Particle Physics Implications of the “Neutrino” Burst from the LMC Supernova

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Three high energy events in the “neutrino” burst observed by Kamiokande II are interpreted to be caused by the arrival of SUSY particles, the photino or the scalar neutrino, with a mass of \( \sim 30 \text{ eV} \).

Shortly after the discovery of the supernova explosion\(^1\) (SN1987A) in the Large Magellanic Cloud (LMC) it was reported\(^2\) by the Kamiokande II Collaboration that a neutrino burst preceded many hours before the optical brightening. A global feature of the twelve neutrino-like events reported there, their average energy of \( \sim 15 \text{ MeV} \), event rate and time span of several seconds, roughly agrees with what is expected\(^3\) in a Type II supernova explosion, in which an inner core of about one solar mass (1.4 \( M_\odot \)) gravitationally collapses and binding energy of \( \sim 3 \times 10^{53} \text{erg} \) is released.

Out of 12 “neutrino” events three stand out in the scatter plot of deposited energy and shower direction (their figure 3): events labeled 7, 8 and 9. These events are characterized by a high average energy (25 MeV) and a high directionality (\( \cos \theta \approx 0.8 \) from LMC). If the forward peaking opposite to the LMC direction implied by these events is real, this would have a great impact on what underlies fundamental processes in the supernova explosion, on which we shall focus our attention in this paper.

As is well known,\(^3\) a nearly spherical collapse of the iron core of \( \sim 1.4 M_\odot \) is expected to emit roughly equal numbers of neutrinos and antineutrinos of three species. Main processes that occur in a water Cerenkov detector are \( \bar{\nu}_e + p \rightarrow e^+ + n \) and \( \nu_e + e \rightarrow \nu_e + e^- \). The first process produces nearly isotropic distribution of \( e^+ \) that carries almost all the energy of the incident antineutrino, while the second process preserves the directionality of \( \nu_e \), with a broad spectrum of the electron energy. The cross sections of these processes are greatly different in the 10 MeV energy region: \( \sigma(\bar{\nu}_\mu) \sim 20 \sigma(\nu_e) \cdot (E_\nu/10 \text{ MeV}), \sigma(\nu_\tau) \sim \sigma(\bar{\nu}_\mu) \sim 1/6 \sigma(\nu_e) \) (\( i = \mu \) or \( \tau \)). A detector such as Kamiokande II is thus most sensitive to the antineutrino of electron type which gives an isotropic distribution. Events 7, 8 and 9, being highly directional, remain unexplained in this context.

We would like to suggest that these three events are associated with the arrival of a yet unknown particle \( U \) which leaves signals only from interaction with atomic electrons, hence is highly directional. First of all, these three events arrive at \( 1.5 \sim 2 \) seconds after the first bunch of 6 events (within 0.7 seconds). If one takes this time delay seriously, \( U \) should have a mass of \( \sim 30 \text{ eV} \) because the delay due to a finite mass \( m \) is given by
\[ \Delta t \sim 2.6 \text{sec}(m/10 \text{eV})^2(E/10 \text{MeV})^{-2} \] (1)

for the LMC source at a distance of 50 kpc away. This range of mass is particularly interesting in view of the possibility of closing the universe if the interaction strength is of weak order.\(^5\) It also contributes to nucleosynthesis as an effective number of neutrino flavor, however within the range allowed by observation.\(^6\)

One can think of many candidates for this unknown particle in plethora of exotic particles. Among them we believe that a light photino \(\tilde{\gamma}\) (neutral Majorana partner of the photon in SUSY theories) or a scalar neutrino \(\tilde{\nu}_e\) (SUSY partner of the neutrino) is most viable and is consistent with present laboratory data and cosmological bounds. The main signal of photino reaction in detectors comes from the elastic scattering off electron, \(\tilde{\gamma} + e \rightarrow \tilde{\gamma} + e\), with a cross section of

\[ \sigma = 0.99 \times 10^{-43} \text{cm}^2(E/10 \text{MeV}) \cdot (M_{\tilde{e}}/65 \text{GeV})^{-4}, \] (2)

where \(M_{\tilde{e}}\) is the mass of the scalar electron \(\tilde{e}\), left and right assumed equal. The elastic scattering off proton or oxygen is irrelevant because it essentially leaves no signal in the detector. The most recent lower bound\(^7\) of the scalar electron mass is \(\sim 65 \text{GeV}\), and the number (2), combined with 3 events seen in Kamiokande, implies \(\sim 2 \times 10^{53} \text{erg}\) of photino emission from SN 1987A. As is discussed below, this flux seems reasonable.

Based on this energy output, one can estimate a total energy of \(\sim 0.9 \times 10^{53} \text{erg}\) for the antineutrino \(\bar{\nu}_e\) if equipartition of energy is assumed among photino and three species of neutrinos, corresponding to a total energy release of \(\sim 7 \times 10^{53} \text{erg}\), marginally consistent with the collapse. Taking an average energy of 10 MeV, we may expect a yield of \(\sim 29\) events for the isotropic \(\bar{\nu}_e\) reaction, disregarding the energy threshold and efficiency of the Kamiokande detector. Kamiokande II has observed only 6 or 9 isotropic events, depending on whether one includes events 10, 11 and 12 which arrive \(\sim 10\) seconds later. A reason for this small yield might be the low efficiency of \(\sim 50\%\) at and below 8.5 MeV. More interesting is the fact that the events 7-9 deposit higher energies than the others which mostly leave energies around 10 MeV, slightly above the threshold energy. This might mean that there are many \(\bar{\nu}_e\) events hidden below the threshold.

The photino may also carry away more energy than \(\bar{\nu}_e\) due to different interaction depth in the supernova core, as in the case of different average \(\bar{\nu}_e\) and \(\nu_\mu\) energies.\(^4\) Suppression of the photino-nucleon cross section due to a large scalar quark mass may indeed help to raise the photino energy. What seems important in this consideration is the dominance of the axial vector coupling of photino-nucleus interaction written in the form of four-Fermi interaction \((\bar{\gamma}_\nu \gamma_5 \gamma_\ell)(\bar{A}_\gamma \gamma_5 \gamma_\ell A)\), reflecting the Majorana nature of the photino if the left- and right-squarks are approximately degenerate. At energies much below the nucleon mass the axial vector interaction predominantly gives rise to interaction with nuclear spin, which yields a smaller rate compared to the vector interaction. This possibility of weaker interaction of the photino in the environment of heavy nucleus deserves a more detailed study.

One should regard the photino as a prototype of particle that may explain the forward events. One only needs a neutral particle that elastically scatters off
electron with cross section of the order (2). Another good candidate of this kind is the scalar neutrino $\bar{\nu}_e$. Cross section of the process $\bar{\nu}_e + e^+ \rightarrow \bar{\nu}_e + e^+$ is given by a sum of the $Z$ exchange and the direct wino ($\tilde{W}$) diagrams. Due to the uncertainty in $\tilde{W}$ masses the rate of this process is again limited by the process $e^+ + e^- \rightarrow \bar{\nu}_e + \bar{\nu}_e + \gamma$, yielding a similar rate to (2): $\sigma(\bar{\nu}_e + e^+ \rightarrow \bar{\nu}_e + e) = 1.5 \times 10^{-43} \text{cm}^2 (E/10 \text{MeV})$ for $m_{\tilde{W}} = 65 \text{GeV}$. The cross section for $\bar{\nu}_e$ is identical. Hence the scalar neutrino is also a viable candidate for the explanation of the three events. Another possibility, a light higgsino, is excluded because of the small coupling to electrons.

Astrophysical implications of light SUSY particles are worthy of more detailed investigation. The photino, having the effective four Fermi interaction, behaves in a similar fashion to the neutrino, thus might contribute to the stellar cooling in dense, compact stars. Limit on the scalar electron mass from this kind of arguments is however not very restrictive. On the other hand, models based on supergravity tend to predict larger masses for these particles. Grand unification leads in the simplest case to a mass relation $m_\gamma = \frac{8}{3}(a/a_s)m_{\tilde{g}}$, implying a very light gluino which is presumably inconsistent with hadron spectroscopy. In more general models, however, it is possible to have a heavier gluino. A light scalar neutrino would require almost exact cancellation of the soft-breaking scalar mass term and the $D$ term. A model with zero-mass scalar neutrino in the lowest order is known.

We have considered a different class of particles for unusual events. Many of the pseudo-Nambu-Goldstone bosons postulated in particle theories have reactions of the following kind: $U + e \rightarrow \gamma + e$ and $U + p \rightarrow \gamma + p$. At energies of $m_e \ll E \ll m_p$, the electron process goes with energy like $a_{e^2}/m_eE$, whereas the proton process goes like $a_{p^2}E^2/m_p$. Thus for roughly equal couplings, $g_e \approx g_p$, the electron process dominates by a large margin of $\sim m_p^4/m_eE^3$, a nice feature to explain the three events. Astrophysical arguments based on stellar cooling however limit the allowed strength of $g_e$, implying that the electron process should have a cross section smaller than the process of $\bar{\nu}_e\phi$ by a factor of $\sim 10^4$ or more. Hence the invisible axion that belongs to this class of particles appears to be ruled out as a possible explanation.

What else can we learn from the observation of the burst? One thing that is striking in the Kamiokande data is the clustering of the arrival time of the first 6 events. This information should reflect the time span of burst at the production site, and if the neutrino has a finite mass, the subsequent time spread on the way to the earth due to different energies according to (1). Assuming the energy spread to be caused by thermal broadening ($\Delta E/E \sim 0.55$), one can derive an upper bound of $m(\nu_e) \lesssim 8 \text{eV}$ for the electron anti-neutrino mass taking an average energy of 10 MeV. This value was obtained by taking 2 seconds for the maximum time duration of the clustering burst at the site of SN 1987A.

In summary, we have suggested that three unusual events in the “neutrino” burst observed in Kamiokande II can be interpreted as a burst of a yet undetected particle in laboratories. From information of the arrival time this particle is likely to have a mass of $\sim 30 \text{eV}$, which surely has a profound implication both in particle physics and in cosmology. A natural candidate of this particle is the light photino or the scalar neutrino. If this is the case, the scalar electron or the wino should be discovered in a mass range slightly above 65 GeV.
We should like to thank for stimulating discussion all the members of the theory group at KEK who shared excitement with us at this unprecedented, dramatic event.

1) W. Kunkel and B. Madore, IAU Circular 4316 (February 24, 1987).

Note added: After completing this work, we were informed that P. Fayet pointed out, prior to the SN1987A event, a potential importance of a light photino in advanced stages of stellar evolution (Phys. Lett. 69B (1977), 489). We thank P. Fayet for reminding us of his old results.