Status of Astrophysical Neutrino Experiments and Prospects

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Abstract

The status of experiments searching for neutrinos of astrophysical sources is reported. This includes solar neutrino experiments, searches for atmospheric neutrinos, Supernova neutrinos, and neutrinos in high energy cosmic rays. Recent results in some of this fields may hint to physics beyond the standard model. Future experiments can find the clue for the solution of this puzzle.

1 Solar Neutrino Experiments

The solar neutrino problem comes from the discrepancy between the ν_e expectations of the solar neutrino flux, as calculated by the Solar Standard Model [1], and the experimental results. In Table 1 the experimental results are compared with the expected values of the standard model.

Table 1:

Experiment	Measured flux S.M. expectation	Threshold (MeV)
Homestake	0.27±0.06	0.814
Kamiokande	0.44±0.06	7.5
Superkamiokande	0.358±0.009±0.014	6.5
Gallium (Gallex, Sage)	0.6 ± 0.06	0.235

All solar neutrino experiments are located in deep underground laboratories in order to shield the detector against cosmic rays. Pioneer work has been performed 1970 by R. Davis and coworkers by detetcing solar neutrinos in a radiochemical experiment by means of the reaction $^{37}Cl + \nu_e \rightarrow ^{37}Ar + e$ at a threshold of 0.814 MeV [2]. Due to this threshold high energetic ^8B neutrinos dominate the signal. Since the flux of this branch is sensitive to small changes of the solar model, astrophysical solutions were discussed at this time as most prominent possibilities.

The radiochemical gallium detectors, GALLEX (Gran Sasso, Italy) [3] and SAGE (Baksan, Russia) [4], have been measuring the integral solar neutrino flux exploiting the capture reaction $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$. As the energy threshold is only 233 keV, this reaction allows to detect the pp-neutrinos from the initial solar fusion step which contribute about 90 % to the total solar neutrino flux.

In a typical run the target, consisting of 30 tons of gallium in the form of 101 t $\mathrm{GaCl_3}$ solution for GALLEX and 55 t of metallic gallium for SAGE, is exposed to the solar neutrino flux for 3-4 weeks. Both experiments use the signature provided by the Auger electrons and X-rays associated with the decay $^{71}\mathrm{Ge} + e^- \rightarrow {}^{71}\mathrm{Ga} + \nu_e$ for identification of ^{71}Ge during a several months counting time.

The combined result of all 65 GALLEX solar runs is $76.4 \pm 6.3\ ^{+4.5}_{-4.9}$ SNU[1]. The present result from SAGE, $74\ ^{+11}_{-10}\ ^{+5}_{-7}$ SNU [4], is in agreement with GALLEX. The overall results from both experiments are only about 60% of the predictions from solar model calculations.

Up to now only the Kamiokande experiment [5] in Japan records solar neutrinos in real time with energy information. In a large water Cherenkov detector elastic neutrino electron scattering is used as detection mechanism. Background rejection is realized mainly by measuring the direction of the scattered electron. It is peak in forward position. Since April 1996 an even larger water Cherenkov detector, Superkamiokande with 22.5kt fiducial target mass, is running. Superkamiokande confirms the data measured before with improved statistics (see Table 1) [6]. The systematic error has been reduced by calibration with a linear electron accelerator.

Information from helioseismology confirm the solar standard model. In addition, experimental results from the LUNA experiment (see M. Junker, this proc.) low energy measurements in the $^3He +^4 He$-channel seem to exclude explanations based on discrepancies in nuclear cross sections. At last, the overall performance of both gallium experiments has been tested by terrestial neutrino sources, and no discrepancy from the expected values has been found [3].

Data analysis of the existing experiments leads to the assumption of se-

[1] 1 SNU = 1 neutrino interaction per second in 10^{36} atoms.

vere supression of the solar ^7Be-branch (e. g. [7]), which probably cannot be explained by modifications of the standard astrophysical model of the sun.

If neutrinos have non-zero masses and if they mix in analogy to the quark sector, neutrino oscillations arise. It can be shown (e. g. [3]) that certain parameter on neutrino masses and mixing angles provide an excellent solution to all observed results. Future experiments may give the clue to the final solution of the solar neutrino puzzle (Table 2).

Table 2:

Experiment	Reaction	Experimental method	Threshold (MeV)	Expected start-up	Statistics [full SSM]
SuperK	$\nu_x e^- \rightarrow \nu_x e^-$	Č events	5.	already running	65/d
GNO	$\nu_e^{71}Ga \rightarrow e +^{71} Ge$	Ge	0.235	1998	1/d
Iodine	$\nu_e^{127}I \rightarrow e +^{127} Xe$	I	0.789	-	-
SNO	$\nu_e d \rightarrow ppe^-$ $\nu_x d \rightarrow \nu pn$	Č events	5.	1997 1999?	20/d 7/d
Borexino	$\nu_x e^- \rightarrow \nu_x e^-$	liquid scint.	0.25	2000	55/d

Superkamiokande (SK) is as reported above already running and has confirmed the discrepancy in the solar neutrino flux as obtained in the Kamiokande experiment. Due to the enhanced statistics SK gets information of the solar ^8B-spectrum by unfolding the experimental data with the theoretical spectrum of neutrino electron scattering. As the phase of neutrino oscillations is energy dependent detected detoriations in the spectral shape could prove the oscillation hypothesis. How pronounced this effect shows up depends on the actual oscillation parameter. For certain parameter day/night effects must show up which are detectable in high statistic experiments as SK.

GNO (Gallium Neutrino Observatory) is a prolongation of Gallex with increased volume and an upgrading of the analysis devices. In this way the Gallex collaboration planes to depress both the statistical and the systematical uncertainties.

SNO is sensitive to ^8B-neutrinos only. Since it will measure both neutral and charged current interaction direct information on neutrino flavour oscillations can be obtained. Here the measured neutral current flux can be considered as a monitor of the total solar neutrino flux independent of flavour oscillations. In addition the neutrino energy spectrum is measured directly. No unfolding is necessary and the same argument for proving neutrino oscillations as for SK holds also for SNO.

The aim of Borexino is to measure in real time the solar neutrino flux with low energy threshold at high statistics, and energy resolving via pure leptonic neutrino electron scattering $\nu + e \rightarrow \nu + e$. Here liquid scintillator (300t fiducial mass) will be target and detector material. The monoenergetic ^7Be-neutrinos give rise to a compton like recoil spectrum in Borexino with a edge at 660 keV. Assuming validity of the standard model a counting rate for ^7Be-neutrinos, which would consist in this case purely as ν_e, of roughly 55/day in Borexino is expected.

In scenarios of total neutrino flavour conversion (i.e. for neutrino mass differences $\Delta m^2 \approx 10^{-6} \rightarrow 10^{-5}\ eV^2$) a reduced flux of approximately 12/day would be measured due to the lower cross section of $\nu_{\mu,\tau}$ scattering, which occurs only via neutral current interaction.

In case of vacuum oscillations (i.e. for neutrino mass differences $\Delta m^2 \approx 10^{-10}\ eV^2$) Borexino would see a distinct time dependent periodical neutrino signal due to the seasonal eccentricity of the earths orbit around the sun.

For neutrino mass differences in the range of $\Delta m^2 \approx 10^{-7}\ eV^2$ and for large mixing Borexino should see a 'day/night' effect due to electron neutrino recovery during the path through the earth.

Borexino also can serve for additional projects in neutrino physics. Via the inverse beta-decay $\bar{\nu}_e + p \rightarrow e^+ + n$ Borexino can look for signals from geophysical neutrinos as well as for neutrinos emitted by european nuclear power plants. The latter would serve as a long baseline neutrino oscillation experiment probing the so-called large mixing angle solution for the solar neutrino problem.

A new radiochemical experiment is under way at Homestake with ^{127}I as target material. At the treshold of 789 keV a quite large fraction of ^7Be-neutrinos contribute to the signal. Two new experiments, still in R&D phase, are Supermunu and Hellaz. Both are based on gas TPC's. Hellaz planes to use a 2000 m^3 TPC filled with He-CH_4 at 5-10 bars, cooled at 77 K. The energy threshold should be $\sim$ 100 KeV. Supermunu is similar to Hellaz, but it should employ CF_4 as target.

We can conclude that there is a good chance that the solar neutrino problem should be solved in the first years of the 21st century. Experiments on ^{7}Be neutrinos, on neutral current events and on time variations could be decisive in this field.

2 Atmospheric neutrinos

Atmospheric neutrinos are produced in the cascade originated in the atmosphere by a primary cosmic ray. Pion and muon decays are the main sources, disintegration of kaons plays a role only at high energies. From these decay channels one expects at low energies about twice muon neutrinos with respect to electron neutrinos. This ratio is not very sensitive to detailed calculations.

The water Cherenkov experiments, IMB in the United States and Kamiokande in Japan, discovered that this ratio between events with a muon and those with an electron was lower than expected. A possible interpretation of this anomaly is the oscillation of the neutrino species in the path length between the production point and the detector (in the range 10 -13000 km). Recently this discrepancy was confirmed by the iron calrorimetric experiment Soudan in Canada. However, the anomaly was not confirmed by the proton decay iron fine-grained experiments at Frejus and by NUSEX. The latter experiment suffered under small statistics.

By separating into a low energy region with $E < 1\ GeV$ and into a high energy region different event topologies in a detector can be defined. The low energy region generally corresponds to events fully contained inside the fiducial volume. High energy events can be defined by the topology of the interaction vertex inside and not fully contained tracks, or with the interaction vertex in the rock outside the detector. In the latter case background considerations imply, that only upgoing muons can be interpreted as neutrino signals.

The absolute neutrino fluxes are predicted with uncertainties of 20%. However the ratio of $\nu_\mu + \overline{\nu_\mu}$ to $\nu_e + \overline{\nu_e}$ fluxes is known to better than 5% and therefore experiments measure the double ratio $R \equiv (\mu/e)_{DATA}/(\mu/e)_{MC}$, where μ/e denote the ratio of μ-like to e-like neutrino interactions.

Due to the huge target mass Superkamiokande (SK) now has the best statistics. Particle identification in SK is based on the pattern of Cherenkov rings. Electrons create diffuse patterns and are separated from sharper Cherenkov rings caused by muons. The misidentification probability for single-ring events is estimated by the collaboration to be $0.8 \pm 0.1\%$. At the end of 1997 at about 20.1 kton-years of SK has been sampled. From these data one obtains: $R = 0.63 \pm 0.03(stat) \pm 0.05(sys)$ [8].

We can conclude, that the deficit of muon neutrinos reported from earlier experiments has been confirmed during the first year of data collection in Super-Kamiokande. In addition the angular distribution of reconstructed tracks has been studied [8] and an asymmetry has been observed for both energy regions. Those results may suggest the neutrino oscillation interpretation.

However, the collaboration concludes, that more data are needed to exclude any possibility of detector related biases.

The atmospheric neutrino discrepancy can be explained either by muon-electron neutrino oscillation, or by the muon- tau neutrino mode. Very recently results from a long baseline reactor experiment at Chooz [9] (France) has been published, which excludes the possibility of relevant muon- electron mixing, as it was necessary for onterpreting the Kamiokande result in terms of oscillations, completely.

The possibilty of muon- tau oscillation can be verified (or falsified) by long baseline accelerator experiments in which muon neutrino beams are created. In Japan a muon neutrino beam from KEK will be directed to Superkamiokande. Data taking there is expected to start in 1999. Projects of long baseline experiments are considered also at CERN to Gran Sasso, and from Fermilab to the underground laboratory at Soudan.

3 Collapsing Stars and Neutrino Observations

At the initial stage of a collapsing star with $M \geq 1.5\ M_{sun}$ the ν_e- flux of the neutronization process $e^- + p \rightarrow n + \nu_e$ dominates. However, during the very early cooling phase neutrinos of any flavour will be created by thermal processes ($e^+ + e^- \rightarrow \nu + \bar{\nu}$). One can estimate that in total $\simeq 10^{53}$ erg in neutrinos will be emitted. Calculations yield comparable, but not equal, fluxes of ν_e, ν_μ and ν_τ.

Approximately $5 \cdot 10^{52}$ erg can be expected in form of $\bar{\nu}_e$, with typical average energies of about 10 MeV. Water Cherenkov detectors such as Kamiokande or IMB are mainly sensitive to $\bar{\nu}_e$, because this neutrinos can be detected via charged current weak interaction (namely $\bar{\nu}_e + p \rightarrow n + e^+$), which has a much higher cross section as neutrino electron scattering. IN february 1987 a neutrino pulse was detected prior to the optical outburst of SN1987a. Kamiokande measured 12 pulses within $\Delta t \simeq 13\ sec$ [10] and IMB detected 8 neutrinos with $\Delta t \simeq 6\ sec$ [11].

This coincidental (within 1 minute precision) neutrino observation in two independent detectors confirms the general princips of supernova mechanism. Calculations yielded 6 ± 4 counts in 2000 t of water for a collapse like SN 1987a (distance $\simeq 50$ kpc), in fair agreement with the number of events seen in both Cherenkov detectors.

Since 1987 several new experiments looking for future supernova neutrinos are under way. The 50kton water Cherenkov detector Superkamiokande in Japan is already under operation, the segmented liquid scintillation detector

LVD (Large Volume Detector) at Gran Sasso is going to be build up.

The Galactic SN rate is estimated to be about 20 ± 8 per millennium [12]. There are only 6 historical supernovae on record which would imply, that roughly 2/3 of all Galactic supernovae have been hidden. Supernovae in the Local Group have been observed in M31 (S And: SN 1885A) and in the Large Magellanic Cloud (SN 1987A). The prediction for the Local Group is slightly above 2 (excluding the Galaxy), which appears consistent. The small observational baseline, however, excludes any firm conclusion from such a comparison.

Therefore supernovae which can be observed in the light of neutrinos are very rarely. In spite of this the development of new detectors looking for supernova neutrinos is considered seriously, because its observation not only would yield important information about processes in stellar collapses, but also could reveil unknown neutrino properties. Superkamiokande would receive about 4000 events from the inverse beta reaction if a supernova at 10 kpc happens[2]. This would be enough statistics to determine a significant neutrino lightcurve. From the prompt ν_e burst one expects about 15 events in a few ms. Its detection would set interesting constraints on neutrino oscillation parameter. Due to neutrino dispersion a direct mass limit of about 1 eV could be set. In addition one would expect to see about 40 events for each $\nu_\mu + \bar{\nu_\mu}$ and $\nu_\tau + \bar{\nu_\tau}$ from elastic neutrino electron scattering. Since the scattered electrons are peaked in forward direction one can separate them from non-directional $\bar{\nu_e}$ reactions. Hence, massive ν_μ or ν_τ would imply delayed forward signals, leading to sensitivities of about 100 eV [13], orders of magnitude more sensitive than existing laboratory limits.

4 High energy neutrino telescopes

Experimental search for high energy cosmic neutrinos is motivated by several items. Without claiming completeness a few are listed here:

- Search for neutrino point sources, like the galactic center and active galactic nuclei (AGN).
- Search for an isotropic high energy neutrino background due to AGN.
- Search for neutrino signals coincident with gamma ray bursts.
- Search for very high energy neutrinos from cosmological origin like strings.

[2]Recall that the solar system is at a distance of about 8 kpc from the galactic center.

- Neutrino emission in the 10 GeV region due to solar WIMP annihilation. Here WIMP stands for Weak Interacting Massive Particles: they are candidates for cold dark matter.

This physical program sets certain requirements on the experimental setup. The detector should be located deep underground in order to shield against background, the target mass must be large (about $1km^3$), and the possibility for measuring the direction of the interacting neutrino must be given.

Two projects are described here, Amanda and Antares. Both rely on Cherenkov detection. Amanda is located at the south pole. Strings with photomultipliers were brought inside the ice. At the end of 1997 two modules have been realized: Amanda A at a depth from 810m to 1000m and Amanda B which is ranges between 1520m and 1950m. Amanda B consists of 4 strings with 20 tubes each which was realized in 1996. In addition there are now installed 6 strings with 36 tubes each.

Crucial for the proper operation are absorption and scatter lenghts of the Cherenkov photons in the ice. In the wavelength band between 340nm and 460nm absorption lengths of about 100m has been measured, whereas the effective scatter length is shorter and was determined to be at 24m for Amanda B. Muon track reconstruction is realized by the timing information of the individual tubes. With this method upgoing muons which result from neutrino interaction can be separated by background muons produced in the atmosphere by cosmic rays.

Antares is aiming towards a deep-sea high energy neutrino telescope. It is planned to set up a "demonstrator", consisting of three strings 100m apart which is scheduled for 1999. Site for the demostrator should be at 2410m depth in the mediterranean sea, close to the city of Toulon, France. Aim is to realize finally a detector with $1km^3$ target volume. The detection concept is very similar to Amanda. Since it is located on the northern hemisphere Antares is sensitive to neutrinos emitted in the southern sky, whereas Amanda is a neutrino telescope for the opposite direction.

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