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# Neutrino Detectors: Present and Future

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**Abstract**

Detectors for neutrino intrinsic property measurements and neutrino oscillations are reviewed, with special emphasis on the future trends. Examples include semiconductor and microwave detectors for the absolute mass and magnetic moment of neutrinos, water Cherenkov, liquid Argon TPC, liquid scintillator and sampling detectors for neutrino oscillations. Technologies experienced significant progress in the past and major advances are planned for the future.



Keywords: Neutrino, Detector, Water Cherenkov, Liquid argon, Liquid scintillator, Sampling, Semiconductor, Microwave

## 1. Introduction

Neutrino detectors experienced significant advances in the past years, powered by the progress of the neutrino physics, in particular the discovery of neutrino oscillations. It is obvious that neutrinos are the least known elementary particle, the most peculiar one in particle physics, and probably the most important one in astrophysics and cosmology.

There are still quite a number of unknowns about neutrinos, such as the absolute mass, the magnetic moment, and oscillation properties. For more than 50 years, people tried different ways to study them, using various neutrino sources and different kind of detectors. Fig. 1 shows the current neutrino problems, the relevant neutrino sources, and the used detection technologies. This picture may not be comprehensive, but shows that many problems can be studies by different ways and one technology can be multi-purpose.

Clearly, this is a very active field and there are many experiments on going [1]. In this proceeding, I will try to cover some of them, with special emphases on detectors for neutrino oscillations and their future trends. I apologize for possible bias and not being able to cover everything.

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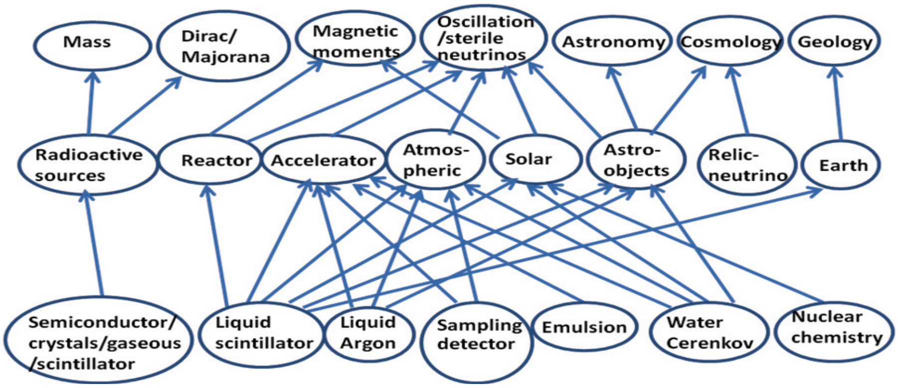



Fig. 1 Neutrino physics problems and the ways to solve them: neutrino sources and detectors.

## 2. Absolute neutrino mass

The absolute electron neutrino mass can be measured by the end point of the β-decay energy spectrum. Since the mass is tiny, the selected β-source should have a lowest possible end point and a high event rate, corresponding to an appropriate life time and a sufficient mass of the source.

There are actually two categories of experiments: 1) the source and the detector are two separate devices, such as Katrin [2] and Project 8 [3], and 2) the source is actually the detector itself, such as Mare[4]. While the second one has a clear advantage that the bulk of the source material will not affect the β energy, the first one may be practically more effective taking into account requirements on the energy resolution and backgrounds.

As a continuation of the Mainz experiment [5], which gave the best limit up to now, Katrin [2] is a large β spectrometer based on the magnetic adiabatic collimation and electrostatic filter [6], as shown in Fig. 2. It uses the $^3H$ source($T_2$ cooled to solid) with an end point of 18.6 keV and a lifetime of 12.3 years. The designed energy resolution is less than 1 eV and the expected sensitivity to the neutrino mass is 0.2 eV/$c^2$ at 90% C.L. The experiment already completed its installation and will start data taking in 2012. Due to the huge size, 10m diameter and 20m long, the spectrometer may become the last one of its kind.

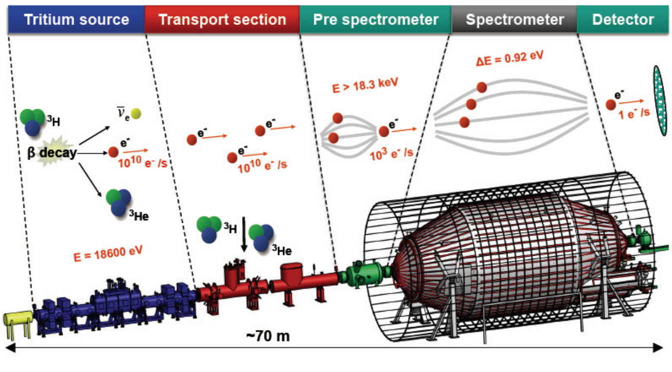



Fig. 2 Schematics of the Katrin experiment.

Project 8 [3] is based on the idea that electrons moving in an uniform magnetic field will emit cyclotron radiation with a (radio) frequency of $\omega = eB/(K+m_e)$, where K is the kinetic energy of the electron. A possible scheme of the experiment is shown in Fig. 3, where RF signals from the target volume filled with low pressure $T_2$ gas, will be detected by an antenna array. This novel method can measure the β energy in a non-destructive way with a resolution improving over time to the level of 1 eV, similar to that of Katrin. However the target mass of Project 8 can scale with the volume, instead of with the area in the case of Katrin, giving a promise to reach a better sensitivity, say 0.1 $ev/c^2$. Of course, such an expected sensitivity may be limited by unknowns and unexpected systematic uncertainties. R&D efforts to detect the RF signal, understand the resolution and systematics are going on.

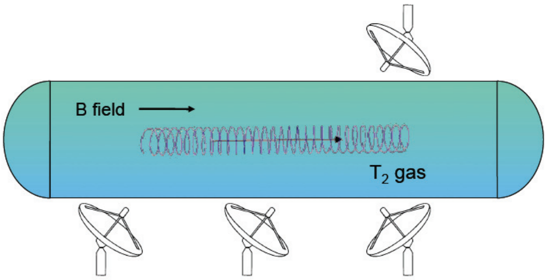


Fig. 3 Illustration of the Project 8 experiment.

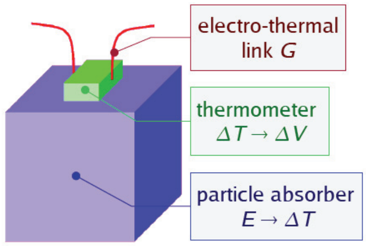


Fig. 4 A crystal bolometer.

The Mare experiment [4] uses the bolometer technology originally developed for neutrinoless ββ-decays. Crystals with a high purity and low radioactive backgrounds kept in a cryostat will "see" signals of charged particles by a tiny temperature increase due to phonons created by the ionization process. As shown in Fig. 4, temperature sensors are attached to the crystal and signals can be read out. By a careful choice of crystals which consist of β emitters, such as $^{187}$Re(Q=2.47 keV) and $^{163}$Ho(Q=2.6 keV), the β energy spectrum can be measured by the source crystal itself. Since the endpoints of $^{187}$Re and $^{163}$Ho are very low, it is a quite promising technique if low background, high mass crystals can be obtained and the tiny ΔT can be measurement with a good resolution. Currently, R&D efforts using $AgReO_4$ crystal and metallic Re have demonstrated the principle, and the group plans to reach an energy resolution of 15 eV in phase I and 5 eV in phase II, which will leads to a neutrino mass sensitivity of 2 $eV/c^2$ and 0.2 $eV/c^2$, respectively.

## 3. Neutrino magnetic moments

The Standard Model predicts that neutrinos have null magnetic moment if massless, and a magnetic moment of the order of $10^{-19}\mu_B$ with the mass in the currently known range, where $\mu_B$ is the Bohr magneton. Neutrino magnetic moments are often sensitive to new physics, which give predictions typically in the range of $(10^{-10}$-$10^{-14})\mu_B$. Indirect searches using supernova and solar neutrinos in a model dependent way can reach a sensitivity at the level of $10^{-10}\mu_B$, while direct searches using reactor neutrinos, looks for deviations of the differential ν-e scattering cross section from the expectation.

Using 1 kg of ultra-low-background and high-purity Ge crystals, the TEXONO experiment [7] reached a background level of 1/(day kg keV) and a threshold of 10 keV. The limit to the neutrino magnetic moment is $1.3\times10^{-10}\mu_B$. Another experiment, GEMMA [8], installed 1.5 kg of HPGe with active shielding of NaI crystals. They plan to have more HPGe crystals, as shown in Fig. 5, with a better shielding, to improve significantly the sensitivity by about a factor of 10.


Fig. 5 Ultra-pure Ge crystals of the GEMMA experiment.

Ultra-pure Ge crystals can be used also for ββ decays and dark matter searches. There are clearly needs to increase the available mass from ~100 kg to ~1000 kg, and push the threshold from 10 keV to the level of few, or even 1 keV. Of course, the main barrier is the cost, which needs to be reduced from ~300K\$/kg to the level of ~30K\$/kg. There is a joint effort by the Shenzhen University, Tsinghua University and IHEP in China to improve the impurity of Ge crystals from industrial level of $\sim 10^{-8}/cm^3$ at a cost of ~8K\$/kg to the desired $10^{-13}/cm^3$. It is quite promising that they already reached an impurity of $\sim 10^{-11}/cm^3$ in the lab. The future of this type of experiments will rely on the availability and cost of HPGe crystals.

## 4. Neutrino oscillations

Current neutrino oscillation experiments [1], based on their sources, can be classified as the atmospheric neutrino experiments such as SuperK, INO, HyperK, etc.; solar neutrino experiments such as SNO, Borexino, XMASS, etc.; accelerator neutrino experiments such as MINOS, OPERA, MiniBooNE, T2K, NOvA, etc.; and reactor neutrino experiments such as KamLAND, Daya Bay, Reno, Double Chooz, etc. Correspondingly, there are four kinds of technologies, including water Cherenkov, liquid Argon TPC, liquid scintillator and sampling detectors for neutrino beams.

### *4.1. Water Cherenkov detectors*

Water Cherenkov detectors are very successful for solar, atmospheric and supernova neutrinos. Transparent water is used as a cheap, massive target, as well as an excellent detector for charged particles and γ's. Fig. 6 shows a typical Cherenkov ring, recorded by an array of photomultiplier tubes(PMT), originated from a muon produced by a muon neutrino through the charge current interaction. Neutrino events can be reconstructed by these rings and the energy is measured by the number of photo-electrons(PE).

The benchmark of water Cherenkov detectors are set by the award-winning SuperKamiokande experiment [9]: total target mass of ~50 kt, PMT surface area coverage of ~40%, energy threshold of ~4 MeV, and the light yield of ~6 PE/MeV.

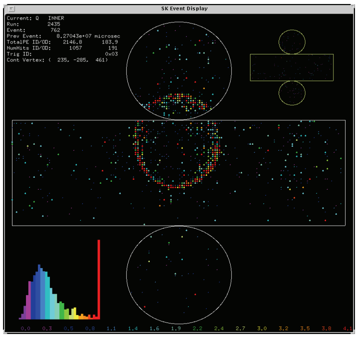


Fig. 6 A typical Cherenkov ring of muon.

Future water Cherenkov detectors plan to increase the mass to the level of ~(0.2-0.5) Mt, for proton decay searches, supernova neutrino studies, and very long baseline accelerator-based neutrino experiments.

A new project, LBNE [10], using the neutrino beam from Fermilab to DUSEL at Homestake mine, is now planed in US. The baseline is 1300km, and one of its detector options is water. There will be two identical detector modules, each with a fiducial mass of 100kt, as shown in Fig. 7. Each module is equipped by 50000 10" PMTs, giving a photocathode coverage of 20%, and a light yield of 3 PE/MeV. The expected energy threshold is 6 MeV, the energy resolution 4.5%/√E, and the vertex resolution 30 cm. Past experience shows that the pattern recognition capabilities is very good for single-ring events, but remains to be demonstrated for multi-ring events if neutrino energy is high.

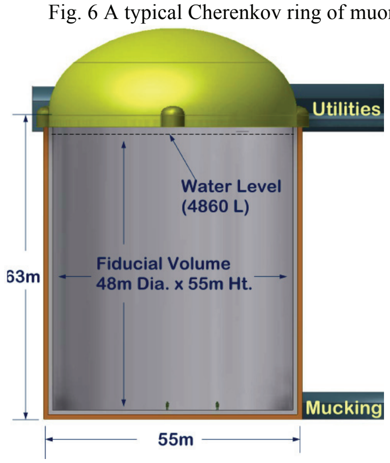


Fig. 7 Schematics of a water module for LBNE.

An exotic idea to improve the pattern recognition capabilities at high energies is the water Cherenkov calorimeter [11], proposed in 2000. Segmented modules with a typical dimension of $1\times1\times10$ $m^3$ are staggered in x- and y-directions, as shown in Fig. 8. One 20" PMT(or a few smaller ones) with a Winston cone is mounted at each end. The algorithm for event reconstruction and pattern recognition are very similar to that of crystal calorimeters at accelerator experiments. Simulation shows, and the prototype proves that its performance is excellent and it is a good candidate for long baseline experiments.

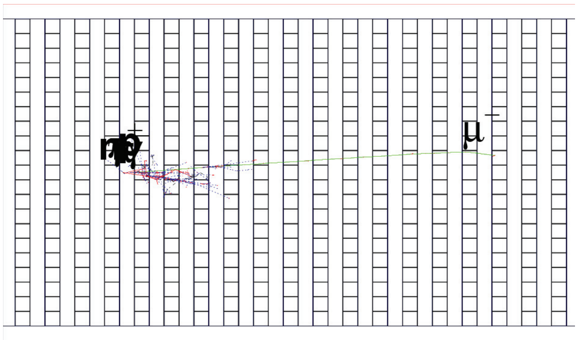



Fig. 8 A Monte Carlo event for charged current muon neutrinos in the water Cherenkov calorimeter.

There are of course technical issues to be clarified for LBNE, such as the PMT survival probability under 60m water pressure, water purification system for such a large volume, and civil construction difficulties for a cavern of 55m diameter, 70m height. None of them are trivial but also not impossible.

The physics program of LBNE is rich, similar those proposed long time ago, including HyperK [12] in Japan, and MEMPHYS [13] in Europe. They all have a total target mass of ~0.5 Mt, divided into two or three caverns. However, a very aggressive proposal in Japan as shown in Fig. 9, TITAND [14], plans to build 16 steel water tanks, each with a mass 0.76 Mt. They are to be place at a depth of 1000m under the sea using mature technologies from the offshore oil industry. Such a detector with a total mass of 10 Mt, can significantly improve the sensitivity to, or even discover proton decays. It can also detect supernova neutrinos almost every year with a number of events more than 10 at a distance less than 5 Mpc.

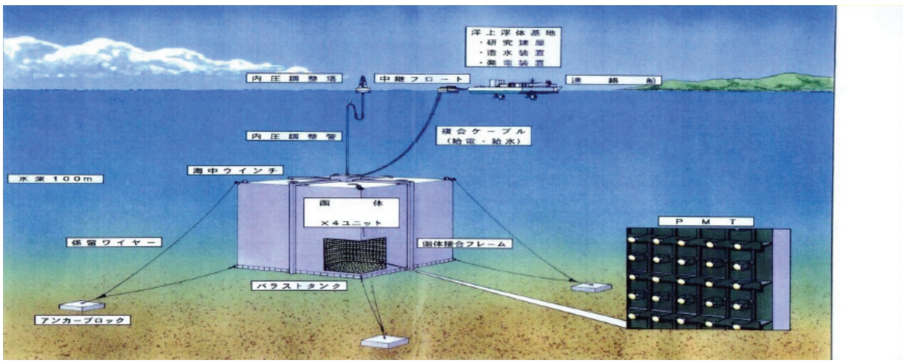



Fig. 9 A schematics of the TITAND experiment.

In addition, there is an idea [15] to dope Gd into the water, so that electron anti-neutrinos can be detected via the inverse β-decay process, as in the case for liquid scintillators. Neutrons from this process will be captured by Gd, releasing a total of 8 MeV γ's. Technically this is feasible since $GdCl_3$ is highly soluble in water with no effects to the water transparency. A 200t R&D project, called EGADS, is now under construction at Kamioka. If successful, it may convert the SuperK detector to a huge flavor sensitive detector for supernova neutrinos, reactor neutrinos and geo-neutrinos.

### *4.2. Liquid Argon TPC*

The idea of liquid Argon Time Projection Chamber(LAr TPC) was originated in 70's and the first proposal of ICARUS [16] to INFN was in 1985. This digital bubble chamber, as a dense target for neutrinos, has all the features dreamed by physicists and is ideal for discoveries, such as the $\nu_e$ appearance from a $\nu_\mu$ beams.

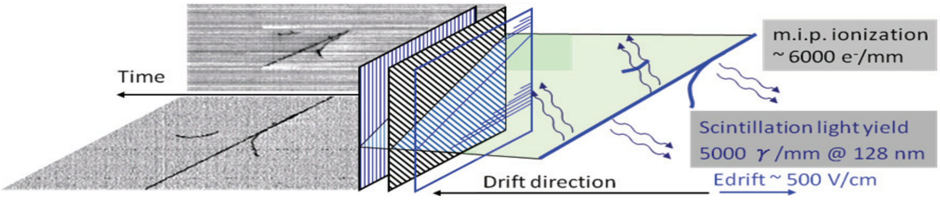



Fig. 10 The working principle of the liquid Ar TPC.

The working principle of the liquid Ar TPC is illustrated in Fig. 10. Similar to that of gaseous TPC, charge particle tracks can be identified and measured precisely. In addition, scintillation photons produced by the liquid Ar can be used to improve the energy resolution. The 600t ICARUS experiment[16], after 20 years of R&D, successfully obtained the desired performance: energy resolution of $\sigma(E)/E=11\%/\sqrt{E(MeV)}+2\%$, tracking resolution of ~1mm for $\sigma_{x,y}$ and ~0.4mm for $\sigma_z$. The dE/dx and the range measurement give excellent particle identification capabilities. A typical charge current $\nu_\mu$ event at ICARUS from CNGS is shown in Fig. 11.

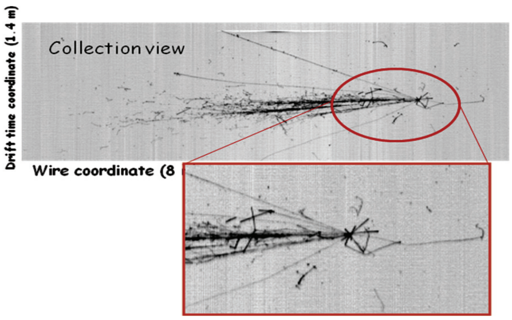



Fig. 11 A charge current $\nu_\mu$ event at ICARUS from CNGS.

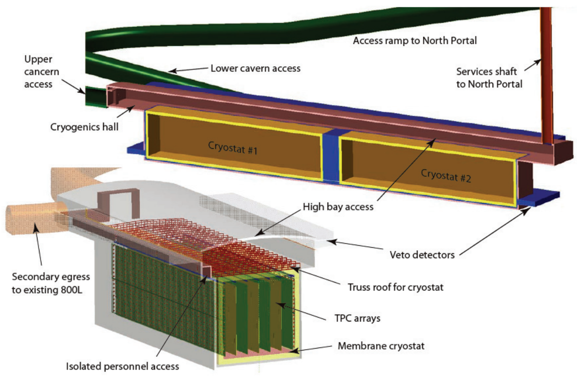



Fig. 12 A schematics of LAr TPC option for LBNE.

The lessons learned from such a long time R&D effort are that impurities of $O_2$, $H_2O$, and $CO_2$ should be controlled to a level less than 0.1 ppb $O_2$ equivalent, in order to obtain a sufficient electron lifetime for the free drift distance of ~4.5m at a field of 500V/cm. Two recirculation and purification systems are introduced, one for the gas phase and one for the liquid phase, in order to satisfy the above requirements.

R&D efforts are also taking place in US and in Japan. Issues to be resolved include the LAr purity for longer electron drift distance, membrane cryostat for multi-kiloton TPC, electron multipliers and readout electronics at the low temperature, etc. A 100t LAr TPC at Fermilab on the on-axis Booster beam and offaxis NuMI beam, called MicroBooNE [17], is now under construction for the detector R&D. It can also be used to measure the low energy neutrino cross section and to study the low energy neutrino excess observed by the MiniBooNE experiment.

One of the main motivations of these R&D is for the LBNE LAr option [18]. Current design chooses to have two 20kt cryostats, as shown in Fig. 12. As from the simulation, physics reaches of LAr is very similar to that of water option with a total fiducial mass of 200 kt. Fig. 13 gives a comparison of the two options. In one sentence, LAr option seems perfect in performance but we may have difficulties to build it, while it is "easy" to build a water detector but we are not fully satisfied with its performance, particularly for multi-rings events at high energies[b]. Even with difficulties, larger LAr TPCs up to a mass of 100 kt are planned in Europe and in Japan [19].

**LAr**

- Pros
  - Beautiful image of events
  - Good energy resolution
  - Good PID and pattern recognition
  - High efficiency
  - Requiring smaller cavern and shallow depth
- Cons
  - Technology for such a volume ?
  - Huge No. of channels
  - Cost ?

**Water**

- Pros
  - Proven technology
  - Cost under control
  - Good energy resolution (slight worse)
  - Good PID & pattern recognition, particularly at low energies and for single rings
- Cons
  - Lower efficiency
  - Multi-rings ?
  - Larger cavern and deep underground

Fig. 13 Comparison of the LAr TPC option and the water option for LBNE.

### 4.3. Liquid scintillators

Liquid scintillators (LS) have been successfully used for solar, reactor and geo-neutrino studies. This is actually the technology used for the neutrino discovery in 50's. Electron anti-neutrinos interact with protons in the organic liquid (typically $C_nH_{2n+2}$), giving a positron and a neutron. The neutron will be moderated and then captured by a proton, releasing a 2.2 MeV $\gamma$. Sometimes Gd is doped into the LS at a typical level of 0.1%, the neutron capture time on Gd is much shorter and the $\gamma$ energy released is 8 MeV.

The current record of the largest detector is KamLAND [20] with a mass of 1000t. A typical liquid scintilllator detector can have a PMT area coverage of (40-80)%, giving a light yield of (300-600) PE/MeV, almost two orders magnitude higher than that of water Cherenkov detectors.

| Groups | Solvent | Complexant for Gd compound | Quantity(t) |
|---|---|---|---|
| Chooz[21] | IPB | Alcohol | 5 |
| Palo Verde[22] | PC+MO | EHA | 12 |
| Double Chooz[23] | PXE+dodecane | Beta-Dikotonates | 40 |
| Daya Bay[24] | LAB | TMHA | 185 |

Table 1 Some of the Gd-loaded liquid scintillators developed in recent years.

Liquid scintillator is a mature technology. It traditionally consists of three gradients, for example, scintillation flours dissolved in Pseudocumene and then diluted by mineral oil. However, Pseudocumene suffers from issues like low flush point, chemical attacks, high cost, etc. Recently, two-gradient LS becomes more popular. By dissolving flours in Linear-Alkyl-Benzene(LAB), it has all the good features we hoped for. Another difficulty is to dope metallic elements, such as Gd, Nd, In, etc. into the liquid

[b] At this moment, liquid Ar TPC option has been selected.

scintillator. It is known that instability of the liquid, or degradation of the liquid transparency, can develop with metals in organic liquids. As an example, table 1 lists some of the Gd-loaded liquid scintillatiors, all at the 0.1% level, developed in recent years.

The Daya Bay experiment developed a new chemical procedure for Gd-loaded LS with the possibility for mass production [24], as shown in Fig. 14. Care must be taken to ensure the cleanness of all the raw materials, and purification processes for PPO, GdCl3 and TMHA are developed. Stability tests of the dry-run batch over two years show that there is no sign of degradation of the light yield and the transparency.

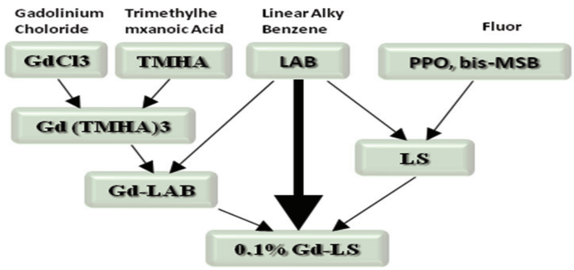



Fig. 14 The chemical procedure for the Gd-LS production at Daya Bay.

The Daya Bay experiment is designed to have a total systematic error on the oscillation probability less than 0.4%, a record precision [25]. Fig. 15 and 16 show the layout of the experiment and the detector. The near-far configuration cancels most of the correlated systematic uncertainties, while multiple modules at each site reduce un-correlated systematic uncertainties. Multiple veto detectors and multiple neutrino modules at each site ensure the redundancy and hence reduce systematic errors. As seen from Fig. 16, each anti-neutrino detector module consists of three nested cylindrical vessels, two acrylic and one stainless steel. PMTs are arranged on the side wall, while optical reflectors are installed at the top and bottom for the photon collection. Such an innovation to save PMTs and ease the complication of engineering seems very successful. The experiment expects to start full data taking in summer 2012.

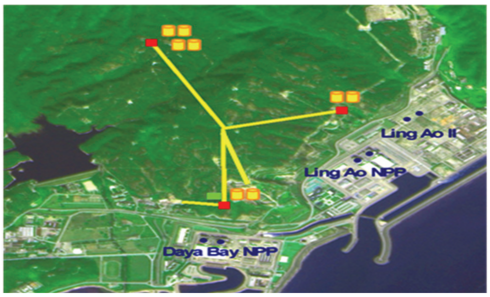



Fig. 15 The layout of the Daya Bay experiment.

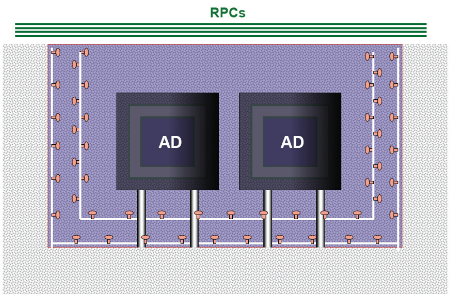



Fig. 16 The layout of the detector of the Daya Bay exp.

The cleanest liquid scintillator detector is Borexino [26], running at Gran Sasso for solar neutrinos from the pp chain and geo-neutrinos. By deploying a sophisticated purification system consisting of filtration, water extraction, vacuum distillation and nitrogen stripping, the energy threshold is successfully reduced to the level of (0.1-0.3)MeV, and impurities reached the level of $(10^{-17}\text{-}10^{-18})$ g/g, as listed in Fig. 17. Clean scintillator detectors can also be used for

| Background | Typical abundance (source) | Goal | Measured |
|---|---|---|---|
| $^{14}C/^{12}C$ | $10^{-12}$ (cosmogenic) g/g | $10^{-18}$ g/g | ~2 x $10^{-18}$ g/g |
| $^{238}U$ (by $^{214}Bi$-$^{214}Po$) | 2 x$10^{-5}$ (dust) g/g | $10^{-16}$ g/g | (1.6 $\pm$ 0.1) x $10^{-17}$ g/g |
| $^{232}Th$ (by $^{212}Bi$-$^{212}Po$) | 2 x $10^{-5}$ (dust) g/g | $10^{-16}$ g/g | (5 $\pm$ 1) x $10^{-18}$ g/g |
| $^{222}Rn$ (by $^{214}Bi$-$^{214}Po$) | 100 atoms/cm$^3$ (air) emanation from materials | $10^{-16}$ g/g | ~ $10^{-17}$ g/g (~1 count /day/100t) |
| $^{210}Po$ | Surface contamination | ~1 c/day/t | May 2007: 70 c/d/t Sep 2008: 7 c/d/t |
| $^{40}K$ | 2 x $10^{-6}$ (dust) g/g | ~$10^{-18}$ g/g | < 3 x $10^{-18}$ (90%) g/g |
| $^{85}Kr$ | 1 Bq/m$^3$ (air) | ~1 c/d/100t | (28 $\pm$ 7) c/d/100t (fast coinc.) |
| $^{39}Ar$ | 17 mBq/m$^3$ (air) | ~1 c/d/100t | << $^{85}$Kr |

double β-decay experiments.

Fig. 17 Impurities in the Borexino Scintillator.

There are several proposals of the future liquid scintillator detectors, LENA [27] in Europe, Hanohano[28] in US, and Daya Bay II [29] in China, with a target mass of ~50 kt. Fig. 18 shows the LENA design as a typical detector. All the proposed detectors can study supernova neutrinos and geo-neutrinos, but Daya Bay II is also good at reactor neutrinos. At a distance of 60 km from the reactor complex, Daya Bay II can precisely measure the reactor neutrino energy spectrum. After a Fourier transformation, the neutrino mass hierarchy can be determined and mixing parameters can be precisely measured.

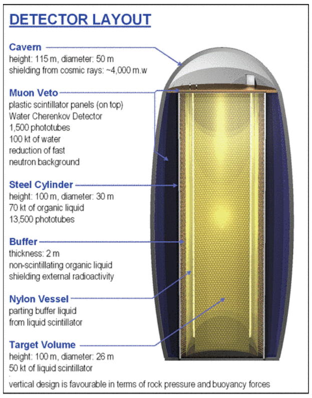



Fig. 18 Design of the LENA detector.

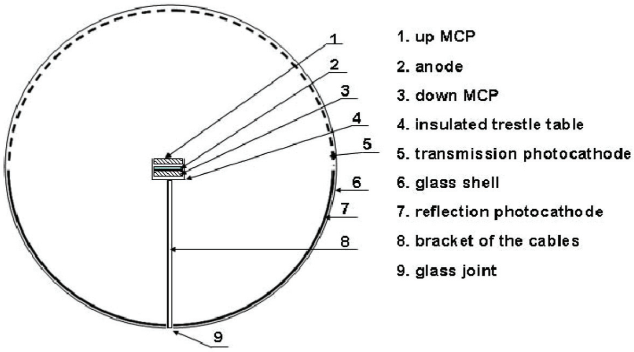



Fig. 19 A new design of PMT with high quantum efficiency.

There are two major technical challenges for such a large detector: transparency of the liquid scintillator and the large area photon detection. In general, the attenuation length of the liquid should be larger than the detector diameter, typically >30m for a 50 kt detector. But currently, the best transparency is only about 15-20m. Efforts are going on to identify the light absorbers and to study the removing method. Another common issue for large water, LS and LAr detectors is low cost, low background, large area, high QE and single PE sensitive photon detectors. One R&D effort pioneered by the University of Chicago is the large area, low cost MCP made of glass with a thin film from Atomic Layer Deposition[30]. Another example is a large area MCP-PMT, as illustrated in Fig. 19. Reflective photocathode is deposited at the lower half of the glass bulb to improve the total quantum efficiency [31].

### *4.4. Sampling detectors for neutrino beams*

Sampling detectors are often used for high energy neutrinos, mainly the neutrino beams from accelerators. The absorber can be Iron, Lead or other dense materials, while the sensitive detector can be emulsion films(OPERA [32]), plastic scintillators(MINOS [33]), liquid scintillators(NOvA [34]), or RPCs(INO [35]). Fig. 20 shows the NOvA detector with a total target mass of 15 kt. Often, there is a need of the near and/or mid detector to monitor the neutrino flux and the beam profile. One example is T2K[36], which consists of a magnet, an electromagnetic calorimeter for $\pi^0$s, and tracking detectors, as shown in Fig. 21.

India plans to build an underground neutrino observatory for atmospheric neutrinos and long baseline neutrino beams [35]. As shown in Fig. 22, the detector, called INO, consists of 50kt magnetized iron plates interleaved by RPCs. The detector has a good tracking, energy and timing resolution, as well as the capability to distinguish the charge of particles since a magnetic field of 1.5 Tesla is generated by magnetized iron plates. The detector is located at a magic position, with almost an equal distance of about 7000 km to major accelerator centers, CERN, JPark and RAL.

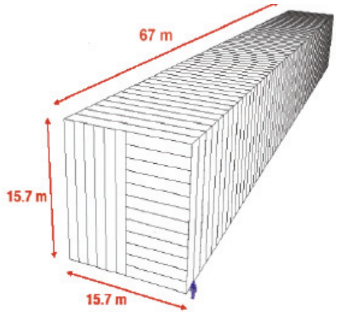



Fig. 20 Schematics of the NOvA far detector.

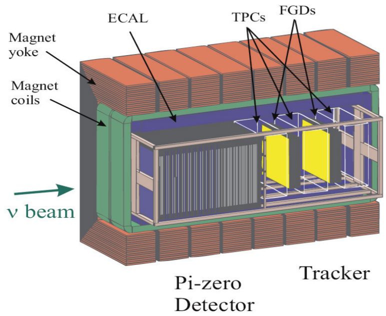
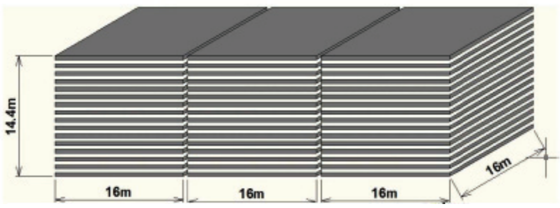



Fig. 21 The near detector of T2K.

A generic Magnetized Iron Neutrino Detector (MIND) for SuperBeams and neutrino factories is now under study [37], as shown in Fig. 23. Its main goal is to look for the CP phase of the neutrino maxing matrix, by the appearance of "wrong-sign" muons in the magnetized iron calorimeter. The baseline assumed is 2000-7500 km, and the total target mass is about 50-100 kt. Such an experiment could be our ultimate dream: sensitivity to $\sin^2 2\theta_{13}$ can be reached to the level of 0.001% and the space for CP phase is almost fully covered.



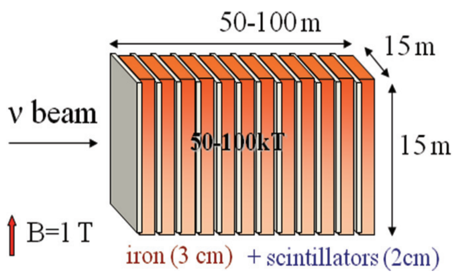




Fig. 22 Schematics of the INO detector.

Fig. 23 The MIND detector for neutrino beams.

In summary, there has been limited progress of neutrino physics since the discovery of neutrino oscillation, but quite some technology advances for a larger mass and a better performing detector. We are all waiting for $\theta_{13}$ to be known, and expect to see more discoveries by employing these new technologies.

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