PROCEEDINGS OF SCIENCE

PoS(IFD2015)016

Future large volume neutrino detectors

S.Bolognesi[*]
IRFU, CEA Saclay, Gif-sur-Yvette, France
E-mail: `Sara.Bolognesi@cea.fr`

A review of future very large neutrino detectors for the measurement of neutrino oscillation parameters is presented. Three main options are compared: the water cherenkov technology, as in Hyper-Kamiokande, the liquid argon technology, as in DUNE, and the liquid scintillator technology, as in JUNO. The prospects, the advantages and the weaknesses of each technology will be addressed.

INFN Workshop on Future Detectors for HL-LHC
16-18 December, 2015
Aula Magna della Cavallerizza Reale, Torino, Italy

---

[*] Speaker.

The neutrino oscillations, which demonstrate that neutrinos have non-zero masses, are a clear signature of physics beyond the Standard Model. The smallness of the neutrino masses is typically explained, through Seesaw models, by the presence of a new, very large, fundamental energy scale. The models introducing new high-energy phenomena to describe the neutrino masses and oscillations may be constrained through the precise determination of the parameters describing the oscillations: three mixing angles, one CP-violating phase and two mass differences.

This review will focus on two main classes of experiments measuring neutrino oscillations exploting accelerator-based neutrino beams or neutrinos produced at reactors. In both the cases, a controlled source produces a flux of neutrinos which is characterized by a complex of detectors placed near the source, while a very large detector is placed far away to detect and measure the neutrinos after the oscillation. The distance between the source and the far detector (baseline) is typically hundreds to thousands kilometers for accelerator-based experiments and one to two kilometers for reactor-based experiments. A standard accelerator-based beam is mainly composed of muon neutrinos (or muon anti-neutrinos when inverting the beam polarity) and the far detector measures the disappearance of muon (anti-)neutrino and the appearance of electron (anti-)neutrino. Reactors produce, instead, electron anti-neutrinos and reactor-based experiments measures their disappearance.

The main unknowns still to be addressed in neutrino oscillations are: the mass hierarchy (MH, normal or inverted) and the value of the mixing phase δ_{CP}. In particular, a non-zero value of δ_{CP} would be the first indication of CP-violation in the leptonic sector, which may play a fundamental role in explaining the matter-antimatter asymmetry in the universe. For a conclusive (5σ) statement on δ_{CP} and MH a new generation of much larger neutrino detectors is needed.

1. Water cherenkov: from Super-Kamiokande to Hyper-Kamiokande

The Super-Kamiokande detector [1] is a big, cilindrical tank, full of ultrapure water, instrumented with thousands of Photo-Multiplier Tubes (PMTs) and located in the Kamioka mine. The Super-Kamiokande neutrino-oscillation measurements are based on the capability of distinguishing the neutrino electron/muon flavour and reconstruct the neutrino energy through the lepton produced in the neutrino interaction with the nucleons in water. Electrons produce, indeed, a very fuzzy cherenkov ring while muons produce a very clear ring. The neutrino energy can be calculated from the lepton angle and momentum (which can be measured through the ring axis and opening angle). The measurement of δ_{CP} comes mainly from the comparison between ν and $\bar{\nu}$ disappearance/appearance rates. Unfortunately, it is not possible to have a clean beam of ν_μ or $\bar{\nu}_\mu$ but there is always a small component of 'wrong-sign' neutrinos which cannot be distinguished, since Super-Kamiokande does not have charge identification capability. To effectively provide separation between neutrino and anti-neutrino events ($\nu_{\mu/e}\, n \to p\, \mu^-/e^-$ from $\bar{\nu}_{\mu/e}\, p \to n\, \mu^+/e^+$), it has been suggested to dope the water with gadolinium [2] in order to tag neutrons.

The Hyper-Kamiokande collaboration [3, 4] proposes to build a detector based on the same technology of Super-Kamiokande and about 20 times larger (∼1 megaton). The detector would be placed in a new mine to be excavated at about 295 km from the Japan Proton Accelerator Research Complex. The main features of Super-Kamiokande and Hyper-Kamiokande are compared in Tab.1. The design of the Hyper-Kamiokande tank(s) is being reviewed and the R&D on the

PMTs is on-going: a big volume and a large number of PMTs maximize the sensitivity but increase the cost, a good compromise may be reach by using a smaller number of PMTs but with larger sensor efficiency. Moreover, particular care is taken in the PMT design to avoid the risk of cascade implosion due to pressure (as in the Super-Kamiokande incident in 2001).

Table 1: Main features of Super-Kamiokande and Hyper-Kamiokande.

	Super-Kamiokande	**Hyper-Kamiokande**
Total volume	50 kton	990 kton
Fiducial volume	22.5 kton	560 kton
Tank(s)	1 vertical, cylindrical 41.4m(h)×39.3m(d)	2 horizontal, egg-shaped 48m(w)×50m(h)×250m(l)
Inner detector: # of PMTs	11129	50000
Outer detector: # of PMTs	1885	25000
Photo-coverage	40%	20%
Sensor Efficiency	18%	29%
(Collection x Quantum eff.)	(22%×80%)	(30%×95%)

1.1 PMT R&D

Three options (as shown in Tab.2) are being considered for the Hyper-Kamiokande PMTs: starting from the Super-Kamiokande technology, robust and well known, and moving to options which would provide higher performances but are still under study. In all cases the PMTs are large (50 cm) and can be possibly covered with protective glass to optimize the pressure resistance. The possibility of an integrated system, including many small (3 inches) inward PMTs for the inner detector placed in a sphere with each one of the outward large PMT for the outer veto volume, is also being discussed. That design would allow to protect the PMTs from pressure and avoid in-water electronics.

Table 2: Options under study for the PMTs in Hyper-Kamiokande.

	SK PMT	**HighQE/CE PMT**	**HighQE hybrid PMT**
Technology	Venetian blind dynode	Box & Line dynode	Avalanche diode
Quantum efficiency	22%	30%	30%
Collection efficiency	80%	93%	95%
Timing resolution (FWHM)	5.5 ns	2.7 ns	1 ns
Charge resolution (σ/peak)	53%	35%	16%

1.2 Gadolinium doping

Neutrons are captured by gadolinium (Gd) with emission of few photons of 8 MeV. This neutron tagging is useful in beam neutrino interactions to distinguish neutrino and anti-neutrino events and would enhance the sensitivity to neutrino from SuperNova and to proton decay.

The MC description of the neutron-capture time has been tested with an Am/Be source and found in perfect agreement with data. A neutron-capture efficiency of ∼90% can be reached with

Gd concentration of 0.2%. To be usable in water cherenkov detectors, this concentration must not spoil the water transparency. A 200 ton scale-model of Super-Kamiokande (EGADS) has been loaded with Gd and is fully operative in the Kamioka mine. Thanks to the positive results of EGADS, which demonstrated a transparency loss smaller than 8% with 0.2% Gd doping, the Super-Kamiokande collaboration decided to run with Gd doping in the future. This possibility is also envisaged for Hyper-Kamiokande.

2. DUNE liquid argon detector: the single- and double-phase options

When a particle passes through an argon volume, it produces ionization charge and scintillation light. The first can be collected in a Time Projection Chamber (TPC), while the second can be collected instrumenting the TPC with PMTs. The light signal provides the time of arrival of the particle in the detector (or the time of the neutrino interaction) thus allowing to measure the position along the drift direction. A liquid argon TPC does not only provide very precise 3D tracking but it is also a fully omogeneous, highly granular calorimeter with very low threshold. Indeed, as demonstrated by event displays from ICARUS [5], MicroBooNE [6] or ArgoNeuT [7], in liquid argon TPCs the interactions can be visualized in full details, similarly to old bubble-chamber experiments. The challenge consists in analyzing this information automatically:

- the particle identification is performed from dE/dx measurement,
- electrons and photons can be distinguished by searching for a minimum ioninzing track between the shower starting point and the interaction vertex (identified by the presence of other outgoing tracks),
- $\pi^0 \to \gamma\gamma$ can be identified by reconstrucing separately the two photon showers (down to very small opening angle, thanks to the good detector granularity),
- the track momentum is computed from the track range (or from multiple scattering if the track is not contained),
- the total calorimetric energy can be measured from the total collected charge (possibly, with a small correction from the collected light).

The DUNE collaboration [8, 9] proposes to build a huge liquid argon detector of 40 kton at the Sunford Underground Research Facility, 1300 km from Fermilab. The DUNE detector is composed of four rectangular TPCs of 14.4 m (w) × 12 m (h) × 58 m (l) (10 ton each). In such a very large detector the ionization charge undergoes a very long drift path. As a consequence, there is a large attenuation of the signal, due to the charge attachment, and the tracking spatial resolution is limited by the charge diffusion. Assuming an electric field between 0.5 and 1.5 kV/cm, the transverse diffusion is of the order of 2 mm (4 mm) for a drift path of 4 m (12 m), setting to few millimiters the useful pitch size for the charge read-out. The attachment is due to oxygen impurities in the liquid argon: in order to keep a collection efficiency of 90% (70%) after a drift of 4 m (12 m) the O_2 pollution should be below 20 ppt, which is the best purity achieved by the ICARUS collaboration for a volume 46 times smaller than the volume of each DUNE module.

Two options are being studied for the DUNE detector: single- and double-phase. In the single-phase option, the charge produced by ionization is drifted to the charge readout plane and collected by wires.The ICARUS detector (600 ton) was based on this technology, as well as, the MicroBooNE detector (170 ton), which started taking data in 2015, and the SBND detector [10] (210 ton), which will start taking data in 2018. A future single-phase liquid argon TPC of 700 ton, conceived as R&D step toward DUNE, will be installed at CERN in 2018. Because of charge attenuation, this technology cannot go beyond few meters of drift, therefore the drifting direction (horizontal, along the width of the DUNE detector) is divided in 4 regions of 3.6 m drift each by alternating anode and cathode planes. The charge is read-out with 3 sets of wires orientated vertically and at +/-45 degrees (one collection view and two induction views). In the double-phase option, instead, the drift path is in the vertical direction (12 m) and the upper part of the detector volume is filled with argon gas. An extraction grid is placed at the interface between liquid and gas and in the gas volume a charge multiplication device (typically a LEM [11]) induces a charge avalanche, then collected by the anode. The charge multiplication device makes the detector more robust against the charge attenuation and allows longer drift paths, and therefore less channels for the same volume. A stable gain of 20 has been demonstrated with a 10 cm × 10 cm LEM. The double-phase charge readout plane for the DUNE detector will be composed of modules of 50 cm × 50 cm and the anode has been designed to guarantee 2 views (x,y) of equal quality. 12 of these modules will be tested in a double-phase prototype of $3\times1\times1$ m^3 (5 ton) at CERN in 2016 and a second larger prototype (WA105 [12]) of $6\times6\times6$m^3 (510 ton) will be installed at CERN in 2018.

Beyond the proper charge collection and read-out, the DUNE experiment will have to face many challenges regarding hardware, software and analysis.

- The scintillation light has to be collected with the best possible efficiency and time resolution. The single-phase design exploits Silicon Photo-Multipliers with wavelenght shifting bars, while the double-phase design exploits standard PMTs with coating.
- A high voltage difference (100 to few hundreds volts) as to be kept stable between the very large surfaces of cathode and anode.
- A very large number of channels has to be kept operational (the possibility of access the electronics is envisaged only in the double-phase option).
- The calibration and detector uniformity (planarity of the charge read-out plane, electric field uniformity, argon purity) has to be assured on a very large volume.
- Given the granularity of the detector, the data-acquisition needs to rely on an efficient zero-suppression algorithm and the reconstruction software will have to combine a very large amount of information.

3. JUNO: a liquid scintillator detector with unprecented energy resolution

The detector in reactor-based neutrino-oscillation experiments consists tipically of a large volume of liquid scintillator where the $\bar{\nu}_e$ produced by the reactor are detected through inverse beta decay: $\bar{\nu}_e\ p \to e^+\ n$. A prompt signal (1-8 MeV, depending on the neutrino energy) is produced by the e^+ through ionization and annihilation, then accompanied by a delayed signal of 2.2 MeV due to neutron capture. To determine the neutrino MH, the JUNO collaboration [13] proposes to build a spherical detector with 35.4 m diameter (20 kton), fill with liquid scintillator, instrumented with about 15000 PMTs, placed at about 50 km distance from two nuclear reactors in China (at the Jiangmen Underground Neutrino Observatory). In order to distinguish inverted and normal hierarchy, JUNO must be able to disentangle experimentally a phase shift in the neutrino oscillation component with sub-dominant amplitude and very fast frequency. To reach this goal, a uniform energy resolution of 3% (at 1 MeV) must be achieved in the very large volume of the detector:

$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}} < 3\% \ @ \ 1\ \text{MeV} \tag{3.1}$$

3.1 4π-acceptance PMTs

In order to keep under control the stochastic effect on the energy resolution (first term in Eq.3.1), a very large light yield must be produced (10000 photo-electrons per MeV) and detected (1200 photo-electrons per MeV). These targets may be achieved with an increased doping, an improved purity, which gives large attenuation length (>20 m), a photo-coverage of 80% and a PMT detection efficiency of about 35%. As can be seen in Tab.2, a detection efficiency (quantum efficiency × collection efficiency) above 25% is actually very challenging. To reach this goal the JUNO collaboration is working on a new spherical PMT design based on Microchannel plates, which replace the dynode chain, to collect the electrons from all the directions (70% collection efficiency). Moreover the PMTs are equipped with a transmission photocathode in the top hemisphere and a reflective photocathode in the bottom hemisphere. The transmission photocathode converts 30% of the light and transmits 40% of the light to the reflective photocathode which further converts 30% of the transmitted light.

3.2 Charge integral vs photon counting

The systematic effects on energy resolution (second and third terms in Eq.3.1) are due to non-uniformities and non-linearities which may be corrected through calibration. Beyond standard effects related with electronics and noise, in a very large volume in presence of very large light yields there is an intrinsic non-uniformity due to the fact that the collected light per PMT changes by a factor 100 between events in the center and events near the edges of the detector. Indeed, high-energy neutrino interactions near the edges may in JUNO give 100 photo-electrons per PMT. When such a large number of signals are superimposed, the estimation of the energy through charge integral become much less precise and possibly biased. This effect may be, in principle, corrected by deploying radioactive sources for calibration in different regions of the detector. In practice, such sources are available only up to 5 GeV and it is very difficult to move the sources to map all the huge JUNO volume (especially near the edges). A possible solution, which is under study, consists in equipping the detector with many small (3 inches) PMTs in the space between the large PMTs previously described. The small PMTs, having only 10% coverage, would collect a much smaller light yield: 50 photo-electrons per MeV, <4 photo-electrons per PMT on average. In this situation, the energy may be measured through photon counting. The small PMTs would therefore be affected by a larger stochastic effect but they would have a much better linearity and uniformity than the large PMTs since they would have constant response also for events with very large light yield (high energy events and/or events near the edges).

4. Challenges along the road of δ_{CP} and mass-hierarchy measurement and complementarity between different technologies

Roughly speaking, the DUNE experiment has larger sensitivity to MH with respect to the Hyper-Kamiokande experiment, while the latter has larger sensitivity to CP-violation. Actually such sensitivities depend strongly on the beam power and the baseline length while in the following we would like to compare the two experiments from the technological point of view. The water cherenkov option is certainly a well known and robust technology allowing to achieve much larger mass than the liquid argon option. DUNE would be indeed the first application of liquid argon to very large scale and, for further developments, the size of the detector will be limited by the charge attenuation along the drift path. On the other hand, Hyper-Kamiokande could provide information only for particles above the cherenkov threshold. As a consequence, the reconstruction of neutrino energy from the final state particles, produced by neutrino interactions in water, relies on model dependent assumptions which are affected by large uncertainties. On the other hand, for the determination of CP-violation, a precise knowledge of the neutrino oscillation as a function of energy is not crucial since the measurement mostly relies on the comparison of neutrino and anti-neutrino appearance/disappearance rates. In this sense, Hyper-Kamiokande power resides on the very large mass which assures very large statistics. DUNE relies instead on a precise measurement of the oscillation energy dependence, thanks to the capability of reconstructing tracks and showers in full details down to very low threshold. The main challenge will consist in achieving a very good control on the detector calibration and uniformity and on the interplay of such effects with uncertainties related with neutrino interaction modelling. The astonishing precision of liquid argon detectors make them a very promising technology for the near and far future of neutrino oscillation studies, especially in conjunction with future multi-MW beams and, possibly, neutrino factories. But such long-term plan must be supported by an ancillary program to constrain the systematics on neutrino interactions.

The JUNO approach makes use of the well known technology of reactor-based experiments, displaced at a much longer baseline to measure the small oscillation phase shift related to the MH. This option is certainly challenging in many respects, as can be seen by comparing JUNO with previous similar detectors in Tab.3.

Table 3: Comparison of JUNO specifics with previous similar detectors.

	KamLAND	**Borexino**	**Daya Bay**	**JUNO**
Mass [ton]	∼1000	∼300	∼170	∼20000
Energy resolution	$6\%/\sqrt{E}$	$5\%/\sqrt{E}$	$7.5\%/\sqrt{E}$	$3\%/\sqrt{E}$
Light yield [p.e./MeV]	250	500	200	1200

It should finally be mentioned that the MH determination is also the main scope of other two projects which aim to measure the oscillation of atmospheric neutrinos by instrumenting with vertical strings of PMTs huge volumes of the Mediterranean sea (ORCA [14]) or of the South Pole (PINGU [15]). The main advantage of such approaches consist in the huge masses, which are obviously well beyond what is affordable with standard (tank-based) detectors. On the other hand, they have much worse precision in reconstructing the neutrino interactions, and thus identifying the neutrino flavour and energy and they exploit the atmospheric neutrino flux which cannot be known/characterized as precisely as in accelerator-based or reactor-based experiments. The main technological challenges in this case are related with the actual deployment and operation of the detecting modules.

5. Conclusions

The proposed next-generation experiments for the measurement of neutrino oscillation parameters, most prominently CP violation and MH, are based on very different technologies which are highly complementary in their weaknesses and strength. Also from a physics point of view, especially in presence of unexpected new physics, as non-standard interactions or sterile neutrinos, the complementarity in the sensitivity of the different experiments is necessary to solve degeneracies between different effects affecting the neutrino oscillations. For a definitive and robust 5σ determination of CP-violation and MH, precise and well-understood measurements with high statistical significance are needed, while the combination from different experiments will avoid uncertainties related with non-standard physics and/or unexpected detector effects.

It should be finally mentioned that experiments like Hyper-Kamiokande and DUNE will also have a primary role in the search for proton decay and neutrinos from SuperNovas. Similarly, experiments like PINGU and ORCA are embedded into wider projects (respectively IceCube [16] and KM3NeT-ARCA [17]) which are opening the very promising field of neutrino astronomy.

References

[1] Y. Fukuda et al. *Nucl. Instrum. Meth.*, A501:418–462, 2003.

[2] J.F. Beacom and M.R. Vagins. *Phys. Rev. Lett.*, 93:171101, 2004, hep-ph/0309300.

[3] K. Abe et al. 2011, arXiv:1109.3262.

[4] K. Abe et al. *PTEP*, 2015:053C02, 2015, arXiv:1502.05199.

[5] S. Amerio et al. *Nucl. Instrum. Meth.*, A527:329–410, 2004.

[6] H. Chen et al. *FERMILAB-PROPOSAL-0974*, 2007.

[7] C. Anderson et al. *JINST*, 7:P10019, 2012, arXiv:1205.6747.

[8] R. Acciarri et al. 2015, arXiv:1512.06148.

[9] R. Acciarri et al. 2016, arXiv:1601.02984.

[10] M. Antonello et al. 2015, arXiv:1503.01520.

[11] C. Cantini et al. *JINST*, 10(03):P03017, 2015, arXiv:1412.4402.

[12] L. Agostino et al. *CERN-SPSC-2014-013, SPSC-TDR-004*, 2014, arXiv:1409.4405.

[13] Z. Djurcic et al. 2015, arXiv:1508.07166.

[14] V. Van Elewyck. *J. Phys. Conf. Ser.*, 598(1):012033, 2015.

[15] M. G. Aartsen et al. 2014, arXiv:1401.2046.

[16] M. G. Aartsen et al. 2014, arXiv:1412.5106.

[17] P. Bagley et al. 2009, http://www.km3net.org/TDR/KM3NeT-TDR.pdf.