CONTRIBUTION OF A LIQUID ARGON TPC TO T2K NEUTRINO EXPERIMENT*

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A 2 km LAr detector would be an important asset for the T2K experiment. Different physics scenarios are considered and for each one the role of a LAr TPC in enhancing the ultimate sensitivity on θ_{13} is studied. The large sample of neutrino interactions in the GeV region would provide crucial information for the study of different types of reactions and of nuclear effects, whereas the inner target would give a direct measurement of the cross sections ratio between Water and Argon. Such a detector would also be an important milestone for the LAr TPC technique providing an extremely valuable experience for future large LAr detectors.

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1. T2K experiment

T2K will be the first long base-line neutrino experiment performed with a super-beam: the number of protons on target (p.o.t.) will be $\sim 10^{21}$ per year. Several beam power upgrades have been considered and in the actual envisaged option the neutrino beam should be ready in 2009 and should reach a power of 1.35 MW by 2012. The far detector, located 295 km away, will be off-axis by 2.5 degrees. The advantage of such a configuration is given by the fact that the neutrino beam reaching the detector will have low energy (E_ν less than 1 GeV) and it will be peaked in a region that maximises the $\nu_\mu \to \nu_x$ oscillation. Super Kamiokande (SK) will be used as far detector and a near detector complex will be built at 280 m. Given the importance of the near detector to reduce the systematics due to differences in near/far spectra, an additional near detector complex at 2 km has been proposed by 27 groups (EU, Japan and USA) since at this distance the difference in near/far spectra is below 5% [1,2].

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2. 2 km complex

2.1. Water Čerenkov

The main features of a Water Čerenkov detector located at 2 km are the following: it is the same target as the far detector, it has the same flux (scaled by a simple geometrical factor), it is a low cost/ton well known technology, and most importantly, it uses the same event reconstruction method as SK. This is fundamental in order to minimise the systematics in prediction at far detector and the only way to make sure that the sources of background are under control to the desired extent.

2.2. LAr TPC

In this section the main features of a LAr TPC are presented. It is a fully active, homogeneous high resolution device (sampling = 0.02 X_0), which means that it will be possible to perform high statistics neutrino interaction studies with a bubble chamber accuracy. It will be able to reconstruct low momentum hadrons, especially recoiling protons: a proton with a momentum equal to 1070 MeV/c (Čerenkov threshold in Water) has a range of about 1 m in LAr. A LAr TPC will also provide an independent measurement of the off axis flux and the QE/nQE event ratio, moreover it will perform an exclusive measurement of NC events with a clean π^0 identification providing an independent determination of systematic errors on NC/CC ratio, and it will measure the intrinsic ν_e CC background. Last but not least it will provide a large statistical sample of neutrino interaction in the GeV region for the study of QE, DIS and RES modelling and of nuclear effects. A LAr TPC at T2K would be an important milestone for this technique: it would be an in-situ R&D and an extremely valuable experience for future large LAr detectors [3–5]. The number of interactions expected in a 100 ton detector for 10^{21} p.o.t. are listed in Table I and an artistic view of the detector is shown in Fig. 1.

TABLE I

Number of interactions per 10^{21} p.o.t. on a 100 ton detector.

Flavour	CC TOT	CC QE	NC
ν_μ	190763	121859	26253
$\overline{\nu_\mu}$	8023	2764	2063
ν_e	3704	1372	725
$\overline{\nu_e}$	372	96	100

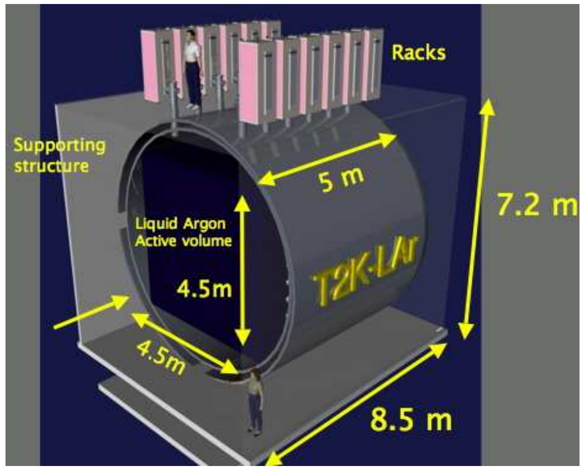

Fig. 1. Artistic drawing of the T2KLAr detector: 3D view.

3. Physics and LAr TPC contribution

There are two physics measurements to be made at T2K: ν_μ disappearance and ν_e appearance. In the following subsection these two measurements are studied focusing on the role played by a LAr TPC. In case on ν_e appearance we analyse three possible scenarios: high statistics (*i.e.* more than 5×10^{21} p.o.t.), low statistics (*i.e.* less than 5×10^{21} p.o.t.) when a signal is measured and low statistics when no signal is measured.

3.1. ν_μ disappearance

This measurement will improve the precision on the knowledge of $\sin^2\theta_{23}$ and Δm^2_{23}. For a precise measurement of the oscillation parameters a good QE/nQE measurement as a function of energy is fundamental in order reduce systematic errors and to achieve the desired results. What Water Čerenkov detector can measure is the sum of QE and nQE single ring events; with a good measurement of the QE part of the spectrum given by LAr it is possible to estimate with good accuracy the nQE component in the Water Čerenkov. This will give a very reliable measurement of $\sin^2\theta_{23}$ and Δm^2_{23}.

3.2. ν_e appearance, high statistics

The ν_e appearance measurement will reduce the present limit on $\sin^2\theta_{13}$ by a factor 20; in order to do that, the systematics arising from the ν_e contamination in the beam and the NC π^0 production must be kept under control at a level of $\sim$ 10%. With a systematic error greater than that,

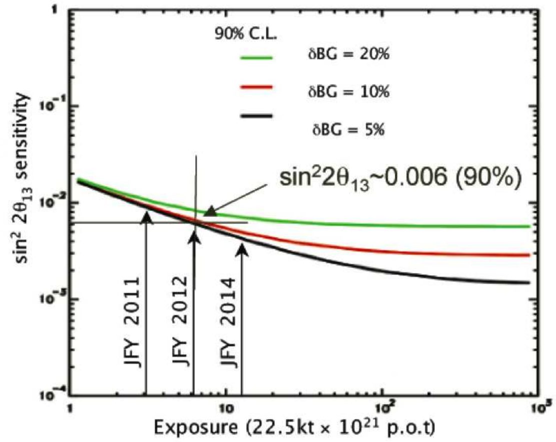

Fig. 2. Sensitivity on θ_{13} with a 90% C.L. as a function of exposure for different values of systematics. On the plot Japanese fiscal years (JFY) calculated according to the actual envisaged beam power upgrade are shown.

taking into account the actual envisaged beam power upgrade, data taking beyond 2012 would leave the sensitivity on θ_{13} almost unchanged (Fig. 2). What Water Čerenkov detector can directly measure is the total background given by ν_e in the beam and NC π^0. Although with such a detector it is not possible to have a clean measurement of the different components of the background, it is possible to estimate the π^0 component from the observed π^0 event rate knowing the rejection efficiency. With a LAr TPC it is possible to measure the ν_e component with very little NC contamination: this way the background will be over-constrained and an overall consistency on its understanding will be demonstrated.

3.3. ν_e appearance, low statistics — signal

During the first 5 years, a signal of a non-vanishing θ_{13} could be measured. In that case the value of θ_{13} would be dominated by systematics on the BG since it must be subtracted from the oscillated events seen. As stated for the case of ν_e appearance high statistics, a LAr detector would help in reducing the systematics on the different components of the BG.

3.4. ν_e appearance, low statistics — no signal

MC studies performed on the 2 km Water Čerenkov detector show that near and far Water Čerenkov detectors are similar but not exactly the same [6]. Performing similar analysis (*e.g.* different reconstruction functions) it is possible to obtain similar results at 2 km and SK, but it is important to know what is the systematic error associated to this. A cross check on the 2 km MC can be done using a different detector (*i.e.* introducing different systematics) to perform the same analysis. The LAr detector can reproduce the cuts of the Water Čerenkov analysis and measure the different components of the BG separately. This way the cuts efficiencies and BG will be over-constrained and an overall consistency will be demonstrated.

4. Detector performance

There are ongoing studies on the detector performance, such as neutrino energy reconstruction, QE/nQE measurement, event selection and e/π^0 separation. For the energy reconstruction we compared two different methods: the former is based on the measurement of the muon momentum only; from that it is possible to calculate the neutrino energy under the assumption that the event is QE. This method is the one used in the Water Čerenkov detector where the threshold for hadrons is normally too high to detect them. The latter takes into account hadronic energy as well, and the neutrino energy is obtained from the total reconstructed momentum. As expected, taking into account the hadronic energy improves the resolution: the RMS on $(E_\nu^{\mathrm{MC}} - E_{\mathrm{vis}})/E_\nu^{\mathrm{MC}}$ distribution decreases from 31% to 22% and the mean value changes from 15% to 2%.

In order to have a good QE/nQE measurement, we are studying two different ways: statistical separation and event by event classification. In the first case the idea is to fit the distribution of the reconstructed invariant mass W with the distributions obtained for QE and nQE events from the MC; from the ratio of the weights of the two distributions we obtain the value of QE/nQE. Alternatively the possibility to perform an event by event separation based on reconstructed final states was investigated. The thresholds on momentum to consider a particle reconstructed are 300 MeV/c for protons (kinetic energy > 50 MeV) and 50 MeV/c for charged pions (kinetic energy > 10 MeV). The results obtained with different neutrino generators are shown in Table II. The two methods yield promising results although they are both MC dependent.

An e/π^0 discrimination study based on their different dE/dx has been carried out. Assuming to know the interaction vertex and considering the fact that in only 5.4% of the cases one photon from the pion converts within the first centimetre, a 0.2 % π^0 efficiency has been obtained by imaging for a 90% electron efficiency.

TABLE II

Event by event separation for different neutrino generators based on reconstructed final states.

Generator	Only μ reconstructed	$\mu + p$ reconstructed	Others reconstructed
NEUT QE	16.7 %	72.3%	11.0%
NEUT nonQE	3.8 %	10.0%	86.2%
NEG QE	30.6 %	66.1%	3.3%
NEG nonQE	0.7 %	4.2%	95.1%
NUX QE, nuclear off	18.5 %	81.5%	0%
NUX nonQE, nuclear off	0.01 %	0.01%	99.98%

5. Inner target

5.1. Motivation, issues and geometry

Using a LAr detector to predict events that take place in Water could introduce errors due to nuclear effects which could affect the goal of precision measurements at T2K. The straight-forward solution is to insert an additional target within the 100 ton LAr detector. This approach (embedded target) is supported by the kinematics of the events (low energy, large angle products, *etc.*). The inner target geometry is chosen in order to have the best performance taking into account real engineering problems: it should be as small as possible in order to minimise the "dead region". Two different types of geometry have been considered: a parallel planes geometry and a cylindrical one: the parallel planes configuration is favoured by the fact that it does not distort the electric field and a larger number of "usable" events is expected at equal volumes.

5.2. Performance

The performance of the reconstruction of the events taking place inside the inner target has been studied for the parallel planes geometry using three different widths: 12.5 cm, 25 cm and 50 cm. Protons are considered "reconstructed" if their momentum is greater than 310 MeV/c (50 MeV of kinetic energy) when entering the LAr volume whereas a threshold of 53.8 MeV/c (10 MeV of kinetic energy) is set for charged pions. These cuts are set in order to make sure that the particle travels at least one centimetre in the LAr active volume so that it is possible to reconstruct a track (*i.e.* at least

3–4 hits are created by the reconstruction algorithm). As it is clear from the result in Table III the number of "usable" events does not scale linearly with the volume but it increases much more slowly. This is due to the fact that although the number of interactions that take place within the inner target do scale linearly with the mass, a particle created in a large inner target has less chances to enter the LAr volume than a particle created in a thin one. Hence, an inner target that minimises the non-active volume is more likely to be chosen. In Fig. 3 it is shown a QE event taking place within the inner target; in this event the proton momentum is 660 MeV/c.

TABLE III

Performance on event reconstruction for different widths (*i.e.* different masses) inner targets for a parallel planes geometry.

mass (ton)	2.69	5.37	10.74
width (cm)	12.5	25	50
total number of QE interaction per10^{21} p.o.t.	3278	6556	13112
QE protons(%)	50	30	19
QE full reconstruction (%)	36	22	14
QE full reconstruction (number per 10^{21} p.o.t.)	1178	1440	1832
total number of no-nQE interaction per 10^{21} p.o.t.	1853	3706	7412
no-nQE protons (%)	32	22	16
no-nQE π^+ (%)	94	85	71
no-nQE π^0 (%)	95	85	76
no-nQE full reconstruction (%)	27	17	9
no-nQE full reconstruction (number per 10^{21} p.o.t.)	500	630	670

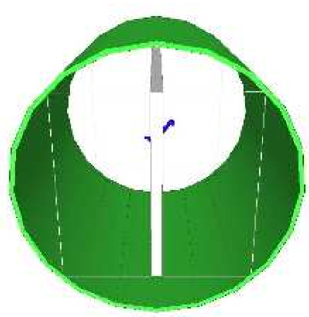

Fig. 3. QE event occurring inside the inner target. The proton momentum is 660 MeV/c.

The correction between Water and LAr is roughly 30%. According to Table III after one year we have 1178 fully reconstructed QE events that took place within the inner target, this means that the statistical error is about 3%. The statistical error will be therefore negligible compared to the expected systematics related to the reconstruction of about 10%. This means that the extrapolation from LAr to Water Čerenkov using the inner target will introduce a correction with an error of the order of 3% (10% × 30%) which is negligible compared to the Water Čerenkov systematics.

6. Conclusions

A 2 km facility has been proposed: at this distance the measured neutrino flux is almost the same as at SK, 295 km away. The flux would be measured with both a 1 kton Water Čerenkov detector which has been optimised to match SK resolution, and a 100 ton fiducial volume liquid Argon TPC which would provide fine grain imaging and low particle detection thresholds for a precise study of neutrino interactions at the relevant energies. The combination of a detector made with the same target as SK, with almost the same detector response, and an extremely fine grained tracking chamber sited on the off-axis beam, will allow for a prediction of the events with very little correction other than that of geometric acceptance. Dedicated simulation tools for T2KLAr geometry have been developed in order to assess detector performance and some results have been presented. It is therefore possible to state that the 2 km facility is the most straight-forward and cost-effective method to reach the best possible sensitivity in θ_{13} , Δm^2_{23} and θ_{23} by characterising the beam with the same flux and target as SK.

REFERENCES

[1] A. Ereditato, A. Rubbia, *Nucl. Phys. Proc. Suppl.* **139**, 301 (2005).

[2] `http://neutrino.ethz.ch/T2K.htm`

[3] A. Rubbia, *Nucl. Phys. Proc. Suppl.* **147**, 103 (2005).

[4] A. Ereditato, A. Rubbia, *Nucl. Phys. Proc. Suppl.* **154**, 163 (2006) [`hep-ph/0509022`].

[5] A. Ereditato, A. Rubbia, *Nucl. Phys. Proc. Suppl.* **155**, 233 (2006) [`hep-ph/0510131`].

[6] M. Fechner, Background extrapolation from T2K 2km detector, NuFact05 proceedings.