Expression of Interest:
Atmospheric Neutrino Neutron Interaction Experiment

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on behalf of the ANNIE Collaboration:

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Fermilab PAC Meeting
January 22, 2014
What is ANNIE?

- A measurement of the abundance of final state neutrons from neutrino interactions in water, as a function of energy.

First use of Large Area Picosecond Photodetectors (LAPPDs) in the context of a small, gadolinium-doped Water Cherenkov detector.

a key measurement for proton decay physics, supernova neutrino detection in water, and fundamental neutrino interaction physics
Motivation

Proton decay searches in planned megaton-scale water Cherenkov detectors such as Hyper-K could achieve unprecedented sensitivity.

However, at such scales, backgrounds from atmospheric neutrinos become problematic.

The backgrounds from atmospheric neutrinos typically produce final state neutrons, whereas PDK rarely does.

Neutron tagging could significantly reduce these backgrounds, but first we need to understand how many neutrons are produced.
Neutron Tagging

Neutrino interactions typically produce one or more neutrons in the final state.

On free protons: Charged Current (CC) interactions produce one neutron.

On heavier nuclei: Both CC and Neutral Current (NC) events can produce excitations and collisions that can kick out more than one neutron.

The number of neutrons depends on (1) the momentum transfer and (2) the particular type of interaction. *How* they depend on these factors is poorly understood.

- The presence or absence of neutrons in the final state can help to discriminate between neutrino interactions and other processes (proton decay)
- The number of neutrons provide a handle with which to discriminate between different kinds of neutrino interactions
**SN neutrino detection**

- Neutron tagging can be used to separate between diffuse supernova background (DSNB) neutrinos and various backgrounds.
- In core collapse Supernovae, the technique can be used to statistically discriminate between various CC, NC interactions and neutrino-electron scattering. It provides some extra information about the flavor dependent fluxes.

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**Neutrino interaction Physics**

Neutron abundances may make it possible to statistically separate between neutral current and charged current interactions.

Neutron multiplicity is also sensitive to differences between 1-body and 2-body currents (where neutrinos scatter off of correlated pairs of nucleons).

Nuclear models present the largest systematics in water-based oscillation experiments.
“ANNIE Hall”
(formerly the SciBooNE pit)

- Veto on muons produced upstream of the detector
- 3m x 3m x (2-3) m tank of Gd enhanced water
- Existing Muon Range Detector (MRD): steel with scintillating bars in between. Stop the muons, measure their energy.
• Expected proton decay backgrounds typically come from interactions between 1-5 GeV.

• The Booster Neutrino beam line provides an energy spectrum peaked near 1 GeV.

• We will see several hundreds of $\nu_\mu$ CC interactions per $10^{20}$ POT per ton in the relevant window, and several tens of events at the highest energies.

• Requiring more than 2 layers hit in the MRD, cuts out low-energy events, but keeps events in the relevant range.

<table>
<thead>
<tr>
<th>$\nu$-type</th>
<th>Total Interactions</th>
<th>Charged Current</th>
<th>Neutral Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$</td>
<td>10210</td>
<td>7265</td>
<td>2945</td>
</tr>
<tr>
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<tr>
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<td>4.4</td>
<td>3</td>
<td>1.4</td>
</tr>
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</table>

Table 1: Rates expected in 1 ton of water with $1x10^{20}$ POT exposure at ANNIE Hall.

• Measured PDK-like bkgd events
The ANNIE Detector System
The ANNIE Detector System

Front Anti-Coincidence Counter

Gd-loaded water volume

Conventional PMTs

LAPPDs

Muon Range Detector

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ANNIE - basic concept
ANNIE – basic concept

- A muon is produced and detected in the MRD
- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light
**ANNIE – basic concept**

- A muon is produced and detected in the MRD
- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light
- Neutrons thermalize
• A muon is produced and detected in the MRD
• LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light
• Neutrons thermalize and stop
ANNIE – basic concept

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- Several tens of microseconds later, the neutrons are captured and produce somewhat isotropic flashes of light from typically 3 gamma showers (8 MeV)
ANNIE – basic concept

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- LAPPDs used to reconstruct vertex position based on arrival of Cherenkov light
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- Several tens of microseconds later, the neutrons are captured and produce somewhat isotropic flashes of light from typically 3 gamma showers (8 MeV)
Timing-based vertex reconstruction is essential to this measurement

Neutrons typically drift over a 2 meter distance.
- In the directions transverse to the beam, this 2-meter window is centered symmetrically about the interaction point.
- In the direction of the beam, it is mostly forward with respect to the interaction point.

In order to get a clean sample of neutrons, this analysis must be restricted to a small ~1 ton fiducial volume situated sufficiently far from the walls of the tank to stop the neutrons.

In order to identify events in this fiducial volume, we need to reconstruct the interaction vertex to better than 10 cm. Accurate timing based reconstruction from the Cherenkov light is essential. **LAPPDs are critical to providing this capability.**
ANNIE Will Likely be the First WCh-Based Physics Measurement to Use LAPPDs

The Large Area Picosecond Photodetectors (LAPPD):

- large, flat-panel, MCP-based photosensors
- <50 psec time resolutions and <1cm spatial resolutions
- based on new, potentially economical industrial processes.
- LAPPD design includes a working readout system.
- Phase I of the commercialization effort by Incom, Inc was very successful

\[ \sigma = 44 \text{ psec} \]

2896 events

\(~44 \text{ psec}\)
Preliminary studies indicate that LAPPDs will meet our performance need.

New technologies often require new reconstruction strategies.

Groups at U Chicago, Iowa State, and Argonne have done considerable work on the application of LAPPDs to W Ch detectors.

Some work has been done to study vertex reconstruction, using a simple algorithm combined the track direction as given by the MRD. These studies give preliminary vertex resolution typically below 5 cm.

These techniques need to be further developed and optimized for the ANNIE detector.

Will compare also test track reconstruction algorithms based purely on LAPPDs (without information from the MRD). Will also study different coverages.
Summary of Tasks/Expertise

- Operation of LAPPDs in a Water Cherenkov detector
  - adapt electronics
  - operational demonstrations
  - submersion in water
- Implementation of reconstruction strategy
  - simulations guided design
  - optimization of timing based reconstruction

<table>
<thead>
<tr>
<th>Task</th>
<th>Expertise</th>
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<tbody>
<tr>
<td>LAPPDs</td>
<td>ANL, U Chicago</td>
</tr>
<tr>
<td>Electronics</td>
<td>U Chicago/ U Hawaii</td>
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<tr>
<td>Conventional PMTs</td>
<td>UC Davis, UC Irvine</td>
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<tr>
<td>Water System</td>
<td>UC Davis, UC Irvine</td>
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<tr>
<td>Simulations and Reconstruction</td>
<td>Iowa State, U Chicago, Queen Mary, UC Irvine</td>
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Timeline

**Preparation**
- Monte Carlo Studies
- Optimize Tank Design
- Optimize Photosensor Coverage
- Design of Font-end and DAQ

**Commissioning**
- Single LAPPD Beam-Tests
- Construction of Tank
- Installation of PMTs
- Installation of FACC

**First Data**
- Final Commissioning
- Systems Integration
- Staged LAPPD Installation
- First Data Runs

2014  2015  2016

More data taking as necessary
• Opportunity to make an important physics measurement.
• High impact on a variety of physics analyses including a near factor of 5 improvement in PDK reach, plus neutrino sign selection vis neutron capture in WCh detectors.
• Opportunity for technological diversity and advanced detector R&D with low footprint.
• First demonstration of LAPPDs in an advanced WCh detector
• Much of the development work has been started. Main development work involves implementation, some customization, and systems testing.
• PAC endorsement of the physics and R&D mission of ANNIE would go a long way in moving this effort forward.

At these early stages, we request modest support from Fermilab in the form of computing resources, and technical expertise in exploring the best ways to utilize “ANNIE Hall”.
Closing Thoughts

• Opportunity to make an important physics measurement.
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$\pi^0 \rightarrow \gamma \gamma$

reconstructed
Backup Slides
Why a Water Cherenkov Experiment?

Especially for the e+pi0 channel, the most sensitive planned experiments are very large WCh detectors such as Hyperkamiokande.

This measurement is relevant to those future searches and therefore must be done in water.

Also, this is not a conventional WCh detector – it is an advanced R&D detector. One cannot know the future budgetary and physics landscape. New technologies provide opportunities that previously were not even foreseeable.
Why do we need to know the number of neutrons? Isn’t neutron tagging a yes/no proposition?

In many cases, neutron tagging will be used to discriminate between different neutrino interactions based on average neutron abundance, rather than merely the presence or absence of a neutron.

In the case of proton decay, the presence of a neutron can be used to reject background events. If neutron detection efficiency is <1, the absence of a neutron alone cannot provide confidence in the observation of PDK.
Doesn’t a tighter momentum cut reduce the backgrounds enough?

Tighter momentum cuts to select only free proton decays do succeed in reducing backgrounds from a few events per Mton per year to 0.15 events per Mton per year (roughly a factor of 10 reduction). However, they also reduce the efficiency, so you have to run for twice as long. This means a factor of 5 improvement in integrated sensitivity. Still good, but could use further improvements.

Also, these arguments apply largely to limit-setting. In the case of an observed candidate, one would still like an unambiguous signature. Neutron tagging will greatly help, in this regard.
Will LAPPDs Be Ready?
Some example neutrino–neutron production mechanisms

- direct interaction of an anti-neutrino on a proton, converting it into a neutron
- secondary (p,n) scattering of struck nucleons within the nucleus
- charge exchange reactions of energetic hadrons in the nucleus (e.g., $\pi^-+p\rightarrow n+\pi^0$)
- de-excitation by neutron emission of the excited daughter nucleus
- capture of $\pi^-$ events by protons in the water, or by oxygen nuclei, followed by nuclear breakup
- secondary neutron production by proton scattering in water
For water, 20% of all protons are essentially free. If these decay, there is no neutron produced as the $\pi^0$ would decay before scattering in the water, and 400 MeV electrons rarely make hadronic showers that result in free neutrons.

Oxygen is a doubly-magic light nucleus, and hence one can use a shell model description with some degree of confidence. Since two protons are therefore in the $p_{1/2}$ valence shell, if they decay to $^{15}$N, the resultant nucleus is bound and no neutron emission occurs except by any final state interactions (FSI) inside the nucleus.

Similarly, if one of the four protons in the $p_{3/2}$ state decays, a proton drops down from the $p_{1/2}$ state emitting a 6 MeV gamma ray, but the nucleus does not break up except by FSI.

Finally, if one of the two $s_{1/2}$ protons decays, there is a chance that the nucleus will de-excite by emission of a neutron from one of the higher shells.

8% x 80% = 6% proton decays with neutrons (Ejiri)

- Neutron production in proton decay events?

<table>
<thead>
<tr>
<th>Hole</th>
<th>Residual</th>
<th>States</th>
<th>$(k)$</th>
<th>$E_\gamma$</th>
<th>$E_p$</th>
<th>$E_n$</th>
<th>$B(k)$</th>
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<td>$^15$N</td>
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<td>0</td>
<td>0</td>
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<td></td>
<td>7.03</td>
<td>$^2$</td>
<td>$^{14}$C</td>
<td>7.03</td>
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<td>0</td>
<td>0.02</td>
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<td></td>
<td>g.s.</td>
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<td>0</td>
<td>0.01</td>
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<tr>
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<td>$^{14}$C</td>
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<td>~21</td>
<td>0</td>
<td>0.02</td>
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<tr>
<td></td>
<td>7.01</td>
<td>$^2$</td>
<td>$^{14}$C</td>
<td>7.01</td>
<td>~14</td>
<td>0</td>
<td>0.02</td>
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<td>~11</td>
<td>0</td>
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<td>$\leq$ 3–4</td>
<td></td>
<td></td>
<td></td>
<td>0.16</td>
</tr>
</tbody>
</table>

Are LAPPD–based WCh Detectors Scalable?

Figure 7: Resolution of timing based vertex fits in the direction transverse to the track direction, as a function of photosensor resolution. There is a factor of 3 improvement as the photosensor resolution goes from 2 nsec to 100 spec.

Since ANNIE is a beam physics measurement, it will be possible to trigger on beam spills. Nonetheless, given the proximity of ANNIE to the surface, we expect some pileup from cosmic rays and there may even be spallation backgrounds. Understanding and addressing the difficulties presented by near-surface operation will be important to study.

4.2 Implementation of Event Reconstruction Strategy

4.2.1 Optimization of Timing-based Reconstruction Techniques

Over the last several years, many novel approaches to WC event reconstruction have been developed and applied to existing and proposed physics experiments. Pattern-of-light fitting techniques, such as those developed for the MiniBooNE collaboration [46] and T2K [47], show promise as a way to maximally extract information from Water Cherenkov detectors. Another interesting approach uses Graphics Processing Units (GPUs) and ray-tracing algorithms to parallelize and quickly propagate photons through the large detector geometries [48]. However, even the great success of these techniques is limited by certain technological assumptions imposed by PMTs. For example, in both the MiniBooNE and T2K reconstruction codes, the timing and charge likelihoods are factorized and calculated separately. This reflects the fact that direct correlations between the positions and times of hits are lost in PMT electronics. With LAPPDs, it may be possible to implement these same approaches with a single likelihood based simultaneously on the positions and times of each hit.

Precision timing is showing promise in improving the capabilities of WC detectors. Continuing work from a group based out of Iowa State University, the University of Chicago, and Argonne National Laboratory sees a factor of 3 improvement in muon vertex resolutions for large, low-coverage detectors with 50 picosecond resolution, rather than a more typical 2 nanoseconds (Fig 7). A causal Hough Transform [50] could even be used to image tracks and EM showers from the positions and times of detected photons, producing reconstructed event displays resembling those of Liquid Argonne detectors (Fig 8) [51]. In fact, one can think of WC detectors with fine time and spatial granularity as "Optical Time Projection Chambers (TPCs)" with the transit time of photons (instead of electron-hole pairs) used to reconstruct events [52].

Continued work on these techniques and, above all, validation in real data will be critical to the
Did Super Kamiokande Make This Measurement?

Super K Collaboration

Neutrons per event vs. Evis (MeV)

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Adapting LAPPDs for Water Cherenkov Detectors

Subtasks:

- Further adapt readout system to our experimental needs (precision, buffer depth, acquisition rates)
- Work out techniques for hi-potting in water
- Operational testing on a small scale

![Graph showing events and time in nsec]

~44 psec

2896 events
More on the MRD

- 12 planes of 2 inch iron plates, and 13 planes of scintillator strips
- Vertical scintillator strips are 0.6x138x20, with 13 strips in two sections, for a total of 182 vertical strips in 7 planes
- Horizontal strips are 0.6x155x20, with 15 strips in two sections, for a total of 180 vertical strips in 6 planes
Task 3 - Development and Benchmarking of Timing-based reconstruction

Figure 7: Resolution of timing based vertex fits in the direction transverse to the track direction, as a function of photosensor resolution. There is a factor of 3 improvement as the photosensor resolution goes from 2 nsec to 100 spec.

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### More Details on the Booster Neutrino Beam

#### Table 1: Rates expected in 1 ton of water with $1 \times 10^{20}$ POT exposure at ANNIE Hall.

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More on Neutrino Interaction Physics

Nuclear effects play a large role in neutrino interactions at the energies of most current and future-planned oscillation experiments. They are among the largest systematics in precision oscillation measurements.

Neutron abundance measurements provide more detailed information on final states and can shine some light on the underlying nuclear physics.

Neutron abundances may make it possible to statistically separate between neutral current and charged current interactions.

Neutron multiplicity is also sensitive to differences between 1–body and 2–body currents (where neutrinos scatter off of correlated pairs of nucleons).
FIG. 1. Spectra of low-energy $\bar{\nu}_e + p \rightarrow \mu^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

FIG. 46. Total events in WC showing contribution from the different interaction channels, for neutron-tagged (left) and untagged (right) events.

FIG. 47. Total events in WC showing contribution from the different flavors, for neutron-tagged (left) and untagged (right).
More on LAPPDs
More on LAPPDs