Birth of Neutrino Astrophysics

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Tsukuba, Japan

For more details, see my review article;

Observational Neutrino Astrophysics Physics Report, 220
(1992) Nos.5&6, pp.229-482.

The content of this talk will appear shortly in Reviews of Modern Physics.
Conception

There was a very important prenatal event. That was the radiochemical work of R. Davis using the reaction $\nu_e + \text{Cl}^{37} \rightarrow e^- + \text{Ar}^{37}$. The conclusion was that the solar neutrinos are only about 1/3 of what you expect from the Standard Solar Model of J. Bahcall.

This could be considered as the conception of the Neutrino Astrophysics and was the impetus for us to begin seriously working on the solar neutrinos.
The experiments

1) KamiokaNDE; Imaging Water Cerenkov, 20% PMT coverage, 3,000tons, ca.3MUS$. Feasibility experiment.

2) Super-KamiokaNDE; the same as above, 40% PMT coverage, 50,000tons, ca.100MUS$.
   Full scale solar neutrino observatory.
(Both 1,000m underground in Kamioka Mine)
(NDE for Nucleon Decay Experiment/
   Neutrino Detection Experiment)
Fish-eye View of KamiokaNDE’s Interior
50cmφ PMT

which made the two
detectors precision devices
Fish-Eye View of Super-KamiokaNDE’s Interior
Detector Performances

1) Through $\mu$ in S-KamiokaNDE
   Shots at 50 nanosecond intervals

2) Discrimination between electron and muon
The $\mu$ has just entered the detector.
The $\mu$ has reached to the bottom of the detector, while the Cerenkov light in water is still on its way.
The data of the outer anti-counter are shown, while the inner data are moved to the top right.
The top e-event has a blurred radial distribution of Cerenkov photons, while the bottom µ-event has a crisp ring image. The discrimination between e and µ is accomplished with an error probability of less than 1%.

The µ–event has the decay electron later.
4 Accomplishments of KamiokaNDE

1) The astrophysical, i.e., with D, T and E, observation of solar neutrinos by means of $\nu_e-e$ scattering.

2) The observation of the neutrino burst from Supernova 1987A by means of anti-$\nu_e$ on $p$ producing $e^+$ plus neutron.

3) The discovery at more than $4\sigma$ of the anomaly in the atmospheric $\nu_\mu/\nu_e$ ratio. Neutrino oscillation. Non-zero masses of $\nu$’s.

4) Killed SU(5) by proton decay lifetime and SUSY SU(5) also by non-zero masses of $\nu$’s.
Solar Neutrinos

Standard Solar Model (SSM)

Solar Neutrino Experiments

<table>
<thead>
<tr>
<th>Target</th>
<th>Data / SSM (BP98)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>$^{37}$Cl</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>$\nu$ (water)</td>
</tr>
<tr>
<td>SAGE</td>
<td>$^{71}$Ga</td>
</tr>
<tr>
<td>GALLEX</td>
<td>$^{71}$Ga</td>
</tr>
<tr>
<td>SK</td>
<td>$\nu$ (water)</td>
</tr>
</tbody>
</table>
The directional observation of the solar neutrinos. The timing accuracy is better than 1 microsecond.

Solar neutrinos (Kamiokande-III)
Dec. 28, 1990 – Feb. 6, 1995 (1036 days)

Number of events / 1036-day

\[ \cos \theta_{\text{sun}} \]

\~390 solar \( \nu \) events

The observed energy spectra of the recoil electrons. It is consistent with the spectra expected from the $B_{8}$ neutrinos. The intensity, however, is only about a half of that expected from the theory. The solar neutrino anomaly discovered by R.Davis's radiochemical experiment was confirmed.

Energy spectrum of solar neutrino events
Kamiokande II and III (2079 days)

Based on ~600 solar $\nu$ events

The detector performance at the beginning of 1987.
The observed signal of the supernova neutrino burst. It was immediately confirmed by IMB experiment in USA. The combined results, $T_\nu$ of 4.5MeV and the total $\nu$ energy output of $3 \times 10^{53}$ erg gave strong support to the theoretical model.
\( \nu_\mu / \nu_e \) has to be 2 or larger
KamiokaNDE data showed the ratio smaller than 2 by more than 4 $\sigma$ and $\nu_\mu/\nu_\tau$ oscillation was given as the likely cause.

$\mu/e$ ratio

M. Shiozawa, for the SK collab., talk at Neutrino 2002, Munich, May 2002
Allowed parameter region by the Kamiokande atmospheric neutrino measurement

Observational Neutrino Astrophysics;
M. Koshiba,
Super-KamiokaNDE
Accomplished
Three things so far.

1) Established the solar neutrino observation with much better statistics.
2) Firmly established, at more than $9\sigma$, the non-zero masses of $\nu$’s and their oscillations.
3) Non-observation of nucleon decays is giving more stringent restriction on the possible type of future grand unified theory.
Solar neutrinos (Super-Kamiokande)
May 31, 1996 – July 13, 2001 (1496 days)

$E_\nu = 5.0 - 20$ MeV

22385 solar $\nu$ events
(14.5 events/day)

$^8\text{B}$ flux: $2.35 \pm 0.02 \pm 0.08 \times 10^6 / \text{cm}^2/\text{sec}$

\[
\text{Data} = \frac{0.465 \pm 0.005^{+0.016}_{-0.015}}{\text{SSM(BP2000)}}
\]

(BP2000: $5.05 \times 10^6 / \text{cm}^2/\text{sec}$)
The Sun as seen by ν’s and its orbit in the Galactic coordinate.

You have to excuse the poor angular resolution because the neutrino astrophysics is still in its infantile stage.
The energy spectra of the recoil electron is indeed consistent to that due to the expected $^8\text{B}$ decay neutrinos.

**Energy spectrum of solar neutrino events**

Super-Kamiokande 1496 days

SK-I 1496day 5.0-20MeV 22.5kt (Preliminary)

- $(6.3\times10^{-3}, 6.9\times10^{-6}\text{eV}^2)$ SMA
- $(0.66, 7.9\times10^{-11}\text{eV}^2)$ Just-so
- $(0.76, 2.2\times10^{-5}\text{eV}^2)$ LMA

Bad fit to SMA and Just-so solutions.
If the observed anomaly of $\nu_{\mu}/\nu_{\text{e}}$ is indeed due to the $\nu_{\text{e}}$-oscillation, the zenith angle distribution will show it over the distances of 10km to 13000km.

Atmospheric neutrino results from SK-1
M. Shiozawa, for the SK collab., talk at Neutrino 2002, Munich, May 2002

1489 day FC+PC data + 1678 day upward going muon data

1-ring e-like 1-ring $\mu$-like multi-ring $\mu$-like up-going $\mu$

Sub-GeV e-like Sub-GeV $\mu$-like Sub-GeV Multi-ring $\mu$-like Upward Stopping $\mu$

< 1.3GeV

Up-going

Multi-GeV e-like Multi-GeV $\mu$-like + PC Multi-GeV Multi-ring $\mu$-like Upward Through Going $\mu$

> 1.3GeV Osc.

Through going

No osc.

0.1

0.2

0.3

0.4

0.5

0.6

0.7

0.8

0.9

1.0

$\cos\theta$

Up-going

Down-going

Flux [10$^{-10}$ cm$^{-2}$ sr$^{-1}$ sr$^{-1}$]
The Neutrino Oscillation

Consider 2 neutrino case for simplicity. The weak eigenstate $\psi_\mu$ is a superposition of $\psi_{m1}$ and $\psi_{m2}$ with a parameter $\theta$, the angle between $\psi_\mu$ and $\psi_{m1}$. Since $E \sim p + (m^2/p)$, the two states, $\psi_{m1}$ and $\psi_{m2}$, make beat with the frequency proportional to $\Delta m^2 = m_1^2 - m_2^2$, thereby changing the relative intensity. This causes a partial transformation of $\psi_\mu$ to $\psi_\tau$. 
The oscillation parameters of the solar neutrinos and of the atmospheric neutrinos.

Allowed region combined with SNO data

Super-Kamiokande 1496 days

Zenith Spectrum $\nu_e \rightarrow \nu_{\mu/\tau}$ (95% C.L.)

Allowed region combined with all solar neutrino data

- Rates: Homestake (Cl), GALLEX (Ga), SAGE (Cl), SK (H2O), SNO CC+NC (D2O)
- Zenith spectra from SK: energy spectra of electrons at 7 zenith angle bins (day + 6 nights)

LMA is the most likely solution.

Implications of Non-zero Neutrino Masses

1) The right handed neutrinos have to exist. Standard Theory has to be modified and SU(5) is discarded as possible GUT.

2) Very low energy neutrinos will make the total reflection at very low temperature. Very nice for the future possibility of observing the 1.9K Cosmic Neutrino Background.
For Fun

From the $\Delta m^2$’s obtained, we can get a possible mass spectra of elementary particles using the See-Saw mechanism. And if we consider a small electromagnetic mass shift occurred in one of the phase changes in the very early Universe, we get the nice regularity as seen in the last slide. Anyone of you challenge to explain this regularity?
Cosmic Dark Matter?

R-neutrinos

quarks

charged leptons

L-neutrinos

70 meV
Thank you for your patience.

M. Koshiba