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S. Recksiegel, A. Hoang, S. Paul

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Astrophysical Neutrinos at Low Energies

Lothar Oberauer
Physikdepartment E15
TU München
85748 Garching, Germany

1 Solar Neutrinos

The measurement of the total flux of solar neutrinos in the GALLEX, GNO [1], and SAGE [2] experiments was a milestone in understanding the basics of the pp-fusion cycle in the center of the sun. Furthermore it was the first evidence for physics beyond the standard model as astrophysical explanations for the observed deficit on the solar ν_e flux were ruled out. Now, after SNO [3] and the reactor experiment KamLAND [4] it is known, that neutrinos oscillate. For the first time neutrino flavor transition has been measured by SNO with an accuracy of about 7 sigma. The survival probability of the high energy solar ^{8}B-neutrinos has been determined to be $(34 \pm 4)\%$. In GALLEX and GNO the survival probability for all solar neutrinos was measured to be $(55 \pm 5)\%$. This difference is a clear hint for matter effects inside the sun as it was predicted by the MSW-mechanism [5]. Low energy solar neutrinos are driven by vacuum oscillations, whereas neutrinos with $E_\nu >$MeV are dominated by matter enhanced flavor transitions. The corresponding oscillations parameter are: $\delta m^2_{21} = m^2_2 - m^2_1 = (+7.9 \pm 0.7)\, eV^2$ and $tan^2\Theta = (0.45 \pm 0.05)$. Solar neutrino spectroscopy revealed a positive sign of δm^2_{21}, because otherwise the MSW effect would not work. Therefore we know that $m_2 > m_1$. It is amazing how experiments which were primary designed to solve astrophysical problems shed light on intrinsic neutrino parameter which could not be approached otherwise.

Future of solar neutrino spectroscopy

Up to now solar neutrino spectroscopy for the high energetic ^{8}B-branch has been performed. The main goal for next future experiments like BOREXINO [6] and KamLAND [7] is the measurement of the monoenergetic ^{7}Be-neutrino flux and neutrinos from other sources in the low energy range. An accuracy of 10% in the measurement of the ^{7}Be-ν rate would lead to a 1% precision for the pp-neutrino flux stemming from the primary $p+p \rightarrow^2 D+\nu_e$ fusion reaction, by taking into account the solar luminosity. As the theoretical uncertainty of the neutrino flux from this branch is also in the

1% range, precise tests of solar models would become possible. In addition the first determination of the CNO-branch would be of major astrophysical interest. Recent results from the LUNA experiment on the $^{14}N(p,\gamma)^{15}O$ fusion reaction [8] lowered the CNO-neutrino flux prediction by a factor ∼2. This would imply an increase for the estimation of the age of globular clusters by 0.7 to 1 Gy.

Measuring the ^{7}Be-flux can be used also to search for new neutrino interactions [9]. In the standard picture including neutrino oscillations a ^{7}Be-neutrino event rate due to elastic scattering on electrons ($\nu + e^- \rightarrow \nu + e^-$) of about 30 counts per day is expected in BOREXINO with a fiducial volume of $110\,m^3$ of liquid scintillator. The recoil electrons from the reaction above will give rise to a sharp Compton-like edge in the energy distribution at 660 keV. Flavor changing neutral current interaction should alter this rate significantly towards lower values.

Besides low energy solar neutrinos BOREXINO is aiming for measuring terrestrial neutrinos as well as neutrinos from European reactors. Here the inverse beta reaction $\overline{\nu}_e + p \rightarrow e^+ + n$ would be used, taking advantage from the delayed coincidence method provided by the prompt positron signal and delayed neutron capture ($n + p \rightarrow^2 D + \gamma$, $E_\gamma = 2.2$ MeV). This clear signature is extremely helpful to reject background events. Between 30 and about 60 counts per year are expected from both sources, depending mainly on geophysical models. The maximal energy of terrestrial neutrinos, stemming from beta decays in the U- and Th-chains, is about 3 MeV, whereas the reactor neutrino spectrum ends at about 8 MeV. Hence, the contributions from both sources can be separated simply by their energy distributions. The measurement of terrestrial neutrinos will reveal information about the content of U and Th in the Earth, while the reactor neutrinos can be used to probe the KamLAND result.

In addition BOREXINO would register about 100 events in case a supernova explosion of type II will happen in the center of our galaxy. With an artificial neutrino source a search for a neutrino magnetic moment will be performed. In 2006 the detector was filled with water and first Cherenkov-events due to high energy accelerator neutrinos from CERN have been observed. Several purification methods have been tested in the "Counting Test Facility" (CTF). With the CTF new limits on the $\overline{\nu}_e$-flux from the sun have been established [10]. Only one background event have been found in a measuring period of about 2 years. It is planned to fill BOREXINO with liquid scintillator in the beginning of 2007 and to start data taking in the same year.

2 Atmospheric Neutrinos

The first evidence for neutrino oscillations came from the Super-Kamiokande (SK) Collaboration in 1998. Atmospheric neutrinos are decay products of pions, kaons (and the generated muons) which are produced in collisions of primary cosmic ray particles with nuclei of the upper atmosphere. Therefore the ratio R of muon neutrinos to electron neutrinos is expected to be $R = (\nu_\mu + \overline{\nu}_\mu)/(\nu_e + \overline{\nu}_e)$ 2. The atmospheric neutrino problem had been under investigation since the 1980's by various experiments, e.g. by the water Cherenkov detectors Kamioka and IMB, who reported $R_{measured}/R_{theory}$ 0.6 and by the iron calorimeters NUSEX and FREJUS who observed $R_{measured}/R_{theory}$ 1. The situation became clearer after 1996 when the 50kton water cerenkov detector Super-Kamiokande [11] started operating and eventually collected enough statistics to perform a zenith angle analysis of the observed electron neutrino and muon neutrino events (In the SK-I data set over 11000 events are used in the oscillation analysis). The zenith angle is defined as the angle between the zenith direction and the direction of the observed neutrino. It turned out that while the number of downward muon events is as expected, the number of upward muon events is significantly reduced. The number of electron events both upward and downward behaves as expected. Because the zenith angle of an event corresponds to the distance L of the neutrino traveled between its creation and detection, the oscillation probability of a neutrino which depends on L, will also depend on the zenith angle. The Super-Kamiokande zenith angle distributions for muon events are in excellent agreement with the neutrino oscillation hypothesis. All observations are compatible with the assumption of $\nu_\mu \rightarrow \nu_\tau$ oscillations. The possibility of $\nu_\mu \rightarrow \nu_e$ oscillations was ruled out by the reactor experiment Chooz [12], and oscillations into sterile neutrinos are disfavoured by the observations of neutral current events in SuperKamiokande as expected in the $\nu_\mu \rightarrow \nu_\tau$ szenario. In addition oscillations into sterile neutrinos would lead to matter effects which would generate different spectral distributions compared to those which have been observed. The oscillation hypothesis is confirmed by a recent L/E analysis of the SuperKamiokande data as well as by the accelerator experiments K2K [13] and Minos [14].

3 Supernova Neutrinos

Solar neutrino physics opened the window to astrophysical observations where neutrinos are used as probes. Indeed the basic idea of thermal nuclear fusion as source for stellar energies was proven by detecting solar neutrinos and in future important details about the pp- and the CNO-cycle may be revealed by new experiments in this field. The first neutrino signal outside of our solar system, even outside from our galaxy was observed in February 1987 when a blue giant star in the Large Magellanic Cloud exploded as a supernova type II at a distance of about 50kpc (ca. 150 light years). In total 19 neutrino events were recorded in two large water Cherenkov detectors (Kamioka, Japan, and IMB, USA) within a time window of about 20 seconds [15]. This observation allowed for the first time to measure the energy release of a gravitational collapse, as about 99% of the total gravitational energy is emitted in neutrinos. In spite of the small number of events the basic idea about the mechanism of a supernova of this nature (i.e. SN-type II) was confirmed. With running detectors, like SuperKamiokande, a supernova type II explosion in our galaxy would be accompanied by a neutrino signal of about 15,000 events. Hence, the development of a gravitational collapse could be followed in great detail. In order to measure flavor dependent fluxes different nuclei as target for neutrino are proposed. In LENA (Low Energy Neutrino Astronomy) a large liquid scintillator detector (total mass around 50kt) is proposed to serve as detector for supernova neutrinos [16]. Here neutrino interactions on protons as well as on ^{12}C could be used which would allow to disentangle the flavor composition of a supernova burst in time and energy. Besides large liquid scintillator detectors water Cherenkov tanks with huge target masses close to 1 Mt (e.g. Hyperkamiokande in Japan, MEMPHIS in Europe, UNO in the USA) as well as 100 kt liquid Argon devices are proposed for future Supernova neutrino detection. The Argon detector GLACIER would open the possibility to detect the electron neutrino content with great statistics. In Europe physicists are working together in the LAGUNA [17] project (Large Apparatus for Grand Unification and Neutrino Astronomy) to explore the physical potential and the technical feasibility of all three approaches.

From all past supernova type II explosions in our universe one expects a low background of relic supernova neutrinos. Up to now only upper limits on the flux of those SNR-neutrinos (electron anti-neutrinos; detection via $\overline{\nu}_e p \rightarrow e^+ n$) are reported. In LENA or in a modified SuperKamiokande detector (Gd-loaded water) the detection of SNR-ν could succeed. After 10 years of measurement with LENA the spectral shape of the SNR-$\overline{\nu}_e$ flux could be determined in the energy window between 10 MeV and 30 MeV and details about gravitational collapses as well as the star formation in the early universe would be explored [16]. The lower energy limit is due to the world wide neutrino emission in nuclear power plants, whereas the upper bound is given by the background of atmospheric neutrinos.

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