Review

The Sun, neutrinos and Super-Kamiokande

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Abstract: In the standard model of elementary particle physics neutrinos are massless, and therefore the actuality of finite neutrino mass indicates a theory beyond the standard model. The Sun produces abundant neutrinos due to nuclear fusion reactions. A pioneering experiment in the early '70s detected neutrinos from the Sun, but found that the observed flux was smaller than expected, which was then called the missing solar neutrino problem. Tremendous efforts were made both experimentally and theoretically to solve this problem. In 2001, almost 30 years after the first indication, data from Super-Kamiokande in Japan and SNO in Canada together provided evidence that neutrino oscillation effectively converts the solar (electron) neutrinos to non-electron type neutrinos. Neutrino oscillation can occur only for those neutrinos with finite neutrino mass.

Keywords: Super-Kamiokande, neutrino oscillation, solar neutrino, neutrino mass and mixing

1. Introduction

The discovery of neutrino oscillation was announced in 1998 based on an observation obtained by studying atmospheric neutrinos in Super-Kamiokande (Super-K). Three years later it was also shown that solar neutrinos oscillate, by comparing two independent experimental results from Super-K in Japan and SNO in Canada. Neutrino oscillation indicates that neutrinos have both masses and mixings. This is evidence of physics beyond the standard model of elementary particle physics, since neutrinos are massless in the standard model. Amazingly, this discovery was achieved 14 years before finding the Higgs boson, the last piece of the standard model. Today about 20 years after the oscillation discovery, neutrino oscillation is still the only compelling and convincing evidence for physics beyond the standard model.

It took about 10 years to discover atmospheric neutrino oscillations after the initial indication of the atmospheric neutrino anomaly. However, the missing solar neutrino problem, first indicated in the early '70s, by a historical chlorine experiment, took more than a 30-year struggle to settle the issue. Many experiments to detect solar neutrinos were conducted using different target materials: chlorine, gallium, water, heavy water and scintillator, and with different technologies. The different neutrino experiments cover different energy regions, so the effect of neutrino oscillation seen in the individual experiment is different. Nevertheless, all of the experiments indicated deficits of the observed solar neutrinos. It was something like to solve a jigsaw puzzle to draw a consistent view among the experiments.

Neutrino oscillation may violate CP invariance. Then there may have been a possibility to create baryon number in the early universe through the CP violating process in the lepton sector. Neutrino studies will be of significant importance in the future of elementary particles and cosmology. The discovery of neutrino oscillations has opened up a new horizon.

In this review, we explain the long and winding road to obtain convincing evidence of solar neutrino oscillations with an emphasis on the role of the Super-K experiment. We briefly summarize historical notes on the Sun and solar neutrinos in section 2. The neutrino interactions relevant for the solar neutrinos are discussed in section 2. The neutrino interactions important for the solar neutrinos are discussed in section 3. Basic concepts and formula of neutrino oscillation are given in section 4.
The early solar neutrino experiments and the solar neutrino problem before the start of Super-K are summarized in sections 5 and 6. The Super-K detector is described in section 7 and the struggle towards understanding solar neutrino oscillation can be found in section 8. The present and the future solar neutrino studies are described in section 9.

2. The Sun and solar neutrinos

2.1. Solar energy—Pre-nuclear era. The Sun produces a vast amount of energy, and is the mother of all the living creatures on Earth. The total energy of 1.37 kW/m² reaching the top of Earth’s atmosphere, is called the solar constant. The corresponding solar energy created at 150 million km away from Earth is $3.83 \times 10^{26}$ J/s, which is called the solar luminosity.

In the middle of the 19th century, the origin of solar energy was a big question. The discovery of energy conservation and the discovery of the fundamental laws of thermodynamics at around the same time stimulated consideration about the source of heat in the Sun. Transformations of the energy of one form to another form were thought to be a possibility.

A constant falling of meteors or asteroids into the Sun may produce heat by the conversion of kinetic energy to thermal energy. But the necessary number of meteorites to keep the Sun shining was not validated observationally, and the idea gradually diminished.

Another idea came along with the concept that the Sun itself contracted slightly, resulting in the liberation of light and heat. The conversion of gravitational energy released during contraction can be thought to be a possible origin of the solar energy. It was called the Helmholtz–Thomson (Kelvin) contraction.

If all of the solar luminosity did originate from the gravitation energy of the contraction, then the corresponding age of the Sun would be

$$t_{\text{grav}} = a(GN M^2_\odot/R_\odot)/L_\odot = 18 \text{ million years}, \quad [1]$$

with $a = 3/4$ for a uniform matter distribution.

This value was too small, and conflicted with an estimate of geologists and evolutionary biologists. In 1859, in the 1st edition of “On the Origin of the Species by Means of Natural Selection” Darwin estimated the age of Earth to be $\sim 300$ million years based on an evaluation of the geological erosion of a valley sufficient for the natural selection of the species produced. We now know that Kelvin’s estimate was too short, and that the geologists and the biologists were correct. We had to wait for nuclear physics to mature at the beginning of the 20th century in order to figure out the correct scenario that nuclear mass transformed into stellar energy.

2.2. Nuclear interactions and solar neutrinos.

It was realized that four hydrogen nuclei are heavier than a helium nucleus, and that hydrogen burns into helium at high temperature to produce 0.7% of the mass energy. Provided that nuclear energy is the origin of solar radiation, the maximum lifetime available is

$$\tau_{\text{sun}} = (M_\odot c^2 / 0.007)/L_\odot \approx 100 \text{ billion years}, \quad [2]$$

assuming that all of the hydrogen is burned. Thus, the calculated lifetime is sufficient to explain the solar age and the whole lifetime of the Sun. Note that the Helmholtz–Kelvin contraction remains as a mechanism to make the core density and temperature high enough at the early development stage of stars in order to ignite nuclear fusion reactions.

In the early ’30s by putting together the newly available knowledge at that time, namely the neutrino hypothesis, the weak interaction formula, a quantum mechanical evaluation of the Gamow factor and so on, the nuclear reactions at high density and temperature, like in the Sun, were investigated.

The net nuclear fusion reaction in the Sun is

$$4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 26.7 \text{ MeV}.$$ 

Most of the energy would be carried away by the charged particles and photons, and eventually be radiated from the surface of the Sun as a solar luminosity several 10 thousands of years later. The Sun is shining owing to energy created long ago in its central core. Neutrinos, on the contrary, taking only 3% of the total energy released, reach the surface of the Sun in 2 seconds and arrive at Earth 8 minutes after emanation. Therefore, neutrinos can monitor the current status of the solar core. A total solar neutrino flux of

$$\phi_{\nu}^{\text{total}} = 6.6 \times 10^{10} \text{ cm}^{-2} \text{s}^{-1}$$

at the top of Earth’s atmosphere could be easily obtained from the net reaction given above with the help of the solar luminosity.

However, the direct conversion of four protons to $^4\text{He}$ is unlikely in the core of the Sun. Therefore, the actual process consists several sequential nuclear chain reactions.
2.3. CNO cycle. The CNO (carbon–nitrogen–oxygen) cycle or Bethe–Weizsacker cycle is one of the two settings of the fusion reaction chains that produce energy in stars using carbon, nitrogen and oxygen as catalysts.\textsuperscript{(3)–(5)} The CNO main cycle can be illustrated as:

\begin{align*}
  ^{12}\text{C} + p &\rightarrow ^{13}\text{N} + \gamma + 1.95\text{MeV}, \\
  ^{13}\text{N} &\rightarrow ^{13}\text{C} + e^+ + \nu_e + 2.22\text{MeV}, \\
  ^{13}\text{C} + p &\rightarrow ^{14}\text{N} + \gamma + 7.54\text{MeV}, \\
  ^{14}\text{N} + p &\rightarrow ^{15}\text{O} + \gamma + 7.35\text{MeV}, \\
  ^{15}\text{O} &\rightarrow ^{15}\text{N} + e^+ + \nu_e + 2.75\text{MeV}, \\
  ^{15}\text{N} + p &\rightarrow ^{12}\text{C} + ^{4}\text{He} + 4.96\text{MeV}.
\end{align*}

The $^{12}\text{C}$ produced during the last reaction would be the input nucleus of the first reaction. Those cyclic processes could go on continuously. The cycle transforms 4 protons to $^4\text{He}$ and the relative abundance of C, N, O does not change. The CNO main cycle dominates in stars of mass which is larger than $1.5 \times \text{M}_\odot$ with higher core temperature than the Sun. Therefore, it is less important for energy production of the Sun.

The CNO main cycle has two $\beta^+$ decay processes to produce neutrinos: $^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$ and $^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e$. The Q-value of the $\beta^+$ decay includes the additional energy from positron annihilation. However, the end-point energies of those neutrinos are 1.20\text{MeV} and 1.73\text{MeV}, respectively, which are below the energy threshold of Super-K. There is a CNO branch cycle starting to make $^{16}\text{O}$ instead of $^{12}\text{C} + ^{4}\text{He}$, but with only 0.0004 probability. There are also sub-dominant branch cycles, but effective only for massive stars. Neutrinos are also produced in those branches, but in any case, Super-K cannot detect them. Nevertheless, they convey important information concerning the chemical composition of the Sun.

2.4. pp-chain. The pp-chain is the dominant process in the Sun at the relatively lower core temperature of $1.5 \times 10^7\text{K}$ and produces, however, neutrinos with energy higher than those from CNO, important for the solar neutrino measurements by Super-K. This was first discussed by Bethe in 1939.\textsuperscript{(5)}

- Common processes for all the branches in the pp-chain. The pp-fusion reaction, $p + p \rightarrow d + e^+ + \nu_e$ (99.75\%), is the first step of the pp-chain and produces deuterons. The relatively low core temperature of the Sun prohibits the photon-disintegration of deuterons to occur. After reaching a sufficient density, deuterons and protons would fuse into $^3\text{He}$. Those produced neutrinos are called pp-neutrinos with an end point energy of 0.420\text{MeV}. An alternative reaction, $p + e + p \rightarrow d + \nu_e$ (0.25\%), produces a monochromatic neutrino with an energy of 1.442\text{MeV}, called pep-neutrinos, as is summarized below:

\begin{align*}
  p + p &\rightarrow d + e^+ + \nu_e \quad (99.75\%) + 1.442\text{MeV}, \\
  p + e + p &\rightarrow d + \nu_e \quad (0.25\%) + 1.442\text{MeV}, \\
  d + p &\rightarrow ^3\text{He} + \gamma + 5.493\text{MeV}.
\end{align*}

All processes of the pp-chain involving neutrino emission are listed in Table 1.

The four different reaction branches (pp-I, pp-II, pp-III, pp-IV(hep)) would follow the common fusion reactions, which terminate separately the reaction chain. Each termination corresponds to one net nuclear fusion reaction of $4p \rightarrow ^4\text{He} + 2e^+ + 2\nu_e + 26.7\text{MeV}$.

- pp-I branch. Two $^3\text{He}$ nuclei are converted into $^4\text{He}$ and two protons:

\begin{align*}
  ^3\text{He} + ^3\text{He} &\rightarrow ^4\text{He} + 2p + 12.859\text{MeV}.
\end{align*}

The pp-I branch needs two common processes, and then produces two pp-neutrinos (0.25\% pep-neutrinos) in one termination.

- pp-II branch. The $^7\text{Be}$ nuclei are involved in the pp-II and pp-III branches, but in different ways. The electron capture of $^7\text{Be}$ produces one monochromatic neutrino. The energy of the neutrino is 0.862\text{MeV} in the case of 90\% and 0.384\text{MeV} in the case of 10\%:

\begin{align*}
  ^3\text{He} + ^4\text{He} &\rightarrow ^7\text{Be} + \gamma + 1.586\text{MeV}, \\
  ^7\text{Be} + e^- &\rightarrow ^7\text{Li} + \nu_e + 0.862\text{MeV}(90\%), \\
  ^7\text{Li} + \nu_e &\rightarrow ^4\text{He} + ^3\text{He} + 0.384\text{MeV}(10\%), \\
  ^7\text{Li} + p &\rightarrow ^4\text{He} + ^3\text{He} + 17.347\text{MeV}.
\end{align*}

- pp-III branch. This branch undergoes the $p^7\text{Be}$ interaction to produce $^8\text{B}$-neutrinos:

\begin{align*}
  ^3\text{He} &\rightarrow ^3\text{He} + e^+ + \nu_e + 0.862\text{MeV}.
\end{align*}
\[ 3\text{He} + 4\text{He} \rightarrow 7\text{Be} + \gamma + 1.586 \text{MeV}, \]
\[ 7\text{Be} + p \rightarrow 8\text{B} + \gamma + 0.137 \text{MeV}, \]
\[ 8\text{B} \rightarrow 8\text{Be}^* + e^+ + \nu_e + 17.980 \text{MeV}, \]
\[ 8\text{Be}^* \rightarrow 4\text{He} + 4\text{He}. \]

\( 8\text{B}(J^p = 2^+) \) decays to the first excited state of \( 8\text{Be}^* (J^p = 2^+) \) with \( E_x \approx 3 \text{MeV} \) that is unstable for \( \alpha \) decay with a width of \( \approx 1.5 \text{MeV} \). The energy of the \( 8\text{B} \)-neutrinos has a high-energy tail, \( E_{\nu,\text{max}} \leq 15 \text{MeV} \), with some uncertainty. See section 8 for more details. Although the termination fraction is very small, the \( 8\text{B} \)-neutrinos can be detected by Super-K. All of the neutrinos observed by Super-K are \( 8\text{B} \)-neutrinos, except for the tiny contribution from pp-IV (hep) neutrons.

- \text{pp-IV(hep) branch. pp-IV is very rare. The} \( 3\text{He} \) nucleus and proton are directly fused:

\[ 3\text{He} + p \rightarrow 4\text{He} + \nu_e + e^+ + 19.795 \text{MeV}. \]

This branch would produce the highest energy neutrinos, called hep-neutrinos, in the pp-chain.

As can be seen above, there are five neutrino production processes in the pp-chain. Each neutrino has its own name based on its production process, as listed in Table 1. The most abundant neutrinos are pp-neutrinos and closely related to the total luminosity of the Sun. The energy of pep-neutrinos and two \( 7\text{Be} \)-neutrinos are monochromatic. Super-K can measure only \( 8\text{B} \)-neutrinos.

Assuming that the reactions in the pp-chain are in equilibrium, then, the production rate of \( 4\text{He} \) through the \( p + p \rightarrow d + e^+ + \nu_e \) and \( d + p \rightarrow 3\text{He} + \gamma \) process, \( R_{31} \) and the destruction rate of the \( 3\text{He} \) nuclei, \( R_{33} + R_{34} \), are in balance. We put aside small contribution of the pep- and hep-neutrinos in order to simplify the explanation. In general the production rate, \( R_{ij} \) (per unit volume and time), is written as

\[ R_{ij} = \langle \sigma v \rangle n(i)n(j)/(1 + \delta_{ij}), \]

where \( v \) is their relative velocity, \( \sigma \) is the interaction cross section and \( n(i) \) is the number density of the \( i \) particle type. The coefficient \( 1/2 \) (for \( \delta_{ij} = 1 \)) reflects the characteristics of the identical particles in avoiding double counts. The production and the destruction rate of \( R_{31} \) and \( R_{33} \) need a factor of 1/2. Furthermore, \( R_{33} \) requires an additional factor of 2 for two \( 3\text{He} \) destructions for 1 termination. The destruction/termination rate of \( R_{33} + R_{34} \) is equal to \( R_{31} \) and equivalent to half of the total neutrino production rate, \( R_{33} + R_{34} = \phi(\text{total}) = \phi(pp) + \phi(7\text{Be}) + \phi(8\text{B}) \). Therefore, the termination fraction, \( T_{ij} \), becomes:

\[ T_{31} = (\phi(pp) - (\phi(7\text{Be}) + \phi(8\text{B}))/\phi(\text{total}), \text{ and} \]
\[ T_{33} = 2(\phi(7\text{Be}) + \phi(8\text{B}))/\phi(\text{total}). \]

Then, a simple relation like

\[ \frac{T_{34}}{T_{33}} = \frac{2(\phi(7\text{Be}) + \phi(8\text{B}))}{\phi(pp) - (\phi(7\text{Be}) + \phi(8\text{B}))} \]

would be obtained.

The total number of neutrinos produced, the total energy released and some simple relations described for example above, could be obtained without detailed standard solar model calculations. Nevertheless, a solar neutrino experiment usually detects neutrinos only in a particular energy interval, and therefore detailed information concerning the spectrum is necessary. The individual neutrino fluxes and spectra, depending on the temperature and the chemical composition of the Sun, must be calculated by using a so-called standard solar model (SSM). Chemical compositions in the Sun are denoted by \( X \) for hydrogen, \( Y \) for helium and \( Z \) for metal (heavier than helium), and satisfy \( X + Y + Z = 1 \).

2.5. Standard solar models (SSMs). In the early 1960s, there was a plan to observe neutrinos from the Sun. A quantitative estimate of the neutrino emission rate was indispensable. In particular the flux calculations of \( 7\text{Be} \)- and \( 8\text{B} \)-neutrinos were crucial for the planned experiment. At around the same time, the basic handling of the standard solar models (SSMs) had been established. SSMs in the early stage were used to calculate the production rate of neutrinos as a function of the density and the temperature inside the Sun.

An SSM requires: 1) hydrostatic equilibrium between the gravitational force and the pressure gradient, 2) energy transport by radiation or convection, and 3) energy production by hydrogen burning. Those are represented by four differential equations. Furthermore an equation of state (EOS), a radiative opacity and cross sections are needed. More details on the SSM calculations can be found in References 16 and 19.

The SSMs are determined only by two initial conditions: the total mass and the initial chemical composition. The total mass is well-known for the Sun, \( 1.99 \times 10^{33} \text{g} \), but the chemical composition is unknown very well. The nuclear burnings change the compositions and make inhomogeneous distributions as the Sun develops, and then several evolutionary sequences of the models would be
constructed as a function of time until reaching to the age of the Sun, \(4.6 \times 10^9\) years. The typical time step in those early models is \(5 \times 10^8\) (or \(1 \times 10^9\)) years. The model at the last step is the “standard solar model (SSM)”, where the neutrino emissions are also calculated.

The initial chemical composition \((X + Y + Z = 1)\) at the starting time of the age zero, namely at the end of the pre-main-sequence, is assumed to be homogeneous. The current surface metal abundance, \(Z/X\), and \(Y\) as a continuous fit parameter,\(^{22}\) are taken as an initial composition for the evolving sequence models. Then, the calculated luminosity from the SSM (at the age of the Sun) is compared against the current observation value. If it does not agree, then the initial composition is altered, and the process is repeated. The iteration continues until the luminosity matches.

### 2.5.1. Outcomes of the SSMs

The SSMs, BP2000\(^{23}\) and BP04\(^{24}\) were frequently used when we were struggling to solve the solar neutrino problem. We intentionally discuss those old versions of the SSMs, since the results of the pp-chain neutrinos would be similar to the later versions and would not change the conclusion of the solar neutrino oscillation interpretations.

It was thought to be important to understand the solar neutrino flux, especially the \(^8\)B-neutrinos flux, which many experiments would measure. Although evidence of the oscillation was obtained without relying on the solar flux calculations, all of the fluxes from the pp-chain were needed to determine precisely the oscillation parameters. There had been critical progress and improvements toward the SSMs in the early 2000s.\(^{23},^{24}\) The opacity was improved to OPAL\(^{25},^{26}\) from the Los Alamos opacity. The EOS was also improved by taking account the OPAL opacity.\(^{27}\) The chemical composition was improved,\(^{28}\) but we would have problems later that would be discussed afterwards. The fusion reaction rates were improved and reevaluated. The results of the sound speed calculation was proved to be consistent with the helioseismology.\(^{29}\) This strongly indicated that the SSMs were validated by the helioseismology. The uncertainties on the solar neutrino flux prediction was reduced and the prediction of the flux became stable. The available models were sufficient for reliable oscillation analysis.

#### 2.5.2. Solar neutrino flux and spectrum

Individual fluxes of pp-, pep-, \(^7\)Be-, \(^8\)B- and hep-neutrinos obtained by the SSMs, BP2000\(^{23}\) and BP04,\(^{24}\) and the capture rate for the two radio-chemical experiments are given in Table 2. There were some improvements of the EOS and the rate of the nuclear reactions to BP04 from BP2000; otherwise, not much difference was seen between two models. BP04+ had an additional change of the surface composition, which showed a conflict with helioseismological measurements. In addition the CNO flux had drastically changed, but the flux of the pp-chain neutrinos was not much affected. So we can see that the pp-chain neutrinos are stable and probably robust even for different surface compositions. The termination fraction obtained is 0.86 for R\(_{33}\) and 0.14 for R\(_{34}\). However the composition strongly affects the CNO flux.

| \(\nu\)-source | BP2000 | BP04 | BP04+ |
|---------------|--------|------|-------|
| \(^7\)Be      | 4.77 \times 10^{-1} (1.00^{+0.10}_{-0.16}) | 4.86 \times 10^{-1} (1.00^{+0.12}_{-0.23}) | 4.65 |
| \(^8\)B       | 5.05 \times 10^{-4} (1.00^{+0.20}_{-0.16}) | 5.79 \times 10^{-4} (1.00^{+0.23}_{-0.28}) | 5.26 |
| hep          | 9.3 \times 10^{-7} | 7.88 \times 10^{-7} (1.00^{+0.16}_{-0.16}) | 8.04 |
| \(^13\)N     | 5.48 \times 10^{-2} (1.00^{+0.21}_{-0.17}) | 5.71 \times 10^{-2} (1.00^{+0.37}_{-0.35}) | 4.06 |
| \(^17\)O     | 4.80 \times 10^{-4} (1.00^{+0.25}_{-0.30}) | 5.03 \times 10^{-4} (1.00^{+0.43}_{-0.30}) | 3.54 |
| \(^17\)F     | 5.63 \times 10^{-4} (1.00^{+0.25}_{-0.21}) | 5.91 \times 10^{-4} (1.00^{+0.44}_{-0.44}) | 3.97 |
| Capture rate  | \(7.6^{+1.4}_{-1.4}\) SNU | \(8.5^{+1.8}_{-1.8}\) SNU | 7.7 SNU |
| Cl           | \(128^{+3.2}_{-3.6}\) SNU | \(131^{+3.3}_{-3.0}\) SNU | 126 SNU |
A typical spectrum (BP2000) is shown in Fig. 1. The figure was made based on the total flux value of BP2000 as a normalization given in Table 2, and the spectrum distributions taken from Reference 30. The contributions from the CNO neutrinos are about 2% of the flux of the pp-neutrinos.

After this time period, new measurements on the chemical composition\(^\text{31)}\)–\(^\text{33)}\) and new opacity determinations\(^\text{34)}\) would become available, resulting in a slightly different prediction, but they mostly affect the CNO neutrinos and have a small effect on the pp-chain neutrinos and no effect on the results of the neutrino oscillation.

The flux of CNO, however, becomes an important ingredient to understand the chemical composition of the Sun, and an important subject of solar neutrinos physics. Unfortunately Super-K does not have sufficient sensitivity for CNO neutrinos. Therefore we do not discuss the latest development on SSMs further in this review article. Those who are interested in CNO neutrinos and metallicity, see References 35–38.

### 3. Neutrino interactions

Neutrinos were postulated by Pauli in 1930 to save a possible violation of energy and angular momentum conservation in $\beta$ decay.\(^\text{10)}\) The neutrino mass was thought to be tiny due to the fact that the measured higher end of the $\beta$ spectrum approached its end-point energy. The neutrino spin was also thought to be $1/2$, considering angular momentum conservation of the $\beta$ decay process. The formula for the current-current interactions were used by Fermi\(^\text{11)}\) to describe $\beta$ decay. Soon after that the neutrino interactions (inverse $\beta$ decay) were calculated by Bethe and Peierls.\(^\text{39)}\) The Fermi theory had been used until establishment of the standard electro-weak theory,\(^\text{40)}\)–\(^\text{42)}\) where neutrinos would be a neutral member of the lepton doublets.

Neutrinos in the standard model have no mass, no electro-magnetic interactions and interact scarcely through weak interactions. Ten MeV neutrinos, for example, may traverse $\sim$10 light years of soil. Neutrinos could be detected through weak interactions with matter by observing produced secondary charged particles. They undergo neutral current interactions as well as charged current interactions.

Large numbers of incoming neutrinos and huge detectors are needed to detect and study neutrinos. But this is not a trivial matter. Therefore, even the basic properties of neutrinos, like masses, were not addressed until recently.

Here we discuss mostly the interaction relevant to the detection of low-energy solar neutrinos.
We also mention other neutrino interactions, as needed.

3.1. Neutrino electron scattering. The neutrino interactions are described based on electroweak theory.\(^{10-12}\) Neutrino electron scatterings can be precisely calculated in the standard model since pure leptonic processes have no hadronic correction, no form factors and no final-state interactions. These processes are especially important for solar neutrino experiments that use water and scintillators as their target material.

A possibility to use \(\nu_e + e^-\) scattering for solar neutrino studies was first suggested in 1964.\(^{45}\) The recoil electron energy spectrum shape and the directionality were calculated for \(^8\)B solar neutrinos by using the current-current interaction theory.\(^{44}\) The cross section of \(\nu_e + e^-\) scattering based on the standard electroweak theory was calculated by \(\dagger\) Hooft\(^{45}\) in 1971; Bahcall\(^{46}\) then obtained the total cross section for the process was also evaluated.\(^{47}\) Such a correction reduces the yields by up to \(2\%\) at the highest electron energy region of the \(^8\)B-neutrino spectrum, but is negligible in the low-energy region. The \(\nu_e + e^-\) total cross section is reduced by \(2\%\).

The differential cross section in the laboratory frame of \(\nu + e^- \rightarrow \nu + e^-\) interactions in the standard model (without radiative corrections) is:

\[
\frac{d\sigma}{dT_e} = \frac{G_F^2 m_e}{2\pi} \left[(c_V + c_A)^2 + (c_V - c_A)^2 (1 - T_e/E_{e})^2 - (c_V^2 - c_A^2)m_T/E_e^2\right],
\]

where \(T_e\) is the kinetic energy of the recoil electron. Those constants, \(c_V\) and \(c_A\), are

\[
c_V = 2\sin^2\theta_W - \frac{1}{2}, \quad c_A = -\frac{1}{2} \quad \text{for} \quad (\nu_{\mu,\tau} + e^-),
\]

\[
c_V = 2\sin^2\theta_W + \frac{1}{2}, \quad c_A = +\frac{1}{2} \quad \text{for} \quad (\nu_e + e^-).
\]

The electron neutrinos undergo charged current (W exchange) and neutral current (Z\(_0\) exchange) interactions, whereas \(\nu_\mu\) and \(\nu_\tau\) interact only through the neutral current. The solar \(\nu_e\) may oscillate into \(\nu_\mu\) or \(\nu_\tau\). Practically \(\sigma(\nu_{e,\mu}\rightarrow e^-)/\sigma(\nu_e\rightarrow e^-) \approx 0.15\). For anti-neutrinos, \(c_A\) can be replaced by \(-c_A\). The maximum kinetic energy of electrons is limited by kinematics,

\[
T_{\text{max}} = \frac{E_{\nu}}{1 + m_e/2E_{\nu}},
\]

similar to the Compton edge. The \(\nu + e^-\) scattering cross sections at the typical energy of 10 MeV are \(\sigma(\nu_e + e^-) \approx 9.0 \times 10^{-44}\) cm\(^2\) and \(\sigma(\nu_{\mu,\tau} + e^-) \approx 1.6 \times 10^{-44}\) cm\(^2\).

In neutrino electron scattering, the direction of the recoil electrons retains the direction of neutrinos within \(\theta_{e\nu}^2 < 2m_e/E_{\nu}\), since the typical solar neutrino energy is much larger than the electron mass. The directional determination of solar neutrinos of 10 MeV is constrained to within 18.6 degrees.

Neutrino electron scattering together with Water Cherenkov technology, would make the event direction determinable. Accordingly, the (heavy) Water Cherenkov detector provides capability to detect the energy, direction and time of the incoming neutrinos. The angular resolution is additionally affected by the multiple scattering of electrons in the target material. The pointing accuracy then becomes \(\sim 2\text{ deg}\) for 10 MeV in a water detector. Nevertheless, this advantage really makes a detector like Super-K to be an astronomical telescope for neutrinos.

3.2. Inverse \(\beta\) decay (IBD). The next simplest neutrino interaction is neutrino nucleon scattering. Inverse \(\beta\) decay (IBD; sometimes, inverse neutron decay) of anti-neutrinos, \(\bar{\nu}_e + p \rightarrow e^- + n\), was used in the early stage of neutrino studies.\(^{30}\) The existence of neutrinos was demonstrated by detecting anti-neutrinos from nuclear reactors through the IBD.\(^{48,49}\) The observed neutrino scattering cross section was shown to be very close to its prediction.

For the IBD of neutrinos, \(\nu_e + n \rightarrow e^- + p\), neutrinos interact with neutrons. But there are no free neutrinos in the target material, and therefore this process is strongly suppressed in the low-energy region.

Anti-neutrinos seem to be irrelevant concerning solar neutrino studies, since solar neutrinos are neutrinos, not anti-neutrinos, unless there is a mechanism, like \(\nu_e \rightarrow \bar{\nu}_e\), oscillations, which so far have not been indicated to exist.

A terrestrial experiment, KamLAND,\(^{40}\) which detects anti-neutrinos from long-distance reactors, can explore the solar neutrino oscillation parameters, assuming CPT invariance. KamLAND detects anti-neutrinos through the IBD process in a few MeV region by employing a liquid scintillator. They confirmed solar neutrino oscillation and scrutinized the oscillation parameters. We discuss this in a later section.

In any case, the lowest order total cross section can be obtained using the neutron lifetime, \(\tau_n\), and
the usual statistical function, \( f \), including the Coulomb correction\(^5\):

\[
\sigma_{\text{total}}(E_e) = \frac{2\pi^2\hbar^3}{m_e^2c^3} \, p_e E_e. \quad [11]
\]

The incoming anti-neutrino energy is \( E_\nu = E_e + (M_n - M_p)c^2 \). For the energy region of a few MeV, and for \( E_\nu > m_e \), the cross section grows as \( \sim E_\nu^2 \). The total cross section at 5 MeV is \( \sim 1 \times 10^{-42} \text{cm}^2 \). But there are some corrections based on higher order calculations. The total correction at 5 MeV is \( \sim 2.4\% \), +1% for radiative corrections and \(-3.4\%\) for the recoil and weak magnetism.\(^5\),\(^3\)

The angular distribution of the recoil positron is given\(^3\) by

\[
\frac{d\sigma}{d\cos \theta} = \frac{G_F^2|V_{ud}|^2 E_p E_e}{2\pi} \left[ f_V(0)^2(1 + \beta_t \cos \theta) + 3 f_A(0)^2 \left( 1 - \frac{\beta_t}{3} \cos \theta \right) \right], \quad [12]
\]

where \( E_e, p_e, \beta_t, \) and \( \cos \theta \) are the positron energy, momentum, velocity and scattering angle, respectively. \( V_{ud} \) is a matrix element of the quark mixing; \( f_V(0) \) and \( f_A(0) \) are the vector and the axial-vector form factors at zero momentum transfer. The ratio \( f_A(0)/f_V(0) = -g_A = -1.27 \). The positron angular distribution is slightly backwards.

### 3.3. Neutrino nucleus interaction.

Neutrino nucleus interactions play important roles in studies of solar neutrinos. Radio-chemical experiments using \( ^{37}\text{Cl} \)\(^4\),\(^5\) and \( ^{71}\text{Ga} \)\(^6\) have proper excited states to detect solar neutrinos. The Homestake experiment\(^7\) uses \( ^{37}\text{Cl} \) and SAGE\(^8\) and Gallex/ GNO\(^9\) use \( ^{71}\text{Ga} \) as target materials. They measure solar neutrinos with different energy thresholds, as described in section 5. In general, neutrino nucleus scatterings involve exclusive scattering to specific bound states at low energy. The simplest nucleus, the deuteron, is very interesting and important for solar neutrino measurements. However, there are no excited states in the deuteron and the only possible channel is deuteron disintegration. SNO\(^1\) used this reaction, and made significant contributions when studying the solar neutrino oscillations described in section 8.

#### 3.3.1. Deuteron.

There are two important interactions involving the deuteron:

\[
\nu_e + d \rightarrow e^- + p + p \quad (\text{CC, Charged Current}) \quad \text{and,} \quad [13]
\nu_x + d \rightarrow \nu_x + n + p \quad (\text{NC, Neutral Current}). \quad [14]
\]

The charged current detects only electron neutrinos and the neutral current is sensitive to all kinds of neutrinos: \( \nu_e, \nu_x \) and \( \nu_x \). The charged current interaction on the deuteron was first studied\(^1\) in the late ’60s by following a proposal for an experiment\(^2\) using deuterons in 1966. The cross section for the neutral current was initially studied in the context of testing the standard model of the electroweak theory.\(^3\)\(^,\)\(^4\) The number of events measured through the neutral current is invariable regardless of the existence of neutrino oscillations. In obtaining the cross sections the effective radius, binding energy of deuterons and final-state interactions need to be considered. There are many techniques to obtain the cross section, but we do not consider the details here; see Reference 67 and those references therein for additional explanations.

The cross section of the CC interactions for 10 MeV neutrinos is \( 2.7 \times 10^{-42} \text{cm}^2 \), and that of the NC interaction is \( 1.1 \times 10^{-42} \text{cm}^2 \). The uncertainties are evaluated to be at the 2% level. The produced electron angular distribution of the charged current interaction is \( 1 - 0.340 \cos \theta_x = 1 \). The direction from the Sun to Earth stands for \( \cos \theta_x = 1 \).

#### 3.3.2. Cl and Ga.

For neutrino nucleus interactions on Cl and Ga, if they are used to detect solar neutrinos, the emanated electrons through the charged-current interactions are not used to identify the reactions. Instead, the de-excitation of the created nuclei, either Ar and Ge, is used. The energy threshold of the Cl reaction is 817 keV and that of Ga is 233 keV.

### 4. Neutrino mass and oscillation

Pauli stated in his famous letter to Meitner\(^1\) the idea to introduce neutrinos in order to save energy conservation; he also mentioned the mass of neutrinos: “The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.” Fermi\(^1\) explained the method used to measure the neutrino mass in \( \beta \)-decay experiments. It was soon realized, even in the early ’50s that the neutrino mass is very tiny, less than 1/5,000 of the electron mass.\(^6\)\(^,\)\(^7\)

After discovering the maximum parity violation\(^1\)\(^,\)\(^2\) in \( \beta \) decay in 1957, neutrinos were then regarded as being two-component neutrinos, the Weyl spinors,\(^3\)\(^,\)\(^4\) of massless particles possessing some defined handedness. The neutrino helicity was measured by Goldhaber\(^7\) in 1958, which proved that the helicity of the neutrino is left-handed, \( \nu_L \). The helicity and the chirality of massless particles are the same.
But, there was no strong reason that neutrinos would be massless. A small mass of neutrinos was not completely excluded. The tiny neutrino masses and mixings are the ingredients of neutrino oscillations.

Neutrino mixings among different flavors were first considered by Maki, Nakagawa and Sakata in 1962, where they said, “We assume that there exists a representation which defined the true neutrinos through some orthogonal transformation applied to the representation of weak neutrinos;

\[
\begin{align*}
\nu_1 &= \nu_e \cos \delta + \nu_\mu \sin \delta, \\
\nu_2 &= -\nu_e \sin \delta + \nu_\mu \cos \delta.
\end{align*}
\]

(\(\delta\): real constant).”,

and then “…weak neutrinos are not stable due to the occurrence of a virtual transmutation \(\nu_e \rightarrow \nu_\mu\) induced by the interaction”. The clear statement concerning neutrino oscillation through flavor mixing was given there.

Note that Pontecorvo described the possibility of neutrino \(\rightarrow\) anti-neutrino oscillation in a 1957 paper, but considered flavor oscillations later in 1962, where they said, “In any case, the mixing matrix is customarily parametrized in many ways, but is most commonly written\(^3\) as

\[
U_{\alpha j} = \left( \begin{array}{ccc}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{array} \right) \left( \begin{array}{ccc}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} & 0 & \cos \theta_{13}
\end{array} \right)
\]

\times \left( \begin{array}{ccc}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{array} \right)
\]

\[
= \left( \begin{array}{ccc}
c_{12}c_{13} & s_{12}s_{13} & s_{12}c_{13} \\
s_{12}c_{13} & c_{12}c_{13} - s_{12}s_{13}c_{13} & c_{12}s_{13} \\
-s_{12}c_{13} & c_{12}s_{13} & c_{12}c_{13}
\end{array} \right).
\]

[18]

where \(c_{ij}, s_{ij}\) stand for \(\cos \theta_{ij}\) and \(\sin \theta_{ij}\). This is similar to the standard quark parametrization, but the value is very different.

The time evolution of a state that coincides with a flavor eigenstate at \(t = 0\) with momentum \(p\) is

\[
|\nu_\alpha(t)\rangle = \sum_j U_{\alpha j}|\nu_j\rangle e^{-iE_j t}.
\]

[19]

Those active, chiral left-handed neutrinos participate in weak interactions in the standard model. The neutrinos produced in an interaction involve superpositions of the three mass eigenstates, if neutrinos have non-zero masses:

\[
|\nu_\alpha\rangle = \sum_{j=1}^3 U_{\alpha j}|\nu_j\rangle,
\]

where \(\alpha\) runs for the three flavors, \(\nu_e, \nu_\mu, \nu_\tau\) and \(j = 1–3\) for the mass eigenstates. The \(3 \times 3\) unitary mixing matrix is generally parameterized by \(3^2 = 9\) parameters, 3 mixing angles and 6 phases. Among the 6 phases only 3, two Majorana phases and one Dirac phase,\(^4\) are physical. The Majorana phases do not affect the neutrino oscillations. Therefore, we consider only one remaining complex phase, which may generate CP violation. The mixing matrix can be parametrized in many ways, but is most commonly written\(^5\) as

\[
U_{\alpha j} = \left( \begin{array}{ccc}
1 & 0 & 0 \\
0 & \cos \theta_{23} & \sin \theta_{23} \\
0 & -\sin \theta_{23} & \cos \theta_{23}
\end{array} \right) \left( \begin{array}{ccc}
\cos \theta_{13} & 0 & \sin \theta_{13} e^{-i\delta} \\
0 & 1 & 0 \\
-\sin \theta_{13} & 0 & \cos \theta_{13}
\end{array} \right)
\]

\times \left( \begin{array}{ccc}
\cos \theta_{12} & \sin \theta_{12} & 0 \\
-\sin \theta_{12} & \cos \theta_{12} & 0 \\
0 & 0 & 1
\end{array} \right)
\]

\[
= \left( \begin{array}{ccc}
c_{12}c_{13} & s_{12}s_{13} & s_{12}c_{13} \\
s_{12}c_{13} & c_{12}c_{13} - s_{12}s_{13}c_{13} & c_{12}s_{13} \\
-s_{12}c_{13} & c_{12}s_{13} & c_{12}c_{13}
\end{array} \right).
\]

[18]

where \(c_{ij}, s_{ij}\) stand for \(\cos \theta_{ij}\) and \(\sin \theta_{ij}\). This is similar to the standard quark parametrization, but the value is very different.

The time evolution of a state that coincides with a flavor eigenstate at \(t = 0\) with momentum \(p\) is

\[
|\nu_\alpha(t)\rangle = \sum_j U_{\alpha j}|\nu_j\rangle e^{-iE_j t}.
\]

[19]

where \(E_j = (p^2 + m_j^2)^{1/2}\). Then, the oscillation probability, \(P(\nu_\alpha \rightarrow \nu_\beta)\), becomes

\[
P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2.
\]

[20]

For simplicity, we first treat the two-neutrino case, which would reveal the characteristics of the neutrino oscillation. In addition, early studies on neutrino oscillations were indeed based upon the two-neutrino oscillation scheme. Namely, the atmospheric
neutrino oscillations and the solar neutrino oscillations could be treated independently in the individual two-neutrino scheme. This lucky situation was due to the consequence of the following situation. The energy ranges relevant for solar neutrinos and atmospheric neutrinos are very different. The two neutrino mass differences have a large hierarchical structure,
\[ \Delta m_{12}^2 \sim 7 \times 10^{-5} \text{eV}^2 \]
\[ \ll \Delta m_{23}^2 \sim 2 \times 10^{-3} \text{eV}^2, \]
and the \( \theta_{13} \) mixing angle is small.

Consequently, \( \theta_{12} \) mixing is mostly responsible for the solar neutrino oscillations (\( \nu_e \to \nu_{\mu,e} \)) and relevant to long-baseline reactor neutrino oscillation experiments (\( \bar{\nu}_e \to \bar{\nu}_e \)). Further, \( \theta_{23} \) drives atmospheric neutrino oscillations (\( \nu_\mu \to \nu_e \)), and is also measured by accelerator long-baseline neutrino oscillation experiments (\( \nu_\mu \to \nu_\tau \)). Short-baseline accelerator reactor neutrino oscillation experiments can extract \( \theta_{13} \) directly. The effect of \( \theta_{13} \) can also be seen as a subdominant \( \nu_e \) appearance in atmospheric neutrinos.

The transition probability in the two-flavor oscillation scheme, \( \nu_\alpha \to \nu_\beta \)
\[ P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_\nu} \right), \]
[21]
where \( \theta \) is the two-flavor mixing angle,
\[ U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}, \]
[22]
and \( \Delta m^2 \) (eV\(^2\)) is the mass-squared difference. \( L \) (in km or m) is the distance to the detector and \( E_\nu \) (in GeV or MeV, in response to the choice of the unit of distance) is the neutrino energy. The wavelength of the oscillation is \( \lambda = 4\pi E_\nu/\Delta m^2 \) or \( \lambda = 2.5 E_\nu/\Delta m^2 \) (in the above unit). If \( \Delta m^2 L/E_\nu \gg 1 \), then \( \sin^2 \left( \frac{1.27 \Delta m^2 L}{E_\nu} \right) \) is averaged out to be 1/2 and the oscillation probability becomes
\[ P(\nu_\alpha \to \nu_\beta) = \frac{1}{2} \sin^2 2\theta. \]
[23]
If \( E_\nu/L \) is close to \( \Delta m^2 \), then an oscillatory behavior may be observable. \( E_\nu/L \) determines the sensitivity to \( \Delta m^2 \). For example, suppose \( \Delta m^2 = 2.5 \times 10^{-3} \text{eV}^2 \), then for neutrinos with an energy of 1 GeV (a la atmospheric neutrino oscillation), the oscillatory pattern can be seen for \( L \sim 400 \text{km} \) and the average reduction can be seen for \( L > \text{a few} \times 400 \text{km} \). For the same configuration, but with a neutrino energy of 5 MeV, the oscillatory pattern can be seen for \( L \sim 2 \text{km} \). Suppose \( \Delta m^2 = 7 \times 10^{-5} \text{eV}^2 \) and for neutrinos with an energy of 5 MeV (a la solar neutrino oscillation), the oscillatory pattern can be seen for \( L \sim 70 \text{km} \) and the average reduction can be seen for \( L > \text{a few} \times 70 \text{km} \). This is the reason why the long-baseline reactor experiment, KamLAND, could explore the solar oscillation parameters.

In more precise studies concerning atmospheric neutrinos, the sub-dominant effects, in three-flavor oscillation have become relevant. Nowadays, atmospheric neutrino oscillations are analyzed in the three-flavor scheme. Small corrections due to the solar terms and Earth’s resonance effect through \( \theta_{13} \) need to be included. The neutrino mass hierarchy and CP-violating effects can be extracted from the three-flavor analysis. A study on the CP phase is only possible in the three-neutrino scheme.

For solar neutrino oscillation, The matter effects would be dominant and very crucial. There are only small effects due to \( \theta_{13} \).

4.2. Matter effect. The effect of coherent forward scattering can be described in terms of the effective potential to neutrinos while traveling through matter. The matter effect can drastically change the neutrino oscillations.\(^{86}\) For those solar neutrinos, passing through any background matter with a variable density, the effect is prominent and large.\(^{87}\)

Any actual background matter that neutrinos pass through consists of electrons, protons and neutrons. Among three kinds of neutrinos with different flavors, only \( \nu_e \)'s are able to fulfill the charged current coherent scattering on electrons. Neutral current interactions are, however, common for all active neutrinos. The potential from the charged current forward scattering is \( \sqrt{2} G_F n_e \) and the potential from the neutral current scatterings is \( \sqrt{2} G_F \sum_f n_f (T_{3f} - 2 \sin^2 \theta_W Q_f) \). Here, \( f \) runs for electrons, protons and neutrons, and \( T_{3f} \) is the third component of the weak isospin and \( Q_f \) is the charge of the background fermions, \( f \). \( T_{3f} \) is \(-1/2, 1/2 \) and \(-1/2 \) for e, p and n. \( Q_f \) is \(-1, 1 \) and 0 for e, p and n. Taking account of the fact that neutrinos pass through a neutral medium, where \( n_p = n_n \), the potential from the neutral current becomes \( \sqrt{2} G_F \left( -\frac{1}{2} n_e \right) \). The potentials corresponding to all flavors of neutrinos are
\[ V_{\nu_e} = \sqrt{2} G_F \left( n_e - \frac{1}{2} n_n \right), \]
[24]
\[ V_{\nu_\mu} = \sqrt{2} G_F \left( -\frac{1}{2} n_n \right). \]
[25]
For example, the effective matter potential for the
\( \nu_e \to \nu_\mu \) oscillation is the difference of the two potentials, \( V_{e\mu} = \sqrt{2} G_F n_e \). Note that there is no matter effect between \( \nu_e \) and \( \nu_\mu \).

4.3. Neutrino propagation in matter. For \( \nu_e \to \nu_\mu \), oscillation, after removing the term that gives a common phase and rearranging the diagonal elements, the differential equation for the neutrino propagation in matter becomes:

\[
\frac{d}{dt} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \frac{1}{4E} \begin{pmatrix} m_1^2 + m_2^2 + A & 1 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} + \begin{pmatrix} A - \Delta m^2 \cos 2\theta & \Delta m^2 \sin 2\theta \\ \Delta m^2 \sin 2\theta & -(A - \Delta m^2 \cos 2\theta) \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix},
\]

where \( A = 2\sqrt{2} G_F n_e \), \( \theta \) is a mixing angle in vacuum and \( \Delta m^2 = |m_3^2 - m_2^2| \). The equation using flavor states is easier for introducing the matter potential.

We define the mass eigenstate in the matter as

\[ \begin{pmatrix} \nu_{1m} \\ \nu_{2m} \end{pmatrix} = \begin{pmatrix} \cos \theta_m & -\sin \theta_m \\ \sin \theta_m & \cos \theta_m \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}. \]

After diagonalizing the mixing matrix, the eigenvalues in the matter, \( M_{1,2}^2 \), would be attained, like

\[ M_{1,2}^2 = (m_1^2 + m_2^2 + A) \pm \sqrt{(A - \Delta m^2 \cos 2\theta)^2 + (\Delta m^2 \sin 2\theta)^2}, \]

and the mixing angle in the matter would become

\[ \tan 2\theta_m = \frac{\tan 2\theta}{1 - A/(\Delta m^2 \cos 2\theta)}. \]

As a check at \( A = 0 \), where there is no matter effect, the eigenvalues and the mixing angle in matter become \( m_1^2, m_2^2 \) and \( \theta \), respectively, back to the vacuum value.

Note that the neutrino propagation in matter with varying density, like in the Sun, can be solved by employing the time-varying mixing angles, \( \theta_m \). But the results obtained for the constant, but with different matter densities (i.e. \( A \leq \Delta m^2 \cos 2\theta \)) may be used to understand the approximated behavior in the varying density.

For the condition that satisfies \( A > \Delta m^2 \cos 2\theta \), neutrinos exist in high density matter. The mixing angle in this matter then satisfies \( \tan 2\theta_m \sim 0 \), namely, \( 2\theta_m \sim 180^\circ \). The eigenstates there become \( \nu_{2m} = \nu_\mu \) and \( \nu_{1m} = 0 \).

At the place where \( A(= 2E\sqrt{2} G_F n_e) = \Delta m^2 \cos 2\theta \) (the resonance condition), the matter effect reveals a strong enhancement. The mixing angle in matter becomes \( \theta_m = \pi/4 \), full mixing, even though the mixing angle in vacuum is small. Neutrinos are then fully mixed: \( \nu_{1m} = \frac{1}{\sqrt{2}}(\nu_e - \nu_\mu) \) and \( \nu_{2m} = \frac{1}{\sqrt{2}}(\nu_e + \nu_\mu) \).

If \( A < \Delta m^2 \cos 2\theta \), then the mixing angle in matter becomes almost that in vacuum, \( \theta_m \sim \theta_1 \), and the higher mass eigenstate becomes \( \nu_{2m} = \nu_\mu \).

What is the effect of matter on solar neutrinos during propagation inside the Sun? When solar neutrinos (electron neutrinos) are produced in the core, which satisfy \( A > \Delta m^2 \cos 2\theta \), they are created mostly as the higher mass eigenstate, \( \nu_{2m} \). Those neutrinos pass through the solar matter towards the surface of the Sun in a varying density, starting from very high density, gradually experiencing lower density and finally exiting from the Sun to the ~zero mass density, vacuum. The neutrinos cross the region where \( A = \Delta m^2 \cos 2\theta \). If they satisfy an adiabatic condition, the mass eigenstate of the neutrinos in matter, \( \nu_{2m} \), always remains in the same mass eigenstates during passage through the Sun. Since \( \nu_{2m} = \nu_\mu \) in the region, \( A < \Delta m^2 \cos 2\theta \), the electron neutrinos created in the core as \( \nu_{2m} = \nu_\mu \) finally exit the Sun as \( \nu_\mu \). The solar neutrinos convert to another type of neutrinos. This process is called an adiabatic resonance conversion (MSW effect\(^{87} \)). The survival probability is \( \sin^2 2\theta \) \(^{84} \).

The resonance condition\(^{84} \) can be written after inserting the necessary numerical values:

\[ \left[ \frac{\rho_e \text{ mol}}{\text{cm}^3} \right] \cdot E(\text{MeV}) = 66 \cdot \left[ \frac{\Delta m^2}{1 \times 10^{-5} \text{eV}^2} \right] \cdot \cos 2\theta. \quad [27] \]

The electron number density, \( n_e(\text{cm}^3) = \rho_e \cdot N_A \), is largest at the center of the core. The maximum density of the core is ~150 g/cm\(^3\) and the helium fraction is 65%. The proton density, therefore, can be ~100 g/cm\(^3\) as the largest value.

The resonance condition for a typical parameter of the small mixing angle solution, \( \Delta m^2 \sim 1 \times 10^{-5} \text{eV}^2 \) and \( \cos 2\theta \sim 1 \), satisfies \( \rho_e \cdot E \sim 70 \).

For the maximum value of \( \rho_e \sim 100 \), \( E \) becomes ~0.7 MeV. Consequently, those neutrinos with energy above ~0.7 MeV, which are produced in the core of the Sun and pass toward the surface, cross the relevant resonance density (lower than 100/cm\(^3\)) within the Sun. Therefore resonance conversion occurs.

For \( 1 \times 10^{-5} \text{eV}^2 \) and \( \cos 2\theta \sim 1 \), the minimum energy becomes ~7 MeV. Since the mass difference
increases the minimum energy for the resonance conversion becomes larger. Those neutrinos with energy below the minimum are not influenced by the matter. In the case of large mixing, for example $\cos 2\theta \sim 0.5$, the minimum energy becomes $\sim 3.5$ MeV, smaller by $\sim 50\%$.

Note that precise knowledge concerning the number density distribution and the neutrino production position distribution is very important for the calculation.

The adiabatic condition\(^8^4\) satisfies

$$\frac{\sin^2 2\theta}{\cos 2\theta} \geq 6.6 \times 10^{-4} E(\text{MeV}) \left(\frac{10^{-5}}{\Delta m^2}\right).$$

[28] The parameter regions of a mass difference larger than $\sim 10^{-5}$-$10^{-4}$ eV\(^2\) and $\cos 2\theta \geq 0.5$ satisfy this requirement.

Typically, the low-energy neutrinos produced in the condition $A < \Delta m^2 \cos 2\theta$ would not pass through the resonance condition before leaving the Sun, and therefore they simply undergo vacuum oscillation. The survival probability is $1 - \sin^2 2\theta/2$.

4.4. Day/night effect. Those neutrinos produced at the center of the Sun traverse Earth during the nighttime before reaching the terrestrial detector, but there are no obstacles between the Sun and the detector during daytime. The location of the Sun that is the time of the day, determines the zenith angle of the Sun, the terrestrial matter density and the length through which the neutrinos pass. Those neutrinos passing through Earth are influenced by Earth’s matter, and in most cases, regenerate $\nu_e$’s through Earth’s matter. Thus, a positive observation of the day/night flux difference is direct evidence of matter oscillation, which also provides another way to determine the oscillation parameters.

5. Early solar neutrino experiments and the solar neutrino problem

The initial motivation to observe neutrinos from the Sun was to confirm the energy sources to be the Sun: the nuclear reactions as described in section 2. Discussions were made in the ’60s concerning a possible detection of the solar neutrinos. Interestingly, flavor mixing of neutrinos was first presented in 1962,\(^7^8\) although neutrino oscillation was not the initial motivation of the solar neutrino measurement at that time. There have been seven solar neutrino experiments: the Homestake Chlorine experiment,\(^8^8\) the pioneering experiment started in the late ’60s, Kamiokande-II, SAGE, GALLEX/GNO, Super-Kamiokande, SNO and Borexino (in chronological order). Three out of the seven experiments (SAGE, Super-Kamiokande and Borexino) are still taking data. Because these solar neutrino experiments have used five different target materials and different detection technologies, they have different energy thresholds and sensitivity. Although we have a variety of handles on the solar neutrino measurements, the common problems of solar neutrino experiments are that they have small cross sections ($10^{-44}$-$10^{-42}$ cm\(^2\)) and large backgrounds (see section 3 in details). The detectors thus need to be big, more than several tens of tons to $\sim$ kilo tons. The small event rates of about one in a few days in the early experiments increased to 10–20 events per day in recent experiments. The radioactive impurities that influence signal detection must be removed.

The deficit of solar neutrinos that the solar neutrino event rate observed was significantly smaller than the prediction of the solar model calculation, was first indicated in the ’70s by the Homestake experiment. This solar neutrino problem, which has been persistent, never diminished and became stronger when adding new results available from new experiments.

In this section we describe the early-stage solar neutrino experiments that took data before Super-K, and the interpretation of those results are mentioned.

5.1. Early indication from the Homestake Chlorine experiment. The idea to use the inverse $\beta$ decay reaction,

$$\nu_e + ^{37}\text{Cl} \rightarrow e^- + ^{37}\text{Ar},$$

for neutrino detection was initially proposed by Pontecorvo\(^5^4\) in 1946 and Alvarez\(^2^5\) in 1949. The energy threshold of the reaction is 817 keV and is not sensitive to low-energy pp-neutrinos. Two encouraging facts were revealed at that time and stimulated construction of the Chlorine detector. The measured cross section of $^3\text{He}(^3\text{He}, \gamma)^7\text{Be}$ was higher than that anticipated.\(^8^5\) This result meant that the $e + ^7\text{Be}$ (pp-II) and the $p + ^7\text{Be}$ (pp-III) processes would occur more frequently and as a result would produce more $^7\text{Be}$- and $^8\text{B}$-neutrinos. In addition, the transition from the ground state of $^{37}\text{Cl}$ to its isobaric analog states in $^{37}\text{Ar}$ was found, besides the usual ground state of $^{37}\text{Cl}$ to the ground state of $^{37}\text{Ar}$ transitions. This would cause enhancement above 5.8 MeV and imply that the detector may acquire more events and increase its sensitivity. Considering those effects, it was thought that a large-scale chlorine detector would have a good chance to observe solar neutrinos.
A three-ton prototype detector was made and placed 1,800 m water equivalent underground in a limestone mine. The detector was exposed for 4 months in order to get $^{37}$Ar with a 35-day lifetime to reach equilibrium. All of the technologies were tested, and the backgrounds were evaluated. They had concluded that a 600-ton detector should be built and placed at 4,000 m water equivalent to reduce the neutron background in order to detect solar neutrinos.

The Homestake experiment was built during the period of 1965 to 1967, after the prototype experiment. The detector was placed underground, 4,200 ± 100 m water equivalent, in the Homestake mine, which kept 615 tons of perchloroethylene (C$_2$Cl$_4$). It experienced 110 days of exposure as a pilot run. A radio-chemical experiment like the Chlorine experiment counts the number of atoms created through the interactions ($^{37}$Ar in this case). The extraction efficiency and the counting efficiency are both important and crucial. Those efficiencies were demonstrated by using injected trace elements, $^{36}$Ar, and $^{37}$Ar, produced by the first neutron irradiation. The neutron source was placed at the center of the detector.

No excess was found for this pilot run, and set the upper limit at 3 SNU (Solar Neutrino Unit: 10$^{-36}$ captures/sec/atom), while the prediction was 20 ± 12 SNU, which was about 2.5-times larger than the current value. In order to improve the signal-to-background ratio, the pulse rise time restriction was adopted. Data taking with this improvement started in 1970, and the experiment measuring solar neutrinos has continued since then.

The Homestake Chlorine experiment initially found that the solar neutrino flux was significantly lower than that expected in the '70s. This was called the “solar neutrino problem, or puzzle”, that the measured solar neutrino flux would be about 1/3 of the predicted value.

Possible interpretations of this deficit were: 1) experimental problems (systematic errors), 2) astrophysical problems (incorrectness of the solar model flux prediction) and 3) neutrino problems (oscillations etc.).

We should note that the radio-chemical experiments were not familiar to physicists, who had to admit an amazing chemical procedure to extract a few atoms from a few hundred tons of material. It was also known that the predictions for the fluxes of $^{7}$Be- and $^{8}$B-neutrinos that were responsible for the Chlorine measurement had large uncertainties. In particular, the astrophysical S-factor, S(E)$_{17}$, was not well-known in the '70s and '80s. Further, the deficit of 1/3 could not accommodate a simple two-flavor vacuum-oscillation interpretation. The MSW effect, the resonance enhancement in the propagation of neutrinos in matter, which was thought to explain the deficit of 1/3, was first presented in 1985. It should be noted that this 1/3 deficit is still a puzzle and not quite consistent with the finally chosen large mixing angle (LMA) solution although the significance of the difference is 2σ level.

The last remark is that in addition to the deficit, the Chlorine experiment had claimed an anti-correlation of the flux of the solar neutrinos with the sunspot numbers, the 11-year solar activity. We now know that the anti-correlation was unfavorable according to the later experiments, however this had caused some confusion.

The Chlorine experiment was the only solar neutrino experiment for about 20 years until the late '80s when the second solar neutrino experiment, Kamiokande-II, would give a new result. The Homestake results were persistent during the long periods, as shown in Fig. 2. The average capture rate during the 25 years was 2.56 ± 0.16(stat.) ± 0.16(syst.) SNU. Since the counting rate was very small, the experiment was limited by the statistics. After the 25-year observation, it reached a 6% statistical error, which is just comparable to the systematic effects from the uncertainties of the extraction efficiency, counting efficiency and non-solar $^{37}$Ar background. More than ~20 years after the initial indication of the deficit and in light of the

![Fig. 2. Observed solar neutrino flux in the Homestake Chlorine experiment after introducing the pulse rise time restriction in 1970, from Reference 90. The averaged value for 25 years is shown at the right.](image-url)
results from new experiments, the possible explanations of the problem were gradually converging on the neutrino properties.

5.2. Real-time and directional measurement — Kamiokande-II. The second solar neutrino experiment was Kamiokande-II, located underground, 2,700 m w.e. in the Kamioka mine, Japan. Kamiokande-II is an imaging water Cherenkov detector having a cylindrical shape, and containing 2,140 tons of purified water as the inner detector viewed by 948 50-cm diameter photomultiplier tubes (PMTs) providing 20% photo-cathode coverage. Surrounding the inner water tank is the outer detector, providing 4π coverage with a water layer ≥1.4 m viewed by 123 50-cm diameter PMTs. The outer detector identifies the outgoing and incoming events and the cosmic-ray muons, and reduces γ-rays from the surrounding rocks. The detailed characteristics of the water Cherenkov detector will be described later in the Super-Kamiokande section. Here, we give only very brief notes on the detector.

The ν + e scatterings are utilized and the Cherenkov light from the recoil electrons are observed. Kamiokande-II is a real-time detector, which is able to obtain directional information concerning the incoming low-energy neutrinos, due to the nature of ν + e scatterings and the characteristics of the Cherenkov light emission.

Kamiokande-II has presented the first real-time solar 8B-neutrino measurements and has demonstrated that those neutrinos are coming from the direction of the Sun. Kamiokande-II has also shown the recoil electron energy distributions down to its energy threshold, which was 9.3 MeV at the beginning of the experiments and reached 7 MeV during the course of the experiment. The electron energy resolution at 10 MeV is 22%. The energy calibration was made by using 1) γ-rays up to ~9 MeV from Ni(n, γ)Ni sources immersed in the water, 2) electrons from μ decay and 3) electrons from spallation products. The first results from Kamiokande-II were presented in 1989. 20 years since publication of the first pilot-run result of the Homestake Chlorine experiment. Kamiokande-II observed 0.46 ± 0.13(stat.) ± 0.08(syst.) of that of the solar model prediction from the 450 days of data taken from January, 1987 to May, 1988. The deficit of the solar neutrinos was confirmed by the real-time and directional measurements. The angular distribution (cos θsun) of the final sample is shown in Fig. 3. The peak towards the Sun is prominent above the almost flat background.

They also made a first measurement of the energy spectrum. The energy distribution is consistent with that of the 8B solar neutrinos, although the absolute rate is about ~1/2 of that expected. This is the first clear demonstration that we are really detecting 8B-neutrinos from the Sun. Since we realized that only the pp-chain could produce high-energy neutrinos, like 8B-neutrinos, the directional Kamiokande-II energy measurement was the first direct proof for the existence of the pp-chain in the Sun.

It was commonly understood that the deficit of solar neutrinos was not entirely an experimental problem, thereby further studies on the validity of the flux calculation and on the unknown neutrino properties were expected.

5.3. Gallium experiments — Problem matured. The first idea of Gallium experiments was proposed by Kuz’min in 1965. The Gallium experiments use 71Ga as a target material for detecting solar neutrinos through the inverse β decay of νe + 71Ga → e− + 71Ge, which are also radio-chemical experiments, like the Chlorine experiment, and therefore count the number of neutrino interactions above an energy threshold of 233 keV. Therefore, the low-energy solar pp- and 8B-neutrinos can be measured. The solar models predicted the individual shares of the “capture rates” of ~55% for pp-neutrinos, ~25% for 8B-neutrinos and ~10% for 8B-neutrinos, respectively. There is a strong constraint on the amount of pp-neutrinos from the solar luminosity, with the belief that the capture rate prediction on the pp-neutrinos is very solid and the uncertainty is only 1–2%. Note, however, that the pp-neutrino capture-rate by the Gallium experiments is only 55% of the total rate.
The absorption cross section of $^{71}$Ga is large, and has log $f_t \sim 4.3$, even for ground-state to ground-state transitions. The transitions to the excited states of $^{71}$Ge may be important for higher energy neutrinos.

The produced nucleus, $^{71}$Ge, has a half life of $\tau_{1/2} = 11.4$ days. The length of the half life is convenient for the chemical extraction accommodating the efficient extraction of about several days. The released energy by the K-capture of $^{71}$Ge is 12 keV, while that of $^{37}$Ar is 2.8 keV, providing better background rejection. The natural abundance is $\sim 40\%$, compared to $\sim 25\%$ of $^{35}$Cl.

SAGE (Soviet American Gallium Experiment) was one of the two initial Gallium experiments, which was situated at the Baksan Underground Neutrino Observatory, having 4,700 m water equivalent, in Russia. SAGE used 30 tons of metallic gallium in four teflon-lined chemical reactors, and kept 7 tons each. The extraction efficiency of the produced $^{71}$Ge through the bubbling was typically $80 \pm 6\%$ and the counting efficiency was $\sim 95\%$, which was estimated by the 7.5 ton pilot-system by adding a known germanium carrier. The initial results were obtained from 5 extractions from January to July, 1990. Before starting the solar neutrino measurement, the impurity of $^{68}$Ge produced by the cosmic rays while on the surface, was removed by bubbling. The backgrounds were kept sufficiently low. SAGE obtained the first solar neutrino result from five extractions in 1990. The observed $^{71}$Ga capture rate was

$$\text{Rate}(^{71}\text{Ga}) = 20^{+15}_{-20} \text{(stat.)} \pm 32 \text{(syst.) SNU}$$

Here, $20$ SNU denotes that 2.6 atoms were observed. The expected production rate was $1.2 \times ^{71}$Ge atoms/day for 30 tons of gallium, corresponding to 17.0 total expected atoms for the current exposure.

This result was consistent to be a null result, which was somewhat of a surprise for the community at that time. Their later results showed a higher value consistent with the other Gallium experiment. The recent data reported after 17 years of running from January, 1990, to December, 2007, with 168 extractions shows $65^{+11}_{-10} \text{(stat.)}^{+2.6}_{-2.8} \text{SNU}.$

In 1992, the GALLEX experiment, another Gallium experiment at the Gran Sasso underground laboratory, 3,300 m water equivalent, in Italy, showed their first measurement of the solar neutrino flux, which was about 63% of the predicted capture rate. GALLEX uses 30.3 tons of gallium (12 tons of $^{71}$Ga) in the form of $\sim 100$ tons of a GaCl$_3$ solution. GALLEX was expected to observe 1.18 atoms/day, namely 14 atoms of $^{71}$Ge present in the target solution after 3 weeks of exposure. The volatility of GeCl$_3$ in the non-volatile GaCl$_3$ makes it possible to extract GeCl$_4$ by bubbling. The extraction efficiency was estimated to be $>99\%$. The GALLEX initial results came from 14 runs during the period of May 14, 1991 to March 31, 1992 for a total of 295 days of exposure. The obtained result was $83 \pm 19 \text{(stat.)} \pm 8 \text{(syst.) SNU}. This was the first positive observation of low-energy primary solar neutrinos. GALLEX was completed on June 17, 1997 as GALLEX IV, and the final results obtained was $77.5 \pm 6.2 \text{(stat.)}^{+4.3}_{-4.5} \text{(syst.) SNU}.$

The two Gallium experiments, SAGE and GALLEX, showed in the middle of the '90s that low-energy solar neutrinos exist, and that the total flux observed is $60–80$ SNU, which is about $\sim 50–60\%$ of the SSM prediction.

We should be concerned about a few facts. The expected capture rate of $55\%$ from pp-neutrino ($\sim 70$ SNU) has very small uncertainties, due to the luminosity constraint. There is also a so-called minimum solar model that calculates the capture rates by activating only the pp-I chain, stopping the pp-II and pp-III chains, resulting in $\sim 80$ SNU for pp-neutrinos. The observed flux of SAGE and GALLEX is consistent with the pp-neutrino fraction of the SSM, and also with the minimum solar model. Their results might suggest that there are no $^7$Be- and $^8$B-neutrinos; nevertheless, the results from the Chlorine and the Kamiokande experiments suggest that there are $^8$B-neutrinos, about $\sim 50\%$ of the prediction, $\sim 5$ SNU for the Gallium capture rates. But there is a further concern about the $^7$Be components. By considering the uncertainty of the experiments and the prediction, the Gallium results could not induce the conclusion that the solar neutrino deficits would definitely come from the neutrino properties.

The GALLEX experiment was upgraded in 1997 to GNO (Gallium Neutrino Observatory) in order to increase the statistics to check against the various predictions. In addition to that, they would provide basic pp-neutrino data over many years and to study the time variations, especially for the solar cycle. There were some experimental improvements towards GNO. The preamplifiers, pulse shape recordings and data acquisition system were re-designed and implemented. GNO started on May 20, 1998 and was completed on April 9, 2003. The result after a total of 58 exposures of GNO is $62.9^{+5.4}_{-5.3} \text{(stat.)} \pm$...
2.5 SNU. By combining with GALLEX, the final result of the Gallium experiment in Gran Sasso is $69.3 \pm 5.5$ SNU.\(^{97}\)

6. Situation of the solar neutrino problem before Super-Kamiokande

6.1. Possible solutions for the solar neutrino deficits. The results of the four solar neutrino experiments, revealing the deficits of the measured flux, are plotted together schematically in Fig. 4. Those shortfalls were persistent and gradually became stronger during the time of the Super-K construction in the early '90s.

Possible resolutions of the deficits were astrophysics problems, where the SSMs were not correct: under-evaluation of the experimental systematics; or the neutrino problems, namely the neutrino mass and oscillations.

Many astrophysical solutions were proposed to fill the gap between the predictions and the observations. The solar neutrino flux depends upon the opacity, the heavy element abundance and the nuclear cross sections that are extrapolated from the laboratory energy to the core temperature. Those factors were re-evaluated by changing the input parameters in the SSMs, while assuming that their uncertainties might be significantly underestimated. A reduction of the neutrino flux could be achieved directly by lowering the core temperature, and also by some particular non-standard solar models, including a WIMP assumption. However, the fact that the Kamiokande data is higher than the Homestake measurement cannot be explained by any possible changes in the astrophysical model\(^{98-100}\). Instead, particle physics solutions fit all of the data very well.

6.2. Particle physics solutions. The experimental data from the four solar neutrino experiments were fitted together while assuming neutrino oscillations. When we handle the propagation of neutrinos through the Sun, the MSW effect, the matter effect in the continuously varying density\(^{87}\) must be taken into account (see section 4 for details).

The four allowed regions in the $(\Delta m^2, \sin^2 2\theta)$-plane are shown partly in Fig. 5. They are called:

- the large mixing angle (LMA) solutions: $[\Delta m^2 = 8 \times 10^{-6} \sim 8 \times 10^{-5} \text{eV}^2, \sin^2 2\theta = 0.6\text{--}0.9]$,
- the small mixing angle (SMA) solutions: $[\Delta m^2 = 3 \times 10^{-6} \sim 1 \times 10^{-5} \text{eV}^2, \sin^2 2\theta = 3 \times 10^{-3} \sim 1 \times 10^{-2}]$,
- the low mass or low probability (LOW) solutions: $[\Delta m^2 = \sim 2 \times 10^{-7} \text{eV}^2, \sin^2 2\theta > 0.8]$, and
- the vacuum oscillation (VAC) solutions: $[\Delta m^2 = \sim 1 \times 10^{-10} \text{eV}^2, \sin^2 2\theta > 0.8]$.

The oscillation parameters in the brackets above show the range of the values in the early '90s.

We now know that LMA is the correct solution, and the best parameter values\(^{83}\) are $\Delta m^2 = 7.37 \times 10^{-5} \text{eV}^2$ and $\sin^2 2\theta = 0.835$. By putting the best parameters for the resonance condition, $\rho_c E(\text{MeV/cm}) \sim 250$ is obtained, so roughly speaking those neutrinos with energy above $\sim 2.5 \text{MeV}$ would pass through the resonance. The adiabatic condition would break down at very high energy well beyond the maximum solar neutrino energy. Therefore, the low-energy neutrinos like pp-, pep- and Be-neutrinos with energy below $\sim 2.5 \text{MeV}$ undergo vacuum oscillation, whereas the high-energy neutrinos above a few MeV undergo adiabatic conversions through the matter effect. In those energy regions that Super-K can cover, nearly uniform suppression is expected. Possible day/night flux differences in the higher energy regions are expected at a few % level.

The SMA solutions are beautiful in that the $\nu_e$'s produced in the core of the Sun may be fully converted to neutrinos other than $\nu_e$. Suppose that we take $\Delta m^2 = 5 \times 10^{-6} \text{eV}^2$ and $\sin^2 2\theta = 5 \times 10^{-3}$, the resonance condition becomes $\rho_c E(\text{MeV/cm}) \sim 33$, so those neutrinos above 0.33 MeV would pass through the resonance. The adiabatic condition is satisfied for neutrinos below $\sim 4 \text{MeV}$. Therefore, those neutrinos between $\sim 0.3$ and 4 MeV undergo adiabatic conversions and, furthermore, the small

![Fig. 4. (Color online) Results from the four solar neutrino experiments at the middle of the '90s. All of the experiments showed the solar neutrino flux deficits.](image-url)
mixing angle makes the full conversion of $\nu_e$ to non-$\nu_e$ neutrinos. For energy above 4 MeV, the adiabatic condition would be gradually breaking, and the level-crossing probability would increase. We thus expect less suppression in the higher energy region. For energy regions where Super-K may observe, we expect strong suppression of the energy spectrum at the low-energy side compared to the high energy.

The mechanism of the neutrino conversion of LOW is similar to LMA, but $\Delta m^2$ is two orders of magnitude smaller than LMA. Assuming $\Delta m^2 = 2 \times 10^{-7} \text{eV}^2$ and $\sin^2 2\theta > 0.8$ as typical parameters, then the critical energy would be $4 \times 10^{-3} \text{MeV}$, above which adiabatic conversions occur. The adiabatic conversions would be satisfied near to the end of the solar neutrino energy. Therefore, we expect uniform suppression above 1–10 keV. Some influence from the breakdown of adiabatic conversion may be seen towards the higher end of the spectrum. A large day/night flux difference in the low-energy region is expected. But the probability for the LOW solution to be the correct solution is very low, since there is a sizable conflict with the low-energy data.

The vacuum oscillation for $\Delta m^2 > 10^{-10} \text{eV}^2$ results in an averaged suppression of $1/2$. In order to reproduce the results of the experimental data that reveal energy dependent deficits, the oscillation wavelength needs to be “just so” matched to the distance between the Sun and Earth. We therefore expect seasonal variations and spectrum distortions.

As shown above, those solutions have different energy-dependent suppressions of the solar neutrino spectrum and different time-dependent phenomena, as shown in Fig. 6.

6.3. Model independent evidence. In the early ’90s, the solar neutrino deficits were presumed to be caused by neutrino oscillations. But the indication would depend mostly on flux calculations, and the oscillation parameters have not been uniquely determined. Evidence was not strong to make any conclusion concerning the oscillation.

As we showed in the previous subsection, the four solutions have distinctive characteristics. We expect spectrum distortions and time variations (day/night flux difference and seasonal variations) for some specific parameters. They are also independent of the absolute flux calculations.

Those distinct features, if observed, would provide definitive evidence for solar neutrino oscillation independent of the total flux calculation, and would single out the unique oscillation parameters.

Next generation experiments would be expected to accumulate sufficient statistics to explore those characteristics. A large and highly sensitive detector, like Super-K, would be needed and suitable for this task.

7. Super-Kamiokande

7.1. Detector. Super-Kamiokande (Super-K), a gigantic imaging water Cherenkov detector, is situated 1,000 m underground in the Kamioka mine, Gifu prefecture, Japan. It is schematically shown in Fig. 7. A horizontal tunnel leads to the experimental area by a 1.7 km drive, and thus the detector is accessible at anytime for service.

Super-K is a cylindrically shaped water tank of 42.2 m in height and 39.6 m in diameter, holding 50 thousand metric tons (kt) of water inside. The inner 32 kt, called the inner detector, is surrounded by
about 11,000 50-cm-diameter photomultiplier tubes (PMTs), covering about 40% of the inner detector surface by their photo-cathode. The fiducial mass used for physics studies is 22.5 kt, where the outer edge of this volume is located 2 m inside the PMT surface plane. The inner detector is surrounded by an outer detector (OD) of ~2 to 3 m thick water layers viewed by 1,885 PMTs of 20 cm diameter, which are utilized for shielding and identifying incoming background particles, like γ’s and neutrons.

Super-K was funded in 1991 as a five-year construction project, which happened just 4 years after the historical observation of a neutrino burst by Kamiokande-II from a supernova in our adjacent galaxy. In 1992 the IMB group joined Super-K, which had been working on the 8,000 ton water Cherenkov detector in the U.S. Therefore, Super-K became a truly international project. The excavation for the cavern was completed in June, 1994. The stainless-steel water tank was fabricated in the following year. The installation of the photomultiplier tubes (PMTs), the front-end electronics and the data-acquisition system took about 6 months. We started to fill the detector with water in January, 1996. The Super-K experiment started at 0:00 on April 1, 1996. The data-taking periods of Super-K are divided into five different phases. Each phase has a different detector configuration, with the characteristics given in Table 3.

After five years of continuous data taking, the initial phase, SK-I, was stopped in 2001 for the replacement of hundreds of electrically defected PMTs and for general detector maintenance. Regrettably, a tragic accident occurred resulting in the loss of 6,777 out of 11,146 PMTs, while filling the water after maintenance. It was caused by a chain reaction of implosions transmitted by shock waves contiguously being created by adjacent implosions. This
accident was presumed to have been initiated by an implosion of one of the PMTs at the bottom of the water tank. After the accident all of the debris was removed and the detector was thoroughly cleaned up. The remaining, safe PMTs were re-distributed in the detector. The total number of PMTs used in the detector after the accident was roughly half of those used in the initial phase. Super-K was restarted as SK-II at the end of the year 2002. This phase with smaller number of PMTs continued for about 3 years. The reduced number of PMTs resulted in a higher energy threshold and poor energy resolution for solar neutrino analysis. After three years of data taking with half of the original PMTs, SK-II stopped for full restoration work in November, 2005. The SK-III detector, equipped with all 11,129 inner PMTs, started to take data in July, 2006 with nearly the same configuration as of SK-I.

SK-III lasted for about two years, and was then switched to the SK-IV phase in September, 2008 without any dead time by changing to the new front-end electronics system (QBEE) from the old system (ATM). The SK-IV stopped in May, 2018 after about 10 years of continuous data taking. See Table 3 for details concerning the running phases of Super-K. The data taking of Super-K was resumed in February, 2019 after major repair work on the water tank. Super-K would now be aimed at observing anti-neutrinos through the inverse $\beta$-decay interactions of $\nu_e$ by adding gadolinium into the water (SK-Gd).

The front-end electronics used for SK-I, II, and III are called ATM (Analog and Timing Module).\(^{106}\) Those events that exceeded the threshold number of hit PMTs within 200 ns were recorded. Then the pulse height and the timing were digitized.

The new system, called QBEE (QTC-Based Electronics with Ethernet), has operated from the beginning of SK-IV. QBEE records all PMT hits, including the dark current, typically a few kHz for each PMT. This is the most prominent feature of the new electronics.

A software trigger was used to extract events from the recorded hit information. It provides a way to lower the threshold, and also to invent a sophisticated trigger. The width of the charge integration is 400 ns through a self-triggering scheme. Each channel has three different gains that provide the overall dynamic range of 0.2 to 2,500 pC, which is 5-times wider than the old ATM system. The energy and timing resolution for single photons is 10% and 0.3 ns, respectively, which is better than the intrinsic resolution of the PMTs. The energy threshold is 0.3 mV, corresponding to about 0.1 pC.

Super-K acquires a few new features with this new system. Neutrino bursts from nearby supernovae can be recorded, up to 6 million events for the first 10 seconds, without any loss. The detection efficiency for the $\mu \to e$ decays remains at about 100% for the first 1 µsec. Thus, the detection of a 2.2 MeV $\gamma$ after neutron capture becomes possible.

### 7.2. Cherenkov light and particle detection.

Low-energy solar neutrinos entering the water Cherenkov detector mostly interact with electrons. The electron neutrinos undergo both charged and neutral current interactions, whereas the oscillated $\nu_\mu$ and $\nu_e$ interact only through the neutral current. Practically, $\sigma(\nu_\mu,e)/\sigma(\nu_e,e) \simeq 0.15$. Details concerning the neutrino interactions are described in section 3.

Relativistic charged particles (electrons for solar $\nu$) emerging from neutrino interactions in water would emit Cherenkov light along their propagation directions. The opening angle of the Cherenkov light, $\cos \theta_c = 1/n\beta$, is 42° in water ($n = 1.33$) and the threshold momentum to produce Cherenkov photons is 0.569 MeV/c for electrons, 115.7 MeV/c for muons and 1.04 GeV/c for protons, respectively. The energy of the charged particles can be obtained from the total number of photons detected.

| Table 3. Running phases of Super-Kamiokande and total number of solar neutrino events accumulated |
|-----------------|-------------|-------------|-------------|-------------|-------------|
| Phase           |  SK-I\(^{102}\) |  SK-II\(^{103}\) |  SK-III\(^{104}\) |  SK-IV\(^{105}\) |  SK-Gd |
| Period          | 96-Apr      | 02-Dec      | 06-Jul      | 08-Sep      | 19-Feb      |
| ID PMT #        | 11,146(40%) | 5,182(19%)  | 11,129(40%) | 11,129(40%) | 11,129(40%) |
| Electronics     | ATM         | ATM         | ATM         | QBEE        | QBEE       |
| Trigger Hardware| Hardware     | Hardware     | Hardware     | Software     | Software    |
| Solar $\nu$     | 1,496 days  | 791 days    | 547.9 days  | 2,970.8 days| 57,844      |
| (# of events)   | 22,401      | 7,212.8     | 8,147.0     | 57,844      |     |

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The number of photons from the Cherenkov radiation per unit path length is

$$\frac{d^2N}{d\tau d\lambda} = \frac{2\pi\alpha Z^2}{\lambda^2} \left( 1 - \frac{1}{\alpha^2 \beta^2} \right) = \frac{2\pi\alpha Z^2 \sin^2 \theta}{\lambda^2}. \quad [29]$$

The ID (inner detector) of Super-K is surrounded by a very large PMT photon-sensitive area that amounts to 40\% of the total inner surface, except for the period of SK-II, 20\%. This detector configuration dispenses \~6 photo-electrons per MeV.

The threshold energy was initially 6 MeV, but soon decreased to 4.5 MeV in 1997, and was kept at 4.5 MeV until 2008, except for the period of SK-II (2002–2005). The energy threshold was determined mostly by the background level, especially radon (Rn) in water. Super-K researchers have made tremendous efforts to reduce the Rn background, and gradually achieved reaching a lower threshold. As of 2018, the detector was operated with a 3.0 MeV threshold, and the analysis threshold was 3.5 MeV. Although the new electronics record every pulse, the current energy threshold of 3.5 MeV (kinetic energy) is still limited by the background level. The event rate at this threshold is 1.7 kHz. After applying the software trigger, \~15 Hz of data are recorded.

Super-K can detect neutrinos with a wide range of the energy from 3 MeV to a few 100 GeV or more, covering the observable energy of 5 orders of magnitudes difference. The energy of the solar neutrinos, 3.5–15 MeV, is the lowest among other sources of neutrinos, namely neutrino bursts from supernovae (10–20 MeV), relic neutrinos from past supernovae (15–30 MeV), atmospheric neutrinos (100 MeV to a few 100 GeV), neutrinos from the annihilation of dark matter (a few 100 GeV) and so on. The energy resolution for the low-energy solar and supernova neutrinos is 14.2\% at 10 MeV.

The directions of the recoil electrons from the \( \nu_e + e \rightarrow \nu_e + e \) interaction are kinematically limited to within \( \theta_{\nu_e} < 2m_e/E \), that is \<18° for the solar neutrinos of 10 MeV. However, the angular resolution is affected by the multiple scattering of electrons in water. It is smeared to be \~26 deg for 10 MeV.

Super-K is a real-time experiment, which can determine the event time with an accuracy of nanosecond. The energy, the direction and the time of the recoil electrons are the essential quantities to accomplish leading-edge astronomy.

### 7.3. Detector performance and backgrounds.

Note that in addition to the regular calibration system using radioactive sources, an electron LINAC was arranged \textit{in situ} to inject electrons with known energy at various positions inside of the water tank. Those LINAC calibrations would provide good references for the energy, direction and vertex reconstructions. We have performed this LINAC calibration twice per every year.

The 5 MeV recoil electron events yield 30 PMT hits. The energy, direction and vertex were reconstructed by the Cherenkov hit pattern and the PMT timing information. The maximum likelihood method was used to obtain the results. The measured response by the LINAC data\textsuperscript{106} shows 16.2 ± 0.2\% and 28.4 ± 0.2\% for the energy and angular resolution at 8.67 MeV. The vertex resolution at the same energy is 85 ± 2 cm. The solar neutrino events at around a few MeV could be well reconstructed.

Studies of $^8$B-neutrinos are limited by background that would come from the spallation products emanating from preceding high-energy muons, the $\gamma$-rays from external origin and daughter nuclei of $^{222}$Rn contaminated in water. The spallation products and the $\gamma$-ray backgrounds need to be reduced by a software algorithm, and the sources of the Rn emanation must be eliminated.

We first applied cuts to reduce noise events. The isolated events with clean Cherenkov patterns of more than 20 µsec apart from time-adjacent events are basically selected.

Correlations to the preceding muons are important information concerning the spallation products that are produced along the tracks of muons. The higher are the energies of the muons moving up, the more are the spallation products produced. Making use of those correlations, 98\% of the spallation products were removed while keeping the signal with an efficiency of nearly 80\%.

Most of the $\gamma$-ray backgrounds would enter the detector from the surrounding rocks. The inner 22.5 kton of fiducial mass was used to reduce those incoming backgrounds. Furthermore, the incoming $\gamma$-rays were selectively removed by introducing an additional cut on the distance to the PMT wall along the backward event direction.

During the past 20 years of performance, the analysis algorithm has been improved, and the cut parameters for the spallation products and the $\gamma$-rays were updated, but their basic concepts remained unchanged, as outlined in our various papers concerning the respective analyses within the respective time periods\textsuperscript{102–105}.

When we explored the low-energy region further, additional cuts were needed to reduce the remaining
background events. Threshold levels as low as 3.5 MeV (K.E.) were achieved in the latest analysis, and further efforts to reduce the threshold are being made. The remaining background events are mostly the daughters of $^{222}\text{Rn}$, namely $^{214}\text{Bi}$, which gives a high-energy $\beta$-ray with an end-point energy of 3.6 MeV. Those events in the resolution tail mimic the solar neutrino interactions. The $\text{Rn}$ contamination could be reduced after many years of struggle, and the current contamination is less than 0.1 mBq/m$^2$.

8. Evidence of solar neutrino oscillation

Solar neutrino measurements by Super-K started in April, 1996, aiming not only to obtain a precise flux value, but also get compelling and definitive evidence of oscillation, independent of absolute flux calculations, like spectrum distortion, time variation of the flux and so on.\textsuperscript{[107]-[109]} The observed event rate of $\sim$15 events/day for SK-I was $\sim$50-times larger than that for Kamiokande-II. This was accomplished not only by the larger fiducial volume ($\times 33$), but also by its lower energy threshold. The number of solar neutrino events was extracted from the peak in the $\cos \theta_{\text{sun}}$ distribution, as shown in Fig. 8, with a precise evaluation of the background shape.

In 2001, more than four years after the start of the experiment, the Super-K Collaboration published two papers.\textsuperscript{[110],[111]} One of them showed the results of precise measurements of the $^8\text{B}$ solar neutrino flux, its spectrum and the time variations using 1,258 days of data,\textsuperscript{[110]} taken between May 31, 1996 and October 6, 2000. The analysis threshold was 4.5 MeV (kinetic energy), except for first 280 days in which the threshold was taken with 6.5 MeV. The solar neutrino flux was obtained by a likelihood fit of the signal and background shapes in the $\cos \theta_{\text{sun}}$ distribution for 19 energy intervals. The observed 18464 $\pm$ 204(stat.) $^{+544}_{-454}$ events inferred a $^8\text{B}$ flux of 2.32 $\pm$ 0.03(stat.) $^{+0.08}_{-0.07}$ (syst.) $\times 10^6 \text{cm}^{-2}\text{s}^{-1}$, assuming no neutrino oscillations. The ratio to the predicted value of the SSM was 45.1 $\pm$ 0.5(stat.) $^{+1.6}_{-1.4}$ (syst.)%.

The $^8\text{B}$-neutrinos originate from the transition to a broad excited state (width of $\sim$1.5 MeV at $E_x = 3\text{MeV}$) of $^8\text{Be}^*$ in the reaction of $^7\text{Be} \rightarrow ^8\text{Be}^* + e^+ + \nu_e$. Therefore, the $^8\text{B}$ energy spectrum is strongly affected by the $^8\text{Be}^* \alpha$ decay and interference with the higher energy states. The measured spectrum was compared to that obtained by Ortiz et al.,\textsuperscript{[112]} who observed experimentally the effect of $\alpha$ decay by a very sophisticated method with reduced systematic errors. The observed Super-K spectrum shape is consistent with the predicted one and no spectrum distortion was found.

The orbital eccentricity causes $\sim$7% of the annual variation of the flux. A hint of the neutrino oscillation may be obtained to find an additional annual variation on top of this eccentricity effect. A fit of the data to the expected variation due to the eccentricity gives a $\chi^2$/d.o.f. = 3.9/7, while the “flat” distribution gives $\chi^2$/d.o.f. = 8.1/7. No seasonal effect was found.

The solar neutrinos in the daytime reach the detector directly, but in the nighttime they need to traverse Earth before arriving. Those neutrinos passing through Earth may be affected by Earth’s matter effect. There may be a difference between the daytime and nighttime fluxes.

The measured daytime flux, $\Phi_d$, and the nighttime flux, $\Phi_n$ of Super-K were

\begin{align*}
\Phi_d^{SK} &= 2.28 \pm 0.04^{+0.09}_{-0.07} \times 10^6 \text{cm}^{-2}\text{s}^{-1}, \\
\Phi_n^{SK} &= 2.36 \pm 0.04^{+0.08}_{-0.07} \times 10^6 \text{cm}^{-2}\text{s}^{-1},
\end{align*}

and thus the asymmetry of the day/night fluxes was

\begin{align*}
A^{SK} &= \frac{(\Phi_n^{SK} - \Phi_d^{SK})}{(1/2)(\Phi_n^{SK} + \Phi_d^{SK})} \\
&= 0.033 \pm 0.022\text{(stat.)}^{+0.013}_{-0.012}\text{(syst.)}.
\end{align*}

Many systematic uncertainties in $A^{SK}$ cancelled out in the ratio, and the remaining ones were the energy scale and the energy resolutions, especially due to the up-down asymmetry of the response and the background shape. The result from 1,258 days of data showed 1.3$\sigma$ from zero asymmetry, which was statistically limited and not definitive.
As described above, the Super-K results from 1,258 days of data showed no energy spectrum distortion, no seasonal variations and a small day/night flux difference. We drew excluded regions in Fig. 9 only by using an observed energy spectrum shape, and the results of time variations without an absolute flux constraint, as shown in the second paper in 2001. The small mixing angle (SMA) solutions and vacuum oscillations (VAC) were rejected from the correct answer in Fig. 9. The Super-K results would indicate that the correct answer would be the large mixing angle (LMA) solutions as a consequence of eliminating other possible solutions. Note that LOW was already a low probability, due to a conflict with the Gallium data, and should be ignored.

LMA in general shows uniform and substantial spectrum suppression, but it must use an absolute flux calculation to provide evidence of oscillation. Needless to say, we found strong spectrum suppression.

A day/night flux difference is the only model-independent evidence for LMA. Super-K observed a small day/night effect (1.3σ), but was not significant statistically to demonstrate LMA as a correct solution. Note that 13 years later, Super-K obtained a ~3σ effect concerning the day/night flux difference. This was a strange situation at that time. Though Super-K rejected SMA and VAC without any absolute flux calculation, and indicated that the allowed parameters were consistent with LMA, the Super-K results alone were, however, not sufficient to conclude that LMA was the correct answer concerning the solar neutrino problem.

The solution came from a different direction. On June 18, 2001, on the same day when the 2 papers from Super-K, mentioned above, were published, SNO, the heavy-water (D$_2$O) Cherenkov detector, announced the first result of their measurement on the charged current interactions of $^8$Be, which was exclusively sensitive to $^8$Be's. SNO is an imaging heavy water Cherenkov detector using deuterons as target material located at the depth of 6,010 m w.e. Creighton mine near Sudbury, Ontario, Canada. The main detector part is a 12 m-diameter spherical acrylic vessel holding 1,000 metric tons of pure D$_2$O, which is viewed by 20 cm photomultiplier tubes with light concentrators. The surrounding barrel-shaped cavity with a maximum diameter of 22 m provides a shield of pure H$_2$O.

Data presented on June 18, 2001 were taken between November 2, 1999 and January 15, 2001 with 240.95 days of live time. The trigger threshold was 18 PMT hits and became 100% above 23 PMTs and the 9 PMT hits approximately equal to 1 MeV. After reductions of the noise and the backgrounds, the events were restricted to be $E > 6.75$ MeV and $R < 5.5$ m. The remaining 1,169 events were simultaneously fitted in terms of $E$, $\cos^3\theta$ and $(R/6)^3$.

The total 975.4 ± 39.7 charged current events observed corresponded to

$$\phi_{\text{SNO}}(\nu_e) = 1.75 \pm 0.07(\text{stat.})^{+0.12}_{-0.11}(\text{syst.}) \times 10^6 \text{ cm}^{-2}\text{s}^{-1}.$$  

The ratio resulting from the SSM was 0.347 ± 0.029.

A comparison of the $^8$B flux obtained from the elastic scattering (ES) interactions, assuming no neutrino oscillation to that from the charged current interactions, provides definitive evidence of solar...
neutrino oscillation. If flavor conversion occurs, the flux from the ES would be larger than that from the CC: \( \phi_{CC}(\nu_e) < \phi_{ES}(\nu_e) \).

The first evidence of solar neutrino oscillation was then obtained by comparing between the SNO charged current measurements and the high statistic Super-K electron scattering measurements:

\[
\phi_{ES}^{ES}(\nu) = 2.32 \pm 0.03^{+0.08}_{-0.07} \text{(stat.)} \times 10^6 \text{cm}^{-2}\text{s}^{-1}.
\]

The difference between ES and CC is

\[
0.57 \pm 0.17 \times 10^6 \text{cm}^{-2}\text{s}^{-1}, \quad \text{or 3.3}\sigma.
\]

This result demonstrated that there are non-electron neutrino components in the solar neutrinos observed on Earth. This is the first definitive evidence without relying on a flux calculation, as shown in Fig. 10. This figure shows solar neutrino oscillations, changing to other neutrinos while traveling from the Sun to Earth. From observations of SNO and Super-K, the total flux of the active \( ^8\text{B} \)-neutrinos was also determined to be

\[
\phi^{^8\text{B}} = 5.44 \pm 0.99 \times 10^6 \text{cm}^{-2}\text{s}^{-1}.
\]

It is quite interesting that evidence of the solar neutrino oscillation was achieved by studying the tail corresponding to only 1/10,000 of the total solar neutrino flux.

9. Current situation and future

A total of 95,608 Super-K solar neutrino events were accumulated from 5,801 effective days of data between May, 1996 and May, 2018 (SK-I(1,496 days), SK-II(791 days), SK-III(548 days), SK-IV(2,971 days)).

Since the first evidence of solar neutrino oscillations was obtained, Super-K researchers have improved the quality of the detector and reduced the total backgrounds. The front-end electronics modules were upgraded. A software trigger and new analysis algorithm were introduced. The water system dynamics was modified so as to reduce the Rn background. The energy threshold has varied as a function of time, depending on the detector configuration and conditions, but finally reached to 3.5 MeV. The transition from vacuum oscillation to adiabatic conversion could be seen in a study of low-energy solar neutrinos.

In 2002, one year after the initial evidence, SNO had directly observed a total flux of active \(^8\text{B} \) solar neutrinos based on their neutral current (NC) measurements, which further confirmed the solar neutrino oscillations in the ratio of CC/NC. The detection of the NC was conducted by employing three different techniques: the detection of 6.25 MeV \( \gamma \)-rays from neutron capture on deuterons; multiple \( \gamma \)-rays from the capture on chlorine of NaCl dissolved in heavy water; and independent detection by \(^3\text{He} \) proportional counters immersed in the detector. The observed \(^8\text{B} \) flux and the uncertainties are

\[
\begin{align*}
5.09^{+0.44}_{-0.43} \text{(stat.)} & \times 10^6 \text{cm}^{-2}\text{s}^{-1} \\
(\text{Deuteron}); \\
4.94^{+0.21}_{-0.23} \text{(stat.)} & \times 10^6 \text{cm}^{-2}\text{s}^{-1} \\
(\text{Chlorine}); \\
5.54^{+0.33}_{-0.32} \text{(stat.)} & \times 10^6 \text{cm}^{-2}\text{s}^{-1} \\
(\text{Neutron Counter}).
\end{align*}
\]

The combined \(^8\text{B} \) flux is 5.25 ± 0.20 × 10^6 cm^{-2}s^{-1}, consistent with standard solar model (SSM) calculations; the uncertainty is 3.5%. SNO was completed in 2006. We use this measured value for the \(^8\text{B} \) flux instead of that from SSMs for global oscillation analyses.

9.1. Oscillation parameters. The high-statistics data from Super-K along with other solar neutrino experiments yielded precise oscillation parameters. A global fit of the latest data from all of the solar neutrino experiments (Super-K, SNO, Chlorine, GALLEX, and SAGE) results in the current best value: \( \sin^2 \theta_{12} = 0.308 \pm 0.014 \) and \( \Delta m^2_{12} = (4.85^{+1.33}_{-0.59}) \text{eV}^2 \), constrained by \( \sin^2 \theta_{13} = \)
0.0219 ± 0.0014, the world-best value, as shown in Fig. 11.

One apparent discrepancy seen in Fig. 11 is that the best-fit parameter based on global analysis using all of the solar neutrino experiments deviates from the value indicated from the KamLAND experiment: \( \sin^2 \theta_{12} = 0.316_{-0.034}^{+0.034} \pm 0.014 \) (syst.) and \( \Delta m_{12}^2 = (7.54_{-0.18}^{+0.18}) \times 10^{-5} \text{eV}^2 \). The significance of the difference in mass square is a little less than 2\( \sigma \), which is not large, but has been persistent for many years.

KamLAND is a long-baseline reactor anti-neutrino experiment located in the Kamioka mine, which uses 1,000 tons of liquid scintillator (LS) in a spherical balloon made of transparent nylon/EVOH composite film placed in a 18 m-diameter spherical stainless-steel container, which shields the LS from external radiation by mineral oil. KamLAND detects low-energy region (pp- and \( ^7 \text{Be} \)-neutrinos), but \( ^9 \text{Be} \) neutrinos is a background. The total photo cathode coverage of a 1,879 PMTs. The typical distance to a few powerful power plants to provide neutrinos is ~180 km, and therefore KamLAND can address the solar LMA solutions with the reactor anti-neutrinos, assuming CPT invariance. The solar neutrino oscillation is a vacuum oscillation in the low-energy region (pp- and \( ^7 \text{Be} \)-neutrinos), but affected by matter in the high-energy region (\( ^8 \text{B} \)-neutrinos), whereas KamLAND sees basically vacuum oscillations of anti-neutrinos. The small discrepancy between the solar neutrino results and the KamLAND results needs to be settled in the near future.

**9.2. Upturn in the low-energy spectrum.** For a large mixing angle solution, the low-energy neutrinos below 1 MeV undergo vacuum oscillation; the survival probability is about ~70%. But for the higher energy neutrinos above a few MeV, the survival probability becomes ~30% due to the adiabatic conversion. Going from the high-energy side to the low-energy side, we would expect an upturn of the survival probability. The transition shape, if observed, is sensitive to \( \Delta m^2_{12} \), and provides another way to determine the oscillation parameters. If a quite different transition shape would be observed from what is expected, then that might indicate a new physics, which is not explained by the standard model of elementary particle physics.

There are no experiments that cover the entire transition region. But Super-K with a very low-energy threshold might explore this region. The lowest energy threshold achieved by Super-K is 3.5 MeV, and Super-K has not observed any upturn yet, as shown in Fig. 12. It is thus quite desirable that Super-K continuously makes efforts to lower the energy threshold so as to examine this effect. The continuous operation of Super-K might find some answers in the future.

**9.3. Day/night flux difference.** The observation of the day/night flux difference directly demonstrates the matter effect, which also gives another way to determine the oscillation parameters independent of the total flux calculations. A precise measurement of the zenith angle distribution might hint at new phenomena.

The day/night asymmetry expected at the Super-K site is about 2–3%, and is mostly in the high-energy region. Precise measurements of the solar day/night effect were made using full SK-I, II and III data and 1,306 days of data from SK-IV covering from May, 1996 until December, 2017, as shown in Fig. 13. The ratios of the flux difference and the flux sum yields \( A_{SK} = (0.033 \pm 0.010 \text{(stat.)} \pm 0.005 \text{(syst.)}) \% \), which is 2.9\( \sigma \) evidence of a day/night flux difference from the Super-K combined fit. The uncertainty is still statistics dominated, and we need further improvements. The systematic uncertainties of the flux were 3.2%, 2.1% and 1.7% for SK-I, SK-III and SK-IV, respectively. Most of the systematic uncertainties are cancelled by taking the flux ratios. Super-K confirmed a matter effect, but obviously needs more data. We also note that those parameters determined solely by the solar day/night effect are consistent with the solar neutrino global solution without the day/night effect.

Therefore, further study of the day/night flux difference is necessary. The results are still statistics dominant, and the size of the Super-K detector is a limiting factor.

The planned 256 kton water Cherenkov detector, Hyper-Kamiokande with an 8-times bigger fiducial mass than Super-K, would be expected. The solar day/night effect is larger in the high-energy region above 8–9 MeV. We expect to measure it with 5–6\( \sigma \) sensitivity, though Hyper-K would have a higher-energy threshold than Super-K. It would take 8 years to construct and would be expected to start in 2028, and should provide many important results, not only concerning the day/night effect, but also concerning neutrino CP violation, supernova neutrinos, proton decay and so on.
The first theoretical prediction was made in the late '30s that a series of nuclear reactions take place to produce the necessary energy from the Sun. About 40 year later in the early '70s, the first solar neutrino experiment detected neutrinos from the Sun and suddenly uncovered the missing solar neutrino problem.

The cause of the problem was recognized as a consequence of neutrino oscillations in the early 2000s. But there was a long and winding road to reach a solution to the solar neutrino problem. Tremendous efforts have been made not only on experiments, but also on theories concerning oscillation phenomena as well as solar neutrino flux calculations. Those efforts had gradually been integrated towards future discovery. The initial evidence was accomplished by Super-Kamiokande and SNO; nevertheless, the results from all of the solar neutrino experiments and precise flux calculations were needed to determine the oscillation parameters. The flux independent results obtained by the Super-Kamiokande experiment especially played an important role to select the correct parameter region.

Research on neutrino oscillation in the future should determine the parameters more precisely, and hopefully bring a conclusion as to whether or not CP is violated. We all hope this research will continue to produce fruitful results. Neutrino oscillation will hopefully be a clue to some new physics beyond the standard model.

I am very delighted to have had an opportunity in my research career to be a witness to studies
towards big discovery: neutrino oscillations. To solve the solar neutrino problem was something like solving a jigsaw puzzle.

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Profile

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