Solar Neutrinos and their Detection Techniques

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Topics to be covered

- Solar Neutrinos
- Solar Neutrino Detection Techniques
- Solar Neutrino Puzzle and Comparison of Different Detection Techniques
- Theoretical Importance of the Experimental Results
Solar Neutrinos

- In the deep interior core of the Sun large amount of energy is produced due to the following nuclear fusion reaction

\[ 4p \rightarrow \alpha + 2e^+ + 2\nu_e + 28\text{MeV} \] (1)

- These neutrinos carry away about 2 – 3% of the total energy emitted by the Sun
- The flux of the neutrinos from the Sun is about \(6 \times 10^{10}\, cm^{-2}s^{-1}\) on the Earth
- Detecting these solar neutrinos is of great importance for the understanding of the Universe
Solar Neutrino Detection Techniques

- Radio-Chemical Detection Method
- Water Cherenkov Detection Method
- Heavy Water Detection Method

**Table: Different Neutrino Experiments**

<table>
<thead>
<tr>
<th>Experiment Method</th>
<th>Name of the Detectors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radio-chemical</td>
<td>GALLEX, SAGE, Chlorine detector</td>
</tr>
<tr>
<td>Water Cherenkov Detector</td>
<td>Kamiokande, Super-Kamiokande</td>
</tr>
<tr>
<td>Heavy Water Detection</td>
<td>SNO (Sudbury Neutrino Observatory)</td>
</tr>
</tbody>
</table>
Radio-Chemical Detection Method

- In this method, the chemical used in the detector after interacting with neutrinos converts into radioactive isotope of another element with a half-life of few weeks
- The count of the radioactive end products measures the neutrino flux
- Reactions are of the form:

\[ \nu_e + X \rightarrow e^- + Y \]  \hspace{1cm} (2)

Table: radio-chemical experiments (SNU is the solar neutrino unit which represents the number of captures occurring per day in $10^{36}$ atoms in the detector)

<table>
<thead>
<tr>
<th>Nuclei X</th>
<th>Nuclei Y</th>
<th>$E_{th}(MeV)$</th>
<th>Half-life(days)</th>
<th>Total capture(SNU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{37}\text{Cl}$</td>
<td>$^{37}\text{Ar}$</td>
<td>0.814</td>
<td>35</td>
<td>7.6</td>
</tr>
<tr>
<td>$^{71}\text{Ga}$</td>
<td>$^{71}\text{Ge}$</td>
<td>0.233</td>
<td>11.4</td>
<td>128</td>
</tr>
</tbody>
</table>
Advantages
- Main advantage is the low-threshold energy of neutrinos

Disadvantages
- Energy of the neutrino cannot be detected in this method
- one cannot determine from which direction the neutrinos are coming
- it cannot be determined at which time the neutrino was trapped in the detector
This method is useful to detect neutrinos with much higher energies even in the GeV range.

The detector material is water.

Incoming neutrinos with energies MeV range hitting the atomic electrons in hydrogen and oxygen atoms which can be treated as elastic scattering as atomic binding energies are negligible.

The scattering with the free electrons are:

$$\nu + e \rightarrow \nu + e$$  \hspace{1cm} (3)

Leads to Cherenkov Radiation.
Water Cherenkov Detector(2)

Advantages The main advantages of this method above the radio-chemical method are:

- The Cherenkov radiation has a forward peaked angular distribution within an angle

\[ \theta \sim \sqrt{\frac{m_e}{E_\nu}} \]  

extrapolating the cone in the backward direction, it can be verified whether the neutrino is coming from the Sun

- The neutrinos can be detected as soon as they arrive in the detector

- This method can also detect \( \nu_\mu \) and \( \nu_\tau \)
Disadvantages

- The major disadvantage of this method is, the incoming neutrinos must be energetic enough to induce the Cherenkov radiation, so there is a lower limit on the energies of the neutrinos to be detected, but near the lower limit the background is too high.
- Though this method can also detect $\nu_\mu$ and $\nu_\tau$, but the efficiency is poor with respect to $\nu_e$. 
Heavy Water Detection

Here the detecting material is heavy water.

3 different channels

- Cherenkov radiation (ES)
- charged current reaction (CC)

\[ \nu_e + d \rightarrow p + p + e^- \]  \hspace{1cm} (5)

- neutral current reaction (NC)

\[ \nu + d \rightarrow \nu + n + p \]  \hspace{1cm} (6)

Detection of the neutron confirms the occurrence of this process.
Advantages

- Cherenkov radiation gives information about the energy and time
- The neutral current process is the main advantage of this process because the cross-sections are the same irrespective of the flavor of the neutrinos
Sun only emits $\nu_e$. So experimentally it is expected to detect all $\nu_e's$

Radio-chemical technique was the first method that started to collect data of the solar neutrinos around 1970. From the start, it was found that there is a shortage of neutrinos compared to the solar neutrino model calculations.

All experiments carried out till the year of 2000 detected neutrino fluxes which were much below the values predicted by calculations.

The detectors that were collecting data at that time were, the Chlorine detector, GALLEX & SAGE (radio-chemical), Kamiokande (water Cherenkov)

The experimental result which was lower than the theoretical calculations predicted by the standard solar model is known as the “solar neutrino puzzle”
2001 the Sudbury detector published CC & ES channel results
Same experiment, same threshold, same method of analysis and same systematic error. Therefore it is possible to compare data from different channels
2002 the Sudbury detector published NC channel result
Solves the solar neutrino puzzle
Table: Different Neutrino Experiment Results (SSM=standard solar model)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Result / SSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homestake</td>
<td>CC</td>
<td>0.27 ±0.03</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>ES</td>
<td>0.44 ±0.06</td>
</tr>
<tr>
<td>SAGE</td>
<td>CC</td>
<td>0.553 ±0.034</td>
</tr>
<tr>
<td>Gallex</td>
<td>CC</td>
<td>0.579 ±0.037</td>
</tr>
<tr>
<td>SNO</td>
<td>CC</td>
<td>0.349 ±0.021</td>
</tr>
<tr>
<td>SNO</td>
<td>ES</td>
<td>0.473 ±0.052</td>
</tr>
<tr>
<td>SNO</td>
<td>NC</td>
<td>1.008 ±0.123</td>
</tr>
</tbody>
</table>
Conclusions

Conclusion from the Experimental Results

- The Sun produces only $\nu'_e$s, however, by the time these neutrinos are detected on the earth, some of the $\nu'_e$s have been converted into other flavors of neutrinos.

Theoretical Implications

- This experimental evidence of changing flavor of neutrinos has great theoretical implications. This changing flavor is also known as the neutrino oscillation.
- Due to this oscillation among different flavors neutrinos are supposed to have mass.
- In the Standard Model of Particle Physics, neutrinos are mass-less.
- To explain this experimental result one has to go beyond the Standard Model.