UPDATE TO THE NUPRISM PROPOSAL (P62)

THE NUPRISM COLLABORATION

1. Introduction

The NuPRISM experiment at J-PARC was first proposed at the previous J-PARC PAC meeting in July, 2015 [1]. The proposal was deferred pending further clarity about the future neutrino program at J-PARC. The full response from the PAC is reproduced below.

> The PAC recognizes the interesting physics goals of the experiment. NuPRISM would certainly be a very valuable addition to the future J-PARC neutrino physics program, especially in view of the Hyper-Kamiokande project. On the other hand, its impact on the current program is more limited. The PAC notes that the main goal of the presently approved T2K program (up to 7.8E21 POT), namely the measurement of the leptonic CPV phase, is expected to be statistically dominated. The PAC defers any decision about the status of this experiment until there is clarity about the future neutrino program at J-PARC. However, given the intrinsic physics interest of NuPRISM from a long-term perspective, the PAC encourages the continuation of R&D studies, including a possible optimization of the location.

Since the last PAC meeting, there have been several important developments regarding the intermediate Japanese neutrino physics program (i.e. prior to the Hyper-Kamiokande era). The T2K experiment has now presented an Expression of Interest for T2K-II, which will attempt a 3 σ measurement of CPV by collecting 20×10^{21} protons on target (POT). In the NuPRISM proposal, it has been shown that NuPRISM will have a significant impact on T2K's world-leading constraint on θ_{23} via ν_μ disappearance for the already-approved T2K POT of 7.8×10^{20}. However, as described in the PAC response above, the impact of NuPRISM on the standard T2K CPV sensitivity was more limited. As discussed in Section 2, this will no longer be the case for T2K-II, as the statistical errors will be reduced to the level of the systematic uncertainties. To reach 3 σ CPV sensitivity, T2K will need to achieve 2-3% systematic uncertainties. The dominant uncertainties are expected to come from the $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ and $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$ cross section ratios, and final state interactions within the target nucleus. Currently, these uncertainties are based purely on theoretical model calculations, and will not be accessible at the ND280 near detector complex. In order to make a robust claim of 3 σ evidence for CPV, these uncertainties must be constrained experimentally.

The other major development since the last PAC meeting is the decision by the Super-Kamiokande collaboration to approve the future loading of gadolinium in the SK detector to enhance the efficiency of neutron capture. This new capability has the potential to significantly reduce atmospheric neutrino backgrounds to proton decay searches, and to provide an additional mechanism to separate neutrinos and anti-neutrinos in both SK atmospheric neutrinos and T2K, which can significantly enhance the sensitivity to the neutrino mass hierarchy and CP violation (CPV), respectively. However, these improvements rely on a precise knowledge of neutron emission cross sections in neutrino and anti-neutrino interactions, which are currently poorly understood. As discussed in Section 3, NuPRISM is the ideal experiment for measuring neutron emission and capture in a Gd-loaded water Cherenkov detector, since the neutron signal can be measured as a function of incident neutrino energy and final state lepton kinematics.

NuPRISM is seeking stage-1 approval at the January 2016 PAC meeting to start the process of developing a full technical design for the detector. Although T2K-II has not yet been approved, the J-PARC main ring power supply upgrade has been approved by MEXT, which strengthens the case for continuing to run T2K beyond the currently approved POT to search for CPV. NuPRISM requires significant lead time to be ready to take data when T2K-II is scheduled to begin. In order to determine the feasibility of constructing NuPRISM in time for T2K-II, J-PARC resources are needed to investigate possible off-site locations for the detector, and to refine the cost estimates for the new facility.

Stage 1 approval is also necessary for international collaborators to continue their participation in the design of NuPRISM and to identify their contributions. In Canada, there is an opportunity to request \$8 million in capital funding for NuPRISM from the Canadian Foundation for Innovations's 2016 (CFI) Innovation Fund competition. Stage 1 approval by March, 2016 is essential for this request to proceed. The UK will be submitting a new 3-year proposal for Hyper-Kamiokande R& D to the Science and Technology Facilities Counsil (STFC) in late 2016. If a technical design of NuPRISM with a refined cost estimate is available by that time, a request for a several million dollar contribution to NuPRISM can be included. In other NuPRISM collaborating countries, such as Switzerland, Russia, Poland, and the United States, stage-1 approval will provide a basis for which new funding for NuPRISM can be sought.

2. NuPRISM and CP Violation Detection

The proposed T2K-II extension to T2K will accumulate 20×10^{21} protons on target (POT) by 2026. Potential beam line and analysis upgrades may further improve the sensitivity of the experiment to detect CP violation. For a favorable value of the CP phase, $\delta_{CP} = -\pi/2$, which is weakly favored by current neutrino oscillation data, T2K-II has the potential to achieve 3σ sensitivity, as shown in Fig. 1. With systematic errors included using the current preliminary update to the T2K systematic error model, the sensitivity barely crosses 3σ with an exposure of 20×10^{21} POT. This significance relies on a favorable value of δ_{CP} and the assumption of improvements to the T2K experiment and analysis equivalent to 50% more statistics. T2K-II will not have 3σ sensitivity if either of

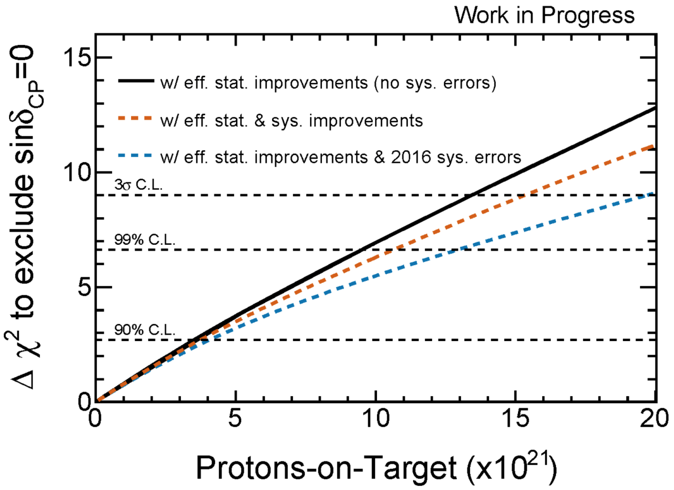

Figure 1. The significance of T2K-II to disfavor a non-CP violating value of δ_{CP} for a true value of $\delta_{CP} = -\pi/2$ as a function of the accumulated POT assuming 50% neutrino mode data and 50% anti-neutrino mode data. The sensitivity with systematic uncertainties is evaluated using the current preliminary systematic error model (blue dashed), or a systematic error model with uncertainties arbitrarily reduced to 2/3 of their current value (red dashed). For all curves, it is assumed that experimental and analysis improvements for T2K-II will yield the equivalent of a 50% improvement in statistics over the current T2K experimental configuration and analysis techniques.

these conditions are not true, or if the systematic uncertainties are larger than expected. Fig. 1 also shows that a reduction of the systematic errors to 2/3 of their current estimated values will improve the signficance such that the same sensitivity can be achieved with 75% of the statistics. The reduction of systematic uncertainties is required to achieve the best CP discovery sensitivity as soon as possible and also to ensure a robust search for CP violation in T2K-II.

The preliminary update of the T2K systematic error estimates is summarized in Table 1, which shows the fractional error on the predicted number of events at Super-K for both horn polarities, ν mode and $\bar{\nu}$ mode, and final state lepton flavors, 1-Ring μ and 1-Ring e. CP violation is detected primarily through the observation of an asymmetry in the oscillation rate observed in the 1-Ring e ν mode and $\bar{\nu}$ mode data samples. The final column in Table 1 highlights the systematic errors that impact the CP violation measurement most strongly by showing the uncertainty on the ratio of predicted 1-Ring e events in ν mode and $\bar{\nu}$ mode.

The systematic errors with the largest impact on the CP violation detection are the uncertainty on the pion final state and secondary interactions at Super-K (3.7%), and the uncertainties on the electron (anti)neutrino cross section differences from the muon (anti)neutrino cross section (3.1%). The final state and secondary pion interaction uncertainties arise from uncertainties on the cascade model that is used to model the pion propagation through the target nucleus and the Super-K detector. This model has been tuned to pion-nucleus scattering data, however, the uncertainty remains significant since there are large model uncertainties in applying the pion-nucleus scattering data, particularly for the modeling of the final state interactions, where the pion is produced inside the nuclear medium.

The uncertainty on the electron (anti)neutrino cross sections enters the measurement since the rates of muon (anti)neutrinos are measured in the near detector while electron (anti)neutrinos are detected in the far detector. Since conventional neutrino beams produce neutrinos from pion decays, there are no precision measurements of electron (anti)neutrino-nucleus scattering at $\mathcal{O}(1\text{ GeV})$ and experiments such as T2K rely on models of neutrino-nucleus scattering to account for the differences in the electron (anti)neutrino and muon (anti)neutrino cross sections. Theoretical uncertainties on the differences in the interaction cross sections have been estimated by Day and McFarland [2]. They include the uncertainty arising from the phase space differences due to the lepton mass difference, the uncertainty on the size of second-class currents, and radiative corrections. For the T2K beam, the error on the interaction rates is estimated to be 3% with significant anti-correlations between the neutrino and antineutrino rates. It should be emphasized that this uncertainty is a theoretical estimate. Given the challenges in the theoretical modeling of neutrino-nucleus interactions, the electron (anti)neutrino cross sections should be confirmed directly with measurements, particularly for an experiment that hopes to report a discovery of CP violation.

The uncertainties on the modeling of the Super-K detector response (1.9%), uncertainties on flux and cross section model parameters directly constrained by the ND280 data (2.4%), and the uncertainty on the NC1γ cross section (1.5%) also contribute significantly to the total systematic error.

NuPRISM measurements are used to reduce the systematic error on the CP violation measurement in a three-step approach, as outlined in the NuPRISM proposal. First, the event rate and final state particle kinematics at Super-K are predicted using the measurements of muon (anti)neutrino candidates in the off-axis angle slices of NuPRISM by applying the same linear combination method that was used for the muon neutrino disappearance analysis described in Section II.F of the NuPRISM proposal. For this procedure, the linear combination of NuPRISM off-axis spectra is used to reproduce the total electron (anti)neutrino flux at Super-K, as illustrated for neutrinos in Fig. 2. This procedure predicts the 1-Ring e rates at Super-K under the assumption of no mass difference between muon and electron (anti)neutrinos. Since the final states in NuPRISM and Super-K are identical, the effect of final state and secondary pion interactions will be directly measured by NuPRISM, removing the uncertainty from final state and secondary interaction modeling, the dominant systematic error estimated by T2K. This analysis step will also reduce the uncertainty on the cross section parameters directly constrained by ND280. The NuPRISM measurement will improve on the ND280 constraints by having nearly identical

Table 1. Errors on the number of predicted events in the Super-K samples from individual systematic error sources in neutrino (ν mode) and antineutrino beam mode ($\bar{\nu}$ mode). Also shown is the error on the ratio 1Re events in ν mode/$\bar{\nu}$ mode. The uncertainties represent work-in-progress for T2K neutrino oscillation results in 2016.

	$\delta_{N_{SK}}/N_{SK}$ (%)				
	1-Ring μ		1-Ring e		
Error Type	ν mode	$\bar{\nu}$ mode	ν mode	$\bar{\nu}$ mode	$\nu/\bar{\nu}$
SK Detector	4.6	3.9	2.8	4.0	1.9
SK Final State & Secondary Interactions	1.8	2.4	2.6	2.7	3.7
ND280 Constrained Flux & Cross-section	2.6	3.0	3.0	3.5	2.4
$\sigma_{\nu_e}/\sigma_{\nu_\mu}$, $\sigma_{\bar{\nu}_e}/\sigma_{\bar{\nu}_\mu}$	0.0	0.0	2.6	1.5	3.1
NC 1γ Cross-section	0.0	0.0	1.4	2.7	1.5
NC Other Cross-section	0.7	0.7	0.2	0.3	0.2
Total Systematic Error	5.6	5.5	5.7	6.8	5.6
External Constraint on θ_{12}, θ_{13}, Δm^2_{21}	0.0	0.0	4.2	4.0	0.1

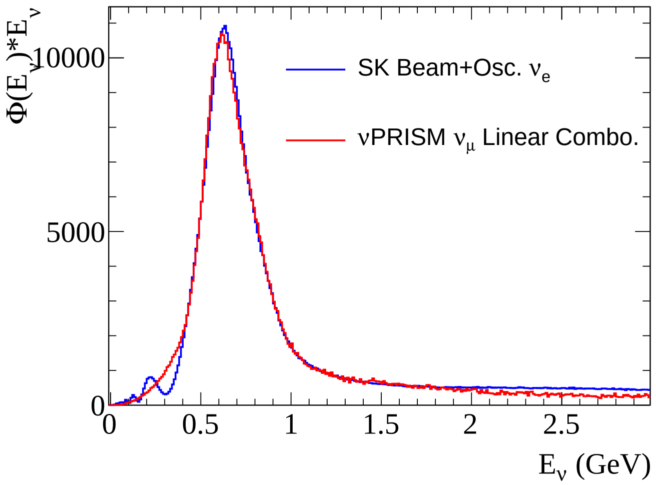

Figure 2. The predicted ν_e spectrum at SK including ν_e from oscillations and intrinsic ν_e (blue) and the spectrum derive from the linear combination of NuPRISM off-axis slices (red).

fluxes in the NuPRISM and Super-K, and by having the same target material and angular acceptance as Super-K.

The second step of the analysis is to directly measure the 1 Ring *e*-like component of the beam that is present in the absense of oscillations. This intrinsic background includes the intrinsic $\nu_e(\bar{\nu_e})$ in the beam from muon and kaon decays, the NC1γ interactions that are indistinguishable from ν_e-CC events, and the NCπ^0 interactions where the second γ is not reconstructed. At the 2.5° off-axis angle position of NuPRISM, the neutrino fluxes associated with these backgrounds are nearly identical to the fluxes at Super-K. This background can be directly measured in NuPRISM using the data taking at 2.5°.

The third NuPRISM input to the CP violation measurement is the measurement of the electron (anti)neutrino cross section relative to the muon (anti)neutrino cross section using the intrinsic electron (anti)neutrino content of the beam from muon and kaon three-body decays. This measurement is used to correct the Super-K prediction from the first step to account for the lepton mass difference. The potential for this measurement has been described in Section II.G of the NuPRISM proposal. There the statistical error for the measurement was estimated for the expected T2K+Hyper-K exposure, which was 1.45×10^{21} POT for the 2.5-4.0° degree off-axis angle range. If NuPRISM is built before 2020, the NuPRISM exposure during T2K-II for neutrino or antineutrino mode in the 2.5-4.0° degree off-axis angle range will be 1.5×10^{21} POT. At that exposure, the statistical error on the cross section measurement for the neutrino energy range of 300-600 MeV is 3%. This number may be improved by increasing the instrumented detector size. The flux uncertainties for the current T2K flux model and a model where hadron interaction modeling errors are reduced by 50% where also estimated in the NuPRISM proposal. The flux errors on the electron neutrino to muon neutrino cross section ratio measurement are estimated to be 3.2% with the current error model and 1.7% with the reduced error model. NuPRISM has the potential to measure the electron neutrino cross section with precision similar to or better than the currently estimated purely theoretical errors. For T2K-II, the exposure in antineutrino mode will be the same as the exposure in neutrino mode, hence the rate of electron antineutrinos is $\sim 1/4$ of the electron neutrino rate. While the NuPRISM measurement will be less precise due to fewer statistics, the required precision for the Super-K prediction is reduced by the same amount since the rate at Super-K is also reduced.

3. NuPRISM Physics with Gadolinium Doping

In 2015, the Super-K collaboration approved the plan to load the Super-K detector with 0.2% gadolinium sulfate, $Gd_2(SO_4)_3$ to enhance the neutron detection capability. Gadolinium, Gd, has a thermal neutron capture cross-section of 49,000 barns, 5 orders of magnitude larger than the capture cross-section on free protons. The neutron capture time for 0.1% Gd loading has been measured to be 28 μs [3]. The Gd-capture produces an 8 MeV gamma cascade which is detectable in NuPRISM.

The detection of neutron captures on Gd can be used to improve the sensitivities of measurements made at $\mathcal{O}(1\ GeV)$ energies. Proton decays are expected to produce a final state neutron less than 10% of the time [4], while atmospheric neutrino interactions have on average 1 or more final state neutrinos (depending on the energy) [5]. The detection of final state neutrons can be used to reduced the atmospheric neutrino background for proton decay searches. Among the atmospheric neutrino interactions, the final state neutron multiplicity is expected to vary depending on whether a neutrino or antineutrino interacts, and whether the interaction is quasi-elastic or inelastic. In the absence of final state and secondary interactions in the detector, the quasi-elastic scattering of a neutrino will produce no neutrons, while the quasi-elastic scattering of an antineutrino will produce a neutron. The presence of final state and secondary interactions will smear these distributions, but a statistical separation of neutrino and antineutrino interactions will be possible. The same neutron tagging can be applied to accelerator neutrino samples to reduce the wrong-sign contamination arising of neutrino (antineutrino) contamination in the antineutrino (neutrino) beam mode.

The application of neutron detection in the proton decay, atmospheric and accelerator neutrino measurements requires accurate knowledge of final state neutron multiplicities for $\mathcal{O}(1\ GeV)$ neutrino interactions. By loading NuPRISM with $\mathrm{Gd_2(SO_4)_3}$, the neutron multiplicities can be measured in the NuPRISM detector using the accelerator produced neutrino interactions. The capability to load NuPRISM with Gd has been described in Section III.H.1 of the NuPRISM proposal. The primary challenge for Gd loading is containment of the Gd loaded water to avoid leaking into the local environment. For containment, a water tight instrumented detector tank is being considered. The determination of the NuPRISM site location is a critical input for the tank design since the size of the instrumented region will depend on the baseline from the neutrino source to NuPRISM.

The backgrounds for neutron detection in NuPRISM have been considered. The dominant background is neutrons that are produced in the outer detector (OD) or surrounding rock from interactions of beam neutrinos. These neutrons coincide with the beam timing, so they cannot be reduced by a timing cut around the beam spill arrival time. The simulated rate of entering neutrons is described in Section II.D.2 of the NuPRISM proposal. The entering neutron rate is estimated with a GEANT4 simulation of the NuPRISM water column and the surrounding rock with neutrino interactions simulated by NEUT 5.1.4.2. The simulation results presented in the proposal assume a 1 km baseline to NuPRISM and 1.6×10^{14} protons per spill. The current accelerator performance projection is for 3.2×10^{14} protons per spill after 2025, hence the simulation has been updated for twice the protons per spill. The potential of an OD veto to select events with a reduced number of entering neutrons has also been investigated. Table 2 shows the rates of neutrons entering the inner detector (ID) for 320 kA horn currents at three different off-axis positions. In the most on-axis position the average neutron rate is 3.89 events for a 4 m radius ID and 2.28 for a 3 m radius ID. The entering neutron rate can be reduced by 27% and 36% respectively by only selecting spills with less than 6 visible interactions in the OD. The background may also be reduced by applying a tight fiducial cut on the reconstructed neutron vertex to exclude neutron captures near the detector wall. Since neutrons produced in a neutrino interaction will typically capture within 1-1.5 m of the primary neutrino interaction, the background can be further reduced by selecting neutron captures near the neutrino interaction vertex, excluding most entering neutrons which will have reconstructed vertices near the detector wall. In the further off-axis positions the entering neutron rate is reduced and a tighter OD

Table 2. The entering neutron rates per 3.2×10^{14} protons on target for NuPRISM with horn currents at 320 kA.

	No OD Veto		< 6 OD Interactions	
Off-axis Angle (°)	ID r=4 m	ID r=3 m	ID r=4 m	ID r=3 m
1.0-1.6	3.89	2.28	2.84	1.46
2.0-2.6	1.26	0.70	1.26	0.70
3.0-3.6	0.48	0.28	0.48	0.28

veto is required to reduce the entering neutron rate. After OD and vertex position cuts the remaining neutron background can be directly measured in spills with no ID interactions, and a statistical subtraction can be applied to the neutron multiplicity measurements. It is expected that the entering neutron rate at 1 km is low enough to perform neutron multiplicity measurements, however given the uncertainties associated with neutron production and low energy neutron scattering, the rate of neutrons produced in the rock should be measured with a dedicated experiment after NuPRISM achieves Stage 1 approval.

The number of charged current ν_μ candidate events expected in NuPRISM for the T2K-II exposure is 2×10^6, 1×10^6 and 4×10^5 for the 1.0-2.0°, 2.0-3.0° and 3.0-4.0° off-axis angle positions respectively. Given these large sample sizes, precision measurements of the neutron multiplicities will be possible, even with tight cuts on the OD activity and vertex position. For given four-momentum transfers, the neutron multiplicities for ν_μ and ν_e interactions are expected to be the same, so the ν_e neutron multiplicity rates can be constrained with the ν_μ candidate data.

NuPRISM can perform unique measurements of the neutron multiplicities that are not possible in other experiments. As illustrated in Fig. 3, the three momentum and energy transfer can be reconstructed for NuPRISM mono-chromatic beams, or the energy can be reconstructed using the quasi-elastic formula, and quasi-elastic and non-quasi-elastic events can be separated kinematically. By measuring the neutron multiplicity as a function of three momentum and energy transfer, the NuPRISM measurements can be applied to different neutrino energies, including higher energy interactions in the SK atmospheric sample. By kinematically separating the quasi-elastic and non-quasi-elastic events, NuPRISM can measure neutron multiplicities for both event types. Any differences can be used to statistically separate quasi-elastic and non-quasi-elastic types in Super-K, improving the reconstructed energy resolution for atmospheric neutrino and accelerator neutrino measurements.

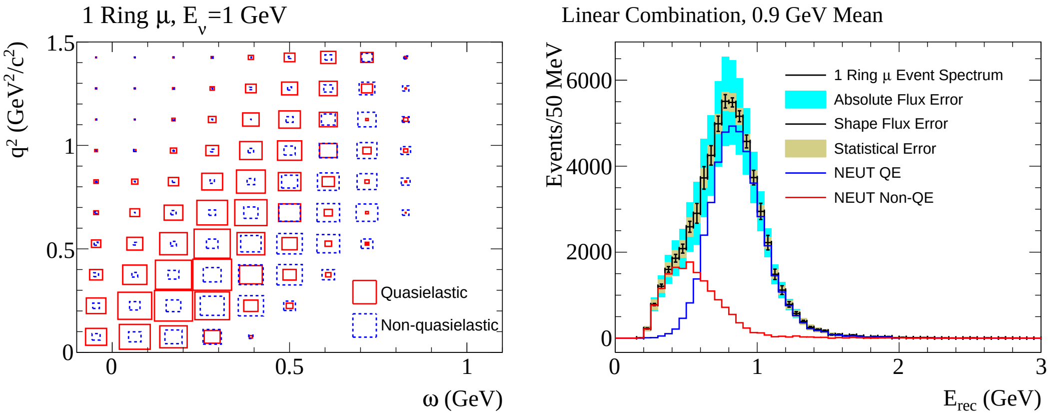

Figure 3. The distribution of reconstructed three momentum and energy transfer for a 1 GeV mono-chromatic beam in NuPRISM (left) and the distribution of reconstructed energy for a 0.9 GeV mono-chromatic beam in NuPRISM (right).

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