neutrino) changes into an outgoing positron (electron) in an interaction with a proton (neutron). These processes are essentially the inverse of β decay. Muon and tau neutrinos from a supernova explosion cannot interact in this manner because they are not energetic enough to make the outgoing lepton.

On free protons the process $\bar{\nu}_e + p \rightarrow n + e^+$ has a cross section given by 9.8×10^{-42} $(E/10\ \text{MeV})^2\ \text{cm}^2$, where E is the energy of the incoming anti-neutrino. At very low energy the angular distribution of the positron is slightly backward peaked with respect to the incoming anti-neutrino direction, having the form $(3\lambda^2+1)-(\lambda^2-1)\cos\theta$ where $\lambda = G_A/G_V = -1.23$ and θ is the angle between the positron and the direction of the incoming anti-neutrino. As the energy increases, weak magnetism

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effects grow in importance such that the angular distribution is isotropic at 20 MeV, and more and more forward peaked the higher the energy above 20 MeV.

The above process and its charge conjugate, $\nu_e + n \rightarrow p + e^-$ can occur on the weakly bound nucleons in the deuteron. However, in this case, at low energy, the transition has to be a pure Gamov–Teller transition ($G_V = 0$) since the two identical nucleons left in the final state must have opposite spins. The cross section is consequently reduced to 2.6×10^{-42} $(E/10\ \text{MeV})^2\ \text{cm}^2$ and at low energy the angular distribution is simply $1 - \frac{1}{3}\cos\theta$.

Neutrinos can also change the tightly bound oxygen nucleus into the ground (and excited) state(s) of fluorine though the reaction $\nu_e + O^{16} \rightarrow Fl^{16} + e^-$. However, the threshold for this reaction is 13 MeV and the cross section, given by 1.1×10^{-44} $(E(\text{MeV}) - 13)^2\ \text{cm}^2$, is far smaller than those above and those that follow, for neutrinos from a supernova.

The next important class of reactions are those semi-leptonic processes initiated by the weak neutral current. Although these cross sections are smaller than those of the semi-leptonic charged current, all neutrino types can contribute since the outgoing lepton is a neutrino and not the heavy muon or tau lepton. The cross section for the neutrino disintegration of the deuteron, $\nu + D_2 \rightarrow p + n + \nu$ is given by 1.0×10^{-42} $(E/10\ \text{MeV})^2$ and as I was remined by Berezinsky a cross section important in scintillator detector is the neutral current excitation of the 15 MeV level in carbon, which decays by gamma emission. This cross section is given approximately by 1.0×10^{-44} $(E - 15)^2$, a small cross section but all neutrinos can contribute.

Finally there are the cross sections for neutrino scattering by the atomic electrons. For $\nu_e + e^- \rightarrow \nu_e + e^-$ and $\bar{\nu}_e + e^- \rightarrow \bar{\nu}_e + e^-$ the cross sections are respectively 0.93×10^{-43} $(E/10\ \text{MeV})$ and 0.40×10^{-43} $(E/10\ \text{MeV})$. For the $\nu_\mu, \nu_\tau + e^- \rightarrow \nu_\mu, \nu_\tau + e^-$ and $\bar{\nu}_\mu, \bar{\nu}_\tau + e^- \rightarrow \bar{\nu}_\mu, \bar{\nu}_\tau + e^-$ processes the corresponding cross sections are 0.16×10^{-43} $(E/10\ \text{MeV})$ and 0.13×10^{-43} $(E/10\ \text{MeV})$ respectively. Bearing in mind that there are five electrons to every free proton in water, and assuming equal fluxes for all neutrino species then the percentage ratio of the scattering on atomic electrons to the inverse β process on the free proton, is closely equal to $10\,\%$ $(10\ \text{MeV}/E)$.

Since the target electron is a light particle, the recoil electron tends to be well collimated with the direction of the incoming neutrino. Although this collimation is smeared by multiple scattering in the detector medium, the mean angle between the electron and the incoming neutrino is nevertheless about 30°.

3. The expected neutrino spectra from a type II supernova explosion

During the collapse of the iron core the electron degeneracy becomes relativistic allowing the weak capture reaction $e^- + p \rightarrow n + \nu_e$ to convert the protons in the core into neutrons. The collapse from a density of $10^{11}\ \text{g cm}^{-3}$ to nuclear density lasts 10–100 ms and is accompanied by the deleptonization phase neutrinos – some $10^{57}\ \nu_e$ with a mean energy of 10 MeV, and the release of $2\text{–}4 \times 10^{53}$ ergs of gravitational energy. This 'flash' of neutrinos, lasting 10–100 ms is not the main neutrino emission, however.

The gravitational energy released heats up the neutron star, and the thermal radiation in the form of gamma rays materialize into electron–positron pairs. Such pairs interact via the weak neutral current to produce the so called thermal phase of neutrino–anti-neutrino pairs of the three species of neutrino. At nuclear density, the cross sections described in the previous section are sufficient to trap the neutrinos within the neutron star. Neutrinos are emitted from the so called neutrinosphere which is of order one mean free path deep from the surface of the neutron star. The energy spectra of the neutrinos are expected to have roughly Fermi–Dirac distributions. Since electron neutrinos have a greater interaction probability than muon or tau neutrinos (see the previous section) their mean free paths are shorter and these neutrinos are emitted from a shallower, and thus larger, neutrino sphere. Electron neutrinos are therefore expected to be characterized by a lower temperature than the muon and tau neutrinos. The thermal phase, in which 99% of the gravitational energy release is expected to be radiated away by the neutrinos is expected to last on the order of ten seconds. During this time the neutrino spectra could show time dependent temperature effects, and a model is needed to account for the many complications not mentioned in this simple description. Such a model, and the prediction of the thermal neutrino spectra have been given by Mayle *et al.* (1987).

4. Observation of neutrinos from the supernova SN1987A

Neutrinos from the supernova SN1987A were detected in two large water Čerenkov detectors which were designed to search for nucleon decay. In such detectors, supernova neutrinos are expected to produce low energy positrons by the inverse β process, and a few percent of electron scatters as discussed previously. These positrons and electrons produce Čerenkov light in the detector which is detected by an array of phototubes surrounding the water volume.

The Kamioka detector is at a depth of 2700 m water equivalent (MWE) and has an inner mass of 2140 t of water, viewed by an array of 948 Hammamatsu 20 in phototubes. A 10 MeV electron produces on the average 26 phototube hits in the array. This inner volume is surrounded by an outer volume of water, 1.2 m thick, which serves as a cosmic ray muon veto and an absorber of gamma rays from the rock walls of the cavity. Purification of the water reduces but does not entirely eliminate the elements U^{238} and Ra^{256} which are sources of low energy gamma rays with energies below 7 MeV. Nevertheless radioactivity in the water has been reduced sufficiently so that a signal threshold can be set at 7.5 MeV, where the trigger efficiency is 50%.

In a 13 s time interval the Kamioka detector observed 12 low energy events, one of which at 6.3 MeV was rejected because it had a large probability of being background (Hirata *et al.* 1987). This cluster of events occurred at 7:35:35 (UT) on the 23 February 1987. There is some uncertainty in the time because a few days after the observation a power failure occurred making it impossible to recalibrate the computer clock.

In the IMB-detector, which is at depth of 1600 MWE, a volume of 7000 t of water is viewed by 2048 in Hammamatsu phototubes each of which is in optical contact with a 60 cm^2 wavelength shifter plate. The detection efficiency is 50% at 35 MeV for this array and the IMB detector observed eight events with energies between 15 and 40 MeV at 7.35:41 UT on 23 February 1987 (Bionta *et al.* 1987). The background for such event clusters in both water Čerenkov detectors is extremely low.

Five events were observed in the Baksan 200 t scintillator hodoscope which is at a depth of 850 MWE (Alekseev *et al.* 1987). It took a considerable time to reconcile the time of observation with the Kamioka–IMB time and the background for such a cluster is high at 0.7 per day. Furthermore five events in a detector small in comparison with the water Čerenkov detectors is difficult to reconcile.

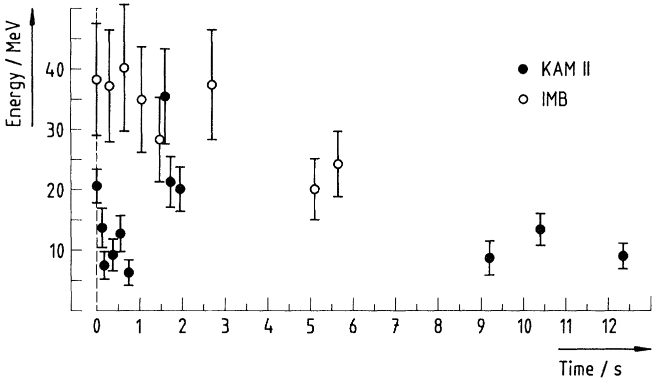

Figure 1. Energies against arrival time of the events detected in Kamioka and IMB.

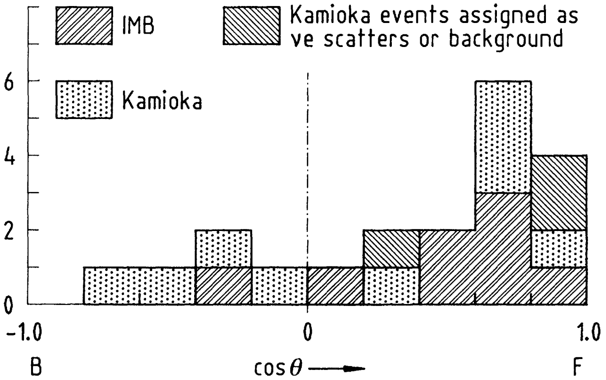

Figure 2. The angular distribution of the Kamioka and IMB events.

Even more problematic are the five events observed in the 90 t liquid scintillator detector at a depth of 4000 MWE under the Mont Blanc (Aglietta *et al.* 1987). These occurred some 4.7 h before the coincident observation of the water Čerenkov detectors, and such a cluster of five events is expected to occur only 0.7 times per year. Since the observations in scintillation detectors cannot be reconciled with the Kamioka–IMB observations, nor in terms of neutrino emission from the collapse of the known projenitor star, they must have some other explanation.

5. Conclusions regarding SN-1987A from the Kamioka and IMB observations

The event energies from the water detectors are plotted as a function of observation time in figure 1, the first event in each experiment defining the zero time. Also plotted in figure 2 is the angular distribution of the positron (or electron) with respect to the direction of the LMC.

On the assumption that the events are due to the inverse β decay process, then their observed energies and the known cross sections enable the flux of $\bar{\nu}_e$ to be determined as a function of energy. The further assumption that the fluxes of the neutrino and anti-neutrino species are the same as that for $\bar{\nu}_e$ enable the energy released in the supernova explosion to be determined. It is a remarkable fact that the

Kamioka and IMB observations are consistent with a total energy release of 3×10^{53} ergs, with an uncertainty of at least a factor of 2, and a Fermi–Dirac temperature of about 4.5 MeV.

The angular distribution is decidedly odd; it has a 4% chance of being a fluctuation from an isotropic distribution. If as many as two events are removed by ascribing them to ν–e scattering then this probability increases to 7%. It has of course to be remembered that the event sample is very small. Nevertheless at the 93–96% confidence level the angular distribution is not understood.

6. Constraints on neutrino properties from SN1987A

Since the neutrinos from the supernova travelled 170000 light years, the best neutrino lifetime limit available has been set on its laboratory lifetime, i.e. $\tau_{\nu\text{lab}} \geqslant 1.7\times10^5$ years. Furthermore at the time of the explosion the MMC satellite failed to detect any gamma rays that would arise from the decay of a putatively massive neutrino, $\nu\rightarrow\nu+\gamma$, nor was any ionization from the possible process $\nu\rightarrow\nu+e^++e^-$ observed. This enabled the best lifetime limit of $\tau\geqslant5\times10^{16}\,m_\nu$ (eV) s to be set against these processes occurring, where m_ν is the putative neutrino mass.

Light from the supernova to the Earth traverses an increased gravitational field near the galactic centre, resulting in a transit time delay of 10^7 s according to general relativity. Since the neutrinos preceded the light signal by at most 4.5 h, it may be concluded that photons and neutrinos follow the same geodesic, and have the same time delay to within 2 parts per thousand (Longo 1988; Krauss & Tremaine 1988).

The neutrino events were observed during a 13 s time interval, an interval comparable with that expected at emission. If the emission had been instantaneous at the LMC then neutrinos with mass would lead to a time dispersal on Earth given by $0.5\,(R/c)\,(m_\nu/E)^2$, where R is the distance to the LMC, c is the velocity of light, m_ν the putative neutrino mass and E its energy. (For the LMC this is $2.6\text{ s}\,(m_\nu/10\text{ MeV})^2\,(E/10\text{ MeV})^{-2}$.) Similarly a putative neutrino charge would lead to a time dispersal arising from its propagation through the galactic magnetic field. However, both the mass and charge limits derivable from the SN1987A data are inferior to laboratory based limits.

The observed neutrino luminosity agrees with the prediction of neutrino emission from a supernova to about a factor of 2. This fact can be used to set limits on the number of neutrino generations and on processes that would lead to extra cooling of the core. The limit on the number of neutrino generations is however far inferior to that set by the LEP experiments at CERN.

Extra cooling would result if the neutrino possessed a magnetic moment which would be allowed if the neutrinos were not massless. In the early stages of the collapse high energy (*ca.* 100 MeV) left-handed neutrinos would convert into right-handed neutrinos by magnetic scattering. These inert neutrinos would escape, increasing the cooling rate. From these considerations a limit of 10^{-11} Bohr magnetons has been derived. Furthermore the right-handed neutrinos could be flipped back into left-handed neutrinos by the galactic magnetic field, and then yield neutrino events with *ca.* 100 MeV energy in the detectors which recorded the SN1987A neutrino events. Since such high energy events were not seen, a limit of 10^{-12} Bohr magnetons has been set (Barbieri & Mohapatra 1988; Lattimer & Cooperstein 1988; Goldman *et al.* 1988). Although numerically superior, these limits are less reliable than those from accelerator/reactor experiments because of the many assumptions involved. Also from cooling considerations, a limit that $g^2_{\mathrm{e\bar{e}}\phi}/4\pi < 10^{-27}$, where $g^2_{\mathrm{e\bar{e}}\phi}$ is the axion–electron coupling, has been set from the SN1987A neutrino observations.

7. Future prospects

The next type II supernova is likely to happen in the local galaxy and it is unlikely it would be observed optically because of the obscuring dust clouds. Since plausible estimates of the rate of such explosions range from one in 10 years to one per century, it is advisable that detectors should have a main aim other than the detection of supernova neutrinos. In the following paragraphs, the type II supernova is taken to occur at 10 kpc, i.e. five times closer than that in the LMC.

The Canadian SNO experiment at a depth of 5000 MWE is a Čerenkov detector containing 1 kt of heavy water surrounded by light water. It has the prime aim of studying solar neutrinos and the heavy water allows the detection of electron neutrinos (ν_e) in particular. From the inverse β decay process on the deuteron, 10 events are expected in the prompt ν_e peak, and 33 events from the thermal pulse. The heavy water is also instrumented with neutron counters to detect the neutrino disintegration of the deuteron from which 760 events are expected at 100 % detection efficiency. Together with the 170 inverse β decay process initiated by $\bar{\nu}_e$ in the surrounding light water, this comparatively large sample of events should yield information on the time development of the neutrino emission. The SNO Collaboration claims that in this sample of 760 events it should be easy to detect a mass above 50 eV for the ν_μ or ν_τ because such a mass would shift the ν_μ or ν_τ event distribution by 3 s and disperse it, with the respect to that initiated by the electron neutrinos and anti-neutrinos. Furthermore, although there are only 10 inverse β decay events in the prompt peak, a mass limit of 3 eV would be placed on the electron neutrino mass, if these events were emitted in 20 ms.

Superkamiokande is a scaled-up version of the Kamioka detector, containing a total mass of 30 kt and a fiducial mass of 22 kt of light water. In such a detector 2800 $\bar{\nu}_e$ events are expected from the inverse β decay process, which should be enough to study the time development of the emission in the thermal pulse. About 100 ν_e and 55 ν_μ, ν_τ electron scattering events are also expected which can be used to establish the direction of the unseen supernova to about 2°, and to search for possible ν_μ and ν_τ masses. The direction information would be a useful guide for satellites searching for X or gamma emission from the supernova which might become visible a year or so after the explosion. (Initially the distance of the supernova from Earth, required for neutrino mass estimates, will be determined from the energetics of the explosion.)

Finally the LVD detector, 1350 tonnes of liquid scintillator, is currently about one third complete in the Gran Sasso Laboratory in Italy (depth 4000 MWE). This detector has the principal aim of searching for Galactic supernova. All three detectors should be complete by 1995, awaiting the next supernova type II explosion whenever that may occur.

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