Results from massive underground detectors on solar and atmospheric neutrino studies and proton decay searches

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Abstract. Massive underground detectors have been playing important roles in particle and astro-particle physics. Results from massive underground detectors on solar and atmospheric neutrino studies and proton decay searches are reviewed.

1. Introduction
Massive underground detectors have long history. In the mid. 1960’s, a solar neutrino experiment was proposed to study the interior of the Sun [1], [2]. The proposed detector was constructed at 4400 m.w.e. underground in the Homestake gold mine in the late 1960’s. It might be fair to mention that this detector was the first massive underground detector, since the total mass of the target material (C\textsubscript{2}Cl\textsubscript{4}) was approximately 600 tons. This detector observed solar neutrinos for the first time confirming that the energy generation in the Sun is due to nuclear fusion reactions. However, the observed flux [3] by this detector was approximately 1/3 of the predicted flux by the standard solar model (SSM). This problem was called the ”solar neutrino problem”. Because the information available by this detector was the event rate only, various massive underground detectors were required to understand the cause of the problem.

In the 1970’s, the idea of Grand Unified Theories emerged [4], [5]. These theories predicted nucleon decays with a typical lifetime of 10\textsuperscript{30} years. If the nucleon lifetime is 10\textsuperscript{30} years, it is possible to observe many proton and bound neutron decays with a massive underground detector. In the early 1980’s, several underground detectors with the masses ranging 100 tons to several ktons were constructed to discover nucleon decays. These experiment did not discover nucleon decays. However, some of these detectors observed neutrinos from a supernova SN1987A [6], [7], discovered the atmospheric \(\nu_\mu\) deficit [8], and confirmed the solar neutrino problem [9]. These results required more studies with the next generation massive underground detectors.

In the following sections, recent results from massive underground detectors on solar and atmospheric neutrino studies and proton decay searches are discussed.

2. Solar neutrino experiments
In 1989, Kamiokande observed the \(^8B\) solar neutrino flux by neutrino electron scattering, \(\nu_e \rightarrow \nu_e\) [9]. This experiment confirmed that neutrinos are coming from the Sun and that
the solar neutrino flux was significantly lower than the standard solar model (SSM) prediction. Subsequently, solar neutrino experiments that used 30 to 60 tons of Gallium were carried out [10], [11]. These experiments were unique in the sense that about half of the calculated event rate was due to fundamental pp solar neutrino reactions. These low energy solar neutrino experiments also observed that the solar neutrino flux was lower than the SSM prediction. Although the solar neutrino deficit was clearly observed in these experiments, the cause of the deficit was not firmly identified, partly because no experiment observed the $\nu_e$ and ($\nu_\mu + \nu_\tau$) fluxes separately. MSW mechanism [12], [13] was a serious possibility, but was not uniquely identified as the solution to this problem.

The situation changed drastically in 2001 and 2002. In 2001, the SNO experiment, which used 1 kton of heavy water ($D_2O$) measured the $^8B$ solar neutrinos by $\nu_e + D \rightarrow e^- + p + p$ (CC) [14], i.e., by charged-current $\nu_e$ interactions. In the mean time, Super-Kamiokande (Super-K) measured the $^8B$ neutrino flux precisely by neutrino-electron scattering [15]. By comparing these results, it was found that the flux measured by Super-K (assuming all the neutrinos are electron-neutrinos) was $3.3 \sigma$ higher than that measured by SNO [14]. This discrepancy was concluded as evidence for solar neutrino oscillations, since $\nu_\mu$'s and $\nu_\tau$'s generated by neutrino oscillations contribute only to the neutrino-electron scattering.

In 2002, the evidence was substantially strengthened by the measurement of the total ($= \nu_e + \nu_\mu + \nu_\tau$) neutrino flux in SNO. The total flux was observed by $\nu_x + D \rightarrow \nu_x + p + n$ (NC) [16]. The observed total flux was consistent with the SSM prediction, confirming the solar neutrino oscillation at the 5.5 standard deviation level [16]. Since the CC/NC ratio is approximately equal to $\sin^2 \theta_{12}$ in the LMA region, the measured solar neutrino fluxes strongly constrain $\sin^2 \theta_{12}$.

Furthermore, a long-baseline reactor neutrino experiment, KamLAND, has been contributing to $\nu_e \rightarrow \nu_x$ oscillation studies. KamLAND is a 1 kton liquid scintillator detector located 2700 m.w.e. deep underground in the Kamioka mine. KamLAND observes reactor anti-electron neutrinos by $\nu_e p \rightarrow e^+ n$. See Figure 1 for the latest results from KamLAND [17]. The observed spectrum distortion is regarded as very strong evidence for ”oscillations”. The mean flight length of the neutrinos detected by KamLAND is 180 km. The observed spectrum distortion together with the known flight length makes it possible to estimate the $\Delta m^2_{12}$ parameter precisely. Combining the solar and KamLAND data, the 1-2 (i.e., solar) oscillation parameters have been measured accurately.

With the increasing accuracy of the solar and KamLAND data, it was pointed out that there might be slight tension in the suggested $\sin^2 \theta_{12}$ value by the solar and KamLAND experiments [18], [19]. The suggested $\sin^2 \theta_{12}$ value from KamLAND was larger than that from solar neutrino experiments. It was also pointed out that the tension can be reduced if $\sin^2 \theta_{13}$ is non-zero [18], [19]. Due to this reason, updated data with a higher precision have been waited for.

In 2009, the SNO experiment published a low-energy analysis of the SNO-I and -II data [20]. With a better understanding of various background and signal distributions, it was made possible to estimate the total neutrino flux accurately by the NC events. The accuracy of the total flux has been improved by more than a factor of 2. It should also be noted that the total $^8B$ solar neutrino flux was measured to an accuracy of approximately 4%, which was a factor of 4 smaller than the estimated uncertainty by the SSM calculation.

As mentioned above, the accurately measured total neutrino flux improves our understanding of the $\theta_{12}$ parameter. The improved allowed region with the most updated solar neutrino data compared with the previous one is depicted in Ref. [21].

Figure 2 shows the estimated oscillation parameters with the updated solar neutrino and the KamLAND data. Since the central value of the measured total $^8B$ solar neutrino flux have not changed much with the 2009 SNO analysis, and since the uncertainty in $\sin^2 \theta_{12}$ by the KamLAND experiment was larger than that by the solar neutrino experiments, the tension, and
therefore the implication for non-zero $\theta_{13}$, has not changed much [20].

![Figure 1](image1.png)

**Figure 1.** Ratio of the background subtracted reactor $\nu_e$ spectrum to the no-oscillation expectation as a function of $L_0/E$. 2881 ton-year of the KamLAND data are used. $L_0 = 180$ km is assumed. (From Ref. [17].)

![Figure 2](image2.png)

**Figure 2.** Left panel: Allowed regions of 12-oscillation parameters by solar neutrino and the KamLAND experiments. Right panel: Allowed $\tan^2 \theta_{12}$ vs. $\sin^2 \theta_{13}$ regions by the solar neutrinos experiments only, KamLAND only, and solar plus KamLAND experiments. (From Ref. [20].)

3. Atmospheric neutrino experiments

Atmospheric neutrino experiments played a fundamental role in the discovery of neutrino oscillations [8], [22], [23], [24], [25], [26]. As of this writing, the statistics of the atmospheric
neutrino events are dominated by the data from Super-K. Therefore, we discuss the atmospheric neutrino results from Super-K.

Super-K have several phases. As of this writing, data up to Super-K-III have been used for the final physics analysis. The total exposure of the detector for fully-contained atmospheric neutrino analysis is 173 kton·yr. In the Super-K data, zenith-angle and energy dependent deficit of $\nu_\mu$ charged current (CC) events has been observed. See Fig. 3 (left), which shows the zenith angle distributions for some sub-samples from Super-K. By fitting the zenith angle distributions [27], the oscillation parameters are accurately measured.

![Figure 3. Left: Zenith angle distributions observed in Super-K-I+II+III (173 kton-year exposure). Top panels show fully-contained (FC) sub-GeV $e$-like (left) and $\mu$-like (right) events. The bottom panels show FC multi-GeV $e$-like (left) and FC multi-GeV $\mu$-like plus partially-contained events (right). Sub- and multi-GeV are defined to be less and more than 1.33 GeV visible energy, respectively. The blue histograms show the prediction without oscillations. The red histograms show the best fit $\nu_\mu \rightarrow \nu_\tau$ expectation. Right: $L/E$ distribution observed in Super-K-I+II+III. The red, blue and green histograms show the best-fit predictions based on neutrino oscillation, decay and decoherence models, respectively.](image)

Although, the Super-K zenith angle data were explained well by oscillations, the sinusoidal oscillation pattern was not seen in the left panel of Fig. 3 due to the smearing. Therefore, Super-K carried out a dedicated $L/E$ analysis using only high $L/E$ resolution events [28]. Figure 3 (right) shows the $L/E$ distribution from Super-K-I+II+III. The $L/E$ distribution shows a dip around $L/E = 500$ km/GeV that corresponds to the first oscillation minimum. The distribution is used to compare the oscillation and other hypotheses, and to constrain the other hypotheses. Due to the observation of the dip, the allowed region of the oscillation parameters, especially that of $\Delta m^2_{23}$, is strongly constrained.

Figure 4 shows the estimated allowed regions of 2-flavor $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters from the atmospheric neutrino and long baseline neutrino oscillation experiments. We find that the allowed regions overlap well, suggesting further that the standard neutrino oscillation scenario is valid. From this figure, we find that $\Delta m^2_{23}$ is most accurately measured by the MINOS
Figure 4. Estimated allowed regions of $\nu_\mu \rightarrow \nu_\tau$ oscillation parameters from atmospheric neutrino and long baseline neutrino oscillation experiments at 68% C.L. (dotted) and 90% C.L. (solid).

The neutrino flight length extends up to 12800 km in atmospheric neutrino experiments. The oscillation length relevant to $\Delta m^2_{12}$ is shorter than the diameter of the earth for $E_\nu$ below 1 GeV. Therefore the effects due to the solar oscillation terms can be observable in atmospheric neutrino experiments. It has been pointed out that these terms play a unique role in atmospheric neutrino oscillations, such as the possible measurement of $\sin^2 \theta_{23}$, (i.e., the discrimination of the octant of $\theta_{23}$) [30]. For simplicity, we assume that $\theta_{13} = 0$. The change in the atmospheric $\nu_e$ flux due to oscillations driven by the solar oscillation terms is written as [30]:

$$\frac{F_{\nu e}^{osc}}{F_{\nu e}^0} - 1 = P_2(r \cos^2 \theta_{23} - 1),$$

where $F_{\nu e}^{osc}$ and $F_{\nu e}^0$ are the atmospheric $\nu_e$ fluxes with and without oscillations, $r(\equiv F_{\nu \mu}^0 / F_{\nu e}^0)$ is the ratio of the un-oscillated atmospheric $\nu_\mu$ and $\nu_e$ fluxes, and $P_2$ is the two neutrino transition probability ($\nu_e \rightarrow \nu_x$) in matter driven by the solar oscillation terms. $P_2$ is large for neutrinos passing through the earth with the energies below 1 GeV. Thus the sub-GeV atmospheric neutrinos play an important role in observing the solar term effect. Since the $\nu_\mu$ and $\nu_e$ flux ratio ($r$) is approximately 2 in the sub-GeV neutrino energy region, the $F_{\nu e}^{osc} / F_{\nu e}^0$ value in Eq.1 is very close to 1 in the case of the maximal 2-3 mixing (i.e., $\theta_{23} = 45^\circ$). However, according to Eq.1, if $\theta_{23}$ is in the first (second) octant ($\theta_{23} < 45^\circ$ ($> 45^\circ$)), an excess (deficit) of the sub-GeV $e$-like events is expected.

Figure 5 shows the $\chi^2$ distribution as a function of $\sin^2 \theta_{23}$ obtained by the Super-K experiment from an oscillation analysis that includes the solar oscillation terms [31]. With the present data, there is no indication for the deviation from $\sin^2 \theta_{23} = 0.5$ even if the solar terms are taken into account.
Figure 5. The $\chi^2 - \chi^2_{\text{min}}$ distributions as a function of $\sin^2 \theta_{23}$ for oscillations without the solar terms (dashed line) and with the solar terms (solid line) by the atmospheric neutrino data from the Super-Kamiokande experiment (173 kton·yr exposure) [31]. $\theta_{13} = 0$ is assumed.

4. Nucleon decay searches

An unambiguous discovery of nucleon decays would have a profound impact to particle physics, since the discovery implies that the electromagnetic, weak and strong forces are unified at a very high energy scale. Therefore dedicated experiments started to search for nucleon decays around 1980 [32], [33], [34], [35], [36] several years after the proposal for the Grand Unified Theories [4], [5]. Due to the importance, the searches for nucleon decays are still continuing. Since the exposure is dominated by the Super-K experiment, the latest results from Super-K are discussed in this section.

4.1. $p \rightarrow e^+ \pi^0$ search

The final state for this decay channel is simple; 3 electromagnetic showers. 2 of them are due to $\pi^0$ decay into 2 gamma rays. The total invariant mass should be consistent with the proton mass, and the total momentum within the Fermi momentum. The produced $\pi^0$ in the oxygen nucleus may interact within the same nucleus, and therefore the detection efficiency is reduced. Figure 6 shows the total invariant mass versus total momentum plots for the data, atmospheric neutrino Monte Carlo, and proton decay Monte Carlo. The data are consistent with the atmospheric neutrino prediction. There has been no candidate event in the signal box. The 90% C.L. lower limit on the lifetime of proton for this decay mode is $1.01 \times 10^{34}$ years. (See Ref. [37] for details of the data analysis with a slightly smaller data sample.)

4.2. $p \rightarrow \pi K^+$ search

This decay mode is not trivial to search for in water Cherenkov detectors, since $K^+$ is invisible in these detectors. Therefore, several methods have been developed to identify low-energy $K^+$ decays, which would imply proton decays into $\pi K^+$. One method ("prompt $\gamma$ search") searches for a 6 MeV de-excitation gamma ray accompanied with a delayed muon of 236 MeV/c from a stopped $K^+$ decay [38]. These signals are expected for proton decays occurring in oxygen nuclei. The gamma rays can be emitted by the excited,
residual nuclei ($^{15}\text{N}^*$). Another method searches for a $\pi^+ + \pi^0$ signal ("$\pi^+ + \pi^0$ search") from a stopped $K^+$. The third method simply searches for a single muon with the momentum consistent with 236 MeV/c. These 3 methods have been used to search for proton decays in Super-K. Table 1 shows the results for the first 2 methods. There has been no candidate event for these 2 methods. In addition, there has been no excess of muon events in the muon momentum distribution around 236 MeV/c. The limit on the proton lifetime for this decay mode is $3.3 \times 10^{33}$ years at 90% C.L.. (See Ref. [39] for details of the data analysis with a slightly smaller data sample.)

5. Summary
Researches with massive underground detectors have almost half a century of history. These detectors have been contributing to particle and astro-particle physics substantially. The solar neutrino problem, which was discovered by the first generation massive underground detector,
Table 1. Search for \( p \rightarrow \pi K^+ \): Summary of the detection efficiency, background and candidate events for the prompt gamma and for the \( \pi^+ + \pi^0 \) searches for SK-I, II and III.

| Mode               | SK-I(92 kt·yr) | SK-II(49 kt·yr) | SK-III(32 kt·yr) |
|--------------------|----------------|-----------------|-----------------|
| Prompt \( \gamma \) search Efficiency(%) | 7.2            | 5.8             | 7.3             |
| Background         | 0.16           | 0.08            | 0.03            |
| Candidates        | 0              | 0               | 0               |
| \( \pi^+ \pi^0 \) search Efficiency(%) | 6.5            | 5.3             | 6.6             |
| Background         | 0.46           | 0.33            | 0.14            |
| Candidates        | 0              | 0               | 0               |

has been understood as due to \( \nu_e \rightarrow \nu_x \) oscillations. Recent solar and reactor long baseline experiments have measured the 1-2 oscillation parameters accurately. Atmospheric neutrino experiments of the previous generation discovered the atmospheric neutrino anomaly. They have also been understood to be due to \( \nu_\mu \rightarrow \nu_\tau \) oscillations. \( \sin^2 2\theta_{23} \) has been measured accurately by atmospheric neutrino experiments. Proton decay has been searched for seriously for almost 30 years. No evidence for proton decay has been found. The present 90% C.L. limits are \( 1.0 \times 10^{34} \) and \( 3.3 \times 10^{33} \) years for \( e^+\pi^0 \) and \( \pi K^+ \) decay modes (preliminary), respectively.

The achievements of the large underground detectors suggest that future massive underground detectors will further contribute to particle and astro-particle physics.

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