Benefits of Gd for High Energy Neutrinos in SuperK-Gd

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Abstract. The SuperK-Gd project is the approved upgrade of the Super-Kamiokande (SK) detector in order to enable it to efficiently (> 80%) detect thermal neutrons by dissolving 0.2% of gadolinium sulphate (Gd$_2$(SO$_4$)$_3$) into its water. This ability has also significant advantages in the analysis of high energy (> 10$^2$ MeV) neutrinos in SK, namely atmospheric and long baseline neutrinos from T2K. Here we present the improvements due to the use of the tagged final state neutrons in the separation of the interacting neutrinos and antineutrinos, the distinction between Neutral Current and Charged Current neutrino interactions, and the neutrino energy reconstruction. We study the impact of those features on both, atmospheric and long baseline neutrino oscillation analyses.

1. Introduction
Super Kamiokande (SK) is a 50 kton water Cherenkov detector located in the Kamioka mine under 1000 m of rock, which began the data taking in 1996. The detector is divided into inner and outer detector, the former is used for physics measurements and instrumented with 11146 20°-PMTs. The outer detector is used as a cosmic $\mu$ veto and is instrumented with 1885 8°-PMTs. The fiducial volume of the detector is 22.5 kton, 2 m away from optically dividing wall between inner and outer detectors.

The SK scientific achievements would improve dramatically if it is able to distinguish $\nu$ from $\bar{\nu}$ interactions, specially for the discovery of DSNB (Diffuse Supernova Neutrino Background) at energies $\mathcal{O}$(MeV) and of the neutrino mass hierarchy and the leptonic CP violation phase at energies $\mathcal{O}$(GeV).

SuperK-Gd [1] is the officially approved project for upgrading the SK detector by adding 0.2% by mass of Gd$_2$(SO$_4$)$_3$ into its water. Gd has the largest thermal neutron cross-section of all stable nuclei, about 49000 barn, capturing 90% of final state neutrons produced in the interactions once they have thermalised. In addition, around 35 $\mu$s ($\sim$ 15 $\mu$s (neutron thermalisation) + $\sim$ 20 $\mu$s (Gd capture and de-excitation)) after the neutron has been captured, the Gd de-excites emitting a $\gamma$-ray cascade with a total energy of 8MeV. This way, SK will be able to detect these neutrons with an efficiency of 80%.
2. Gd-neutron Tagging in High Energy Neutrino Physics

2.1. $\nu - \bar{\nu}$ Separation

Main interactions in the 0.1-10 GeV energy region are CC, being more likely for a $\bar{\nu}$ to have larger neutron multiplicity in the final state. Neutron multiplicity is the most relevant variable in the likelihood computation, done using a neural network, for the $\nu - \bar{\nu}$ separation. In average, $\sim \!70\%$ of true $\nu$ and $\bar{\nu}$ are correctly classified, which slightly varies depending on the neutrino energy.

2.2. NC-CCDIS $\nu_\mu$-CC$\nu_e$ Separation

Atmospheric MultiRing e-like sample contains $\nu_e$ in the most sensitive energy region to the MH, but it is largely contaminated with NC and $\nu_\mu$, mainly from CC-DIS interactions, which demean its potential MH sensitivity. NC events deposit a large fraction of the $\nu$ energy in the nucleus, implying a large neutron production due to the interaction of mesons inside the nuclear media. In addition, those $\nu_\mu$ coming from CC-DIS interactions show a halfway behaviour between NC and CC $\nu_e$ because they also deposit a large energy fraction in the nuclear media. Neutron multiplicity is crucial role in the likelihood computation, achieving $80\%$ of true NC and DIS are correctly classified.

2.3. Neutrino Energy Corrections

The more energetic is the incoming neutrino the more energy fraction is spent on neutral hadron production ($\pi$, $\eta$, $\kappa$...). Most of the times, these interact inside the nuclear media producing a significant amount of neutrons in the final state of the neutrino interaction. This suggests that the neutron multiplicity brings along information about the fraction of the neutrino energy invisible to the detector. Although it provides a huge improvement in the energy reconstruction its effect in the sensitivity is small due to the small statistics.

3. Application to Neutrino Oscillation Analyses

3.1. Long Baseline T2K Neutrinos

Neutron energy correction improves the energy reconstruction similarly to the usage of the precise knowledge of T2K $\nu$ incoming direction. Main impact of Gd-tagging on T2K oscillation analysis comes from $\nu - \bar{\nu}$ separation, which has a $78\%$ efficiency in this energy range. This significantly improves the sensitivity to CP violation discovery, GLoBES [2] is used, and $3.9 \cdot 10^{21}$ POT assumed.
3.2. Atmospheric Neutrinos

The sensitivity to the CP violating phase is improved due to the better classification of SubGeV neutrinos and antineutrinos. Plots below show the sensitivity for rejecting $\delta_{CP} = 0$ and the sensitivity to the wrong mass hierarchy rejection depending on $\theta_{23}$ for exposure equivalent to SK-IV lifetime, 2339 days. It is seen that, in addition, to the better MultiGeV event selection, the neutron energy corrections also improves the MH sensitivity.

References

[1] Beacom and Vagins 2004 Antineutrino Spectroscopy with Large Water Čerenkov Detectors Phys. Rev. Lett. 93 171101
[2] Huber Lindner Winter 2005 Simulation of long-baseline neutrino oscillation experiments with GLoBES, Comput. Phys. Commun. 167 195
[3] Fukuda et. al., (Super-Kamiokande Collaboration) 1998 Evidence for Oscillation of Atmospheric Neutrinos Phys. Rev. Lett. 1562–1567

Figure 4. Leptonic CP-phase sensitivity comparison for current SK (black) and for future SuperK-Gd (pink), for NH (left and continuous) and IH (right and dashed).

Figure 5. Neutron distributions for neutrino and antineutrino for the atmospheric MultiGeV e-like sample.

Figure 6. Neutron distributions for NC, CC-DIS and CC events for the atmospheric MultiRing e-like sample.