ANNIE:
Accelerator Neutrino Neutron Interaction Experiment

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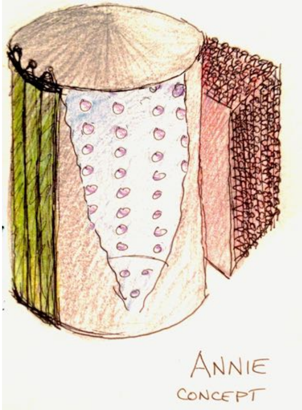
What is ANNIE?

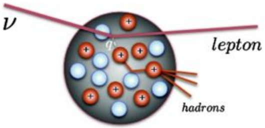
- ANNIE stands for Accelerator Neutrino Neutron Interaction Experiment

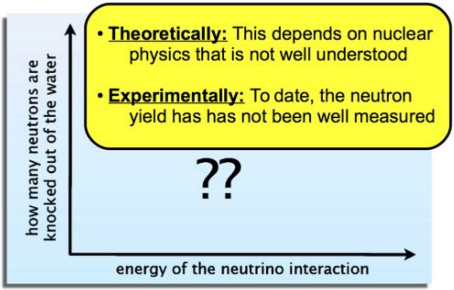


- $\sim$ 20 ton Water Cherenkov Detector
- 9 feet in diameter and 13 feet tall (2.74 m $\times$ 3.96 m)
- Gadolinium-doped water
- To be located in the SciBoone Hall in Fermilab
- Phase I (technical development and background characterization) is ongoing
- Read more: Letter of Intent

Motivation

- Primary Goal: A measurement of the abundance of final state neutrons (neutron yield) from neutrino interactions in water, as a function of energy.





Q: Why do we want to know this?
A: Relevant to studies of:

- Proton decay measurements
- Supernova neutrino observations
- Neutrino interaction physics

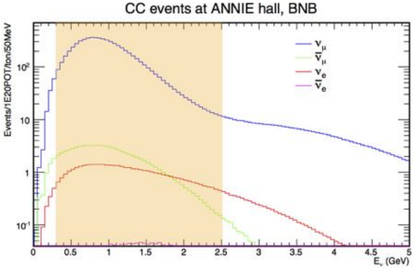
- Also: technical development

The neutrino beam

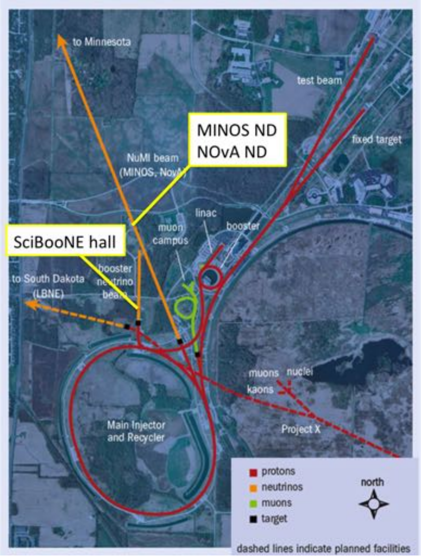
- We need 3 things in a beam:
  - Energy peaked in the range of the proton mass/atmospheric neutrino flux
  - Statistics
  - Low pileup rate
- ANNIE is designed to run in the Booster Neutrino Beam (BNB) at Fermilab. ANNIE will be situated in the former SciBooNE hall

Relevant BNB statistics at this site:

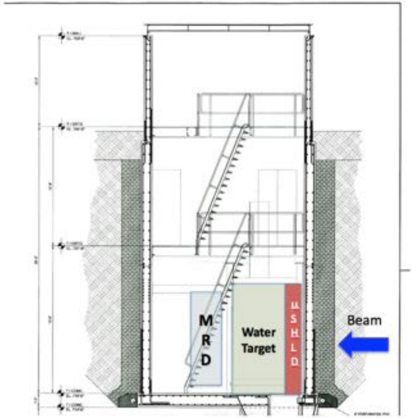
- On-axis neutrino beam
- 100 meters from target
- 4×10^{12} P.O.T. per pulse
- $\sim$ 700 MeV peak energy
- 93% pure ν_μ (in ν mode)
- $\sim$ 7 k ν_μCC events / 1E20 POT



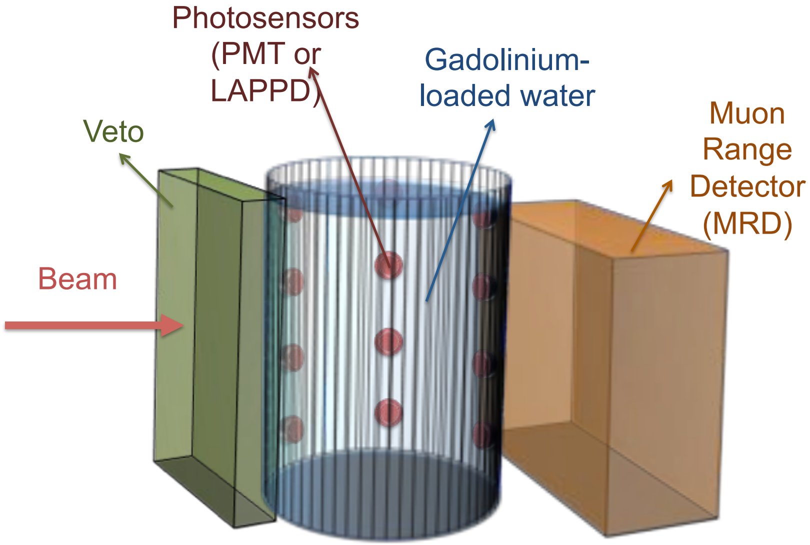
ANNIE location at Fermilab



The SciBoone 'pit'

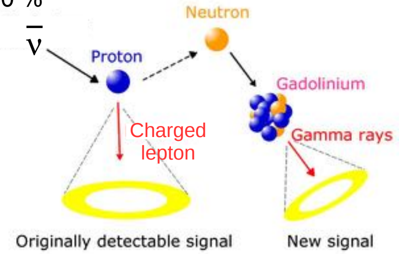


Major components of ANNIE



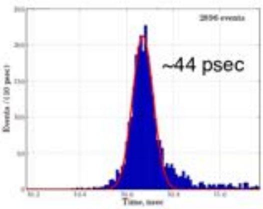
Gadolinium doping

- In ordinary water: n thermalizes, then is captured on a free proton
  - Capture time is ~200 μsec
  - 2.2 MeV gamma emitted
  - Detection efficiency @ SK is ~20 %
- When n captured on Gd:
  - Capture time ~20 μsec
  - ~8 MeV gamma cascade
  - 4 - 5 MeV visible energy
  - 100% detection efficiency

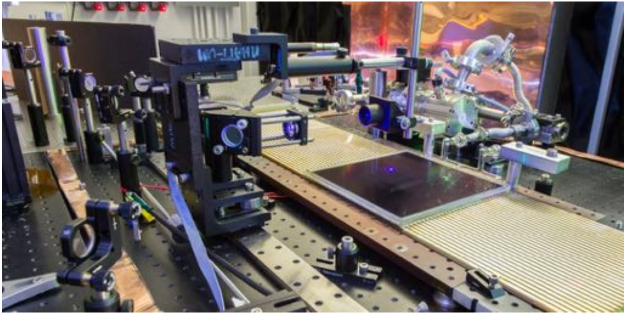


LAPPDs

- Large Area Picosecond Photo-Detectors (LAPPDs) are:
  - Large, flat-panel multi-channel plate (MCP) based photosensors
  - Based on new, potentially economical industrial processes
- ANNIE will be the first use of LAPPDs in water, as well as first use in a high energy physics experiment
  - Pioneering work for other HEP expts (*e.g.*, Ar-based ν & DM)
  - High spin-off potential for medical imaging, etc.
- LAPPDs offer:
  - **50 – 100 psec** timing resolution
  - **< 1 cm** spacial resolution
    - Imaging sensors, can resolve individual hits on a single module
    - May be possible to reconstruct track parameters from light on a single tile!



LAPPDs



- ANNIE will take advantage of *hybrid* photosensor deployment:
  - A few LAPPDs (10 – 20?) to do precise vertex reconstruction for HE events
  - A larger number (100 – 200) of PMTs will:
    - Obtain energy reconstruction for HE beam muons
    - Gather light from delayed neutron capture for neutron multiplicity studies

Phased approach

Sept 2015

- Installation

- Phase I: Test experiment:
  - measurement of neutron backgrounds
  - operate the water volume with PMTs
  - ready for testing of limited number of LAPPDs when available

Dec 2015

- Phase II: First physics run:
  - limited, but sufficient LAPPD coverage
  - focus on CCQE-like events

Dec 2016

- Phase III: Second physics run:
  - full LAPPD coverage (10-20%)
  - more detailed even reconstruction
  - compare neutron yields for CC, NC, and inelastic

Dec 2017

More about phase I

Available components:

- ANNIE tank with the 58 working Type-S PMTs, an inner volume of Gd-water
- existing WATCHMAN readout
- 1+ LAPPDs

Technical goals:

- Operation of the type-S PMTs in water
- Basic electronics - ability to see beam structure, prompt evt, and delayed captures
- In situ optical calibration with pulsed LED or fiber laser
- Neutron calibration with a source?
- Data-MC certification

Physics goals:

- Comparison of in situ and ex situ measurements of neutron rates
- Understand skyshine and dirt neutrons - rates, position dependence, time structure

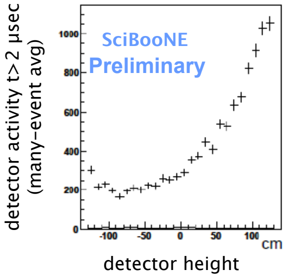
More about phase I: backgrounds

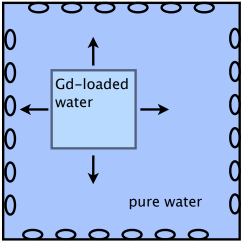
ANNIE will see neutron backgrounds from 2 sources:

- **skyshine:** neutrons from the beam dump migrating into the Hall from above
- **dirt neutrons:** neutrons produced by neutrino interactions in the rock, upstream of the detector

We need to understand these backgrounds before we determine the final configuration of ANNIE.

With a Phase I detector, we can test the first LAPPDs submerged in water, as they become available.





Summary

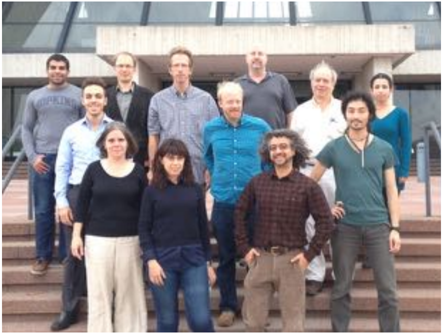
- ANNIE will measure neutrino-nucleus interactions in the energy range of atmospheric neutrinos
- Primary physics goal is neutron yield as a function of neutrino energy
- Technical goals include:
  - First Gd-doped water Cherenkov detector to run in a neutrino beam
  - First application of LAPPDs in water and for high energy physics
- ANNIE Phase I is currently ongoing!
  - Finishing planning and starting construction this summer
  - Primary goal is Background neutron measurement
- Read more: http://arxiv.org/abs/1504.01480

The ANNIE collaboration

34 collaborators

15 Institutions

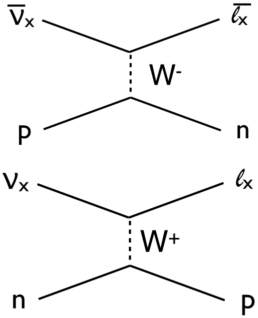
- Argonne National Laboratory
- Brookhaven National Laboratory
- Fermi National Accelerator Laboratory
- Imperial College of London
- Iowa State University
- Johns Hopkins University
- MIT
- Ohio State University
- Ultralytics, LLC
- University of California at Davis
- University of California at Irvine
- University of Chicago, Enrico Fermi Institute
- University of Hawaii
- Queen Mary University of London



Backup

Final State neutrons I

Final State Neutrons



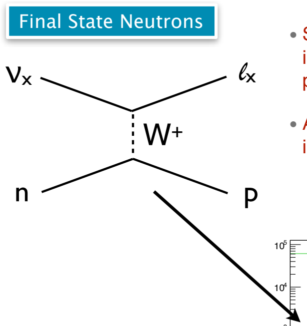
At the tree level, neutrino-nucleon interactions produce either one or zero neutrons

However, a variety of more complicated neutrino-nucleus interactions enhance the likelihood of one or more final-state neutrons

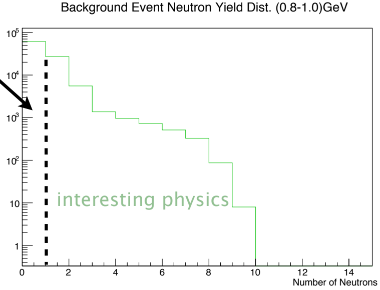
The abundance of final state neutrons is a strong handle on various neutrino nucleus models

Also a strong handle for discriminating between signals and backgrounds in various neutrino and PDK analyses

The theoretical underpinnings of this observable are not well known
FS neutron abundances have not been well measured



- Studying neutron yields for a pure neutrino beam is particularly interested, because the trivial case produces **NO** neutrons.
- Any final state neutrons will come from the interesting physics we want to study!



Final State neutrons III

Neutron Production Mechanisms

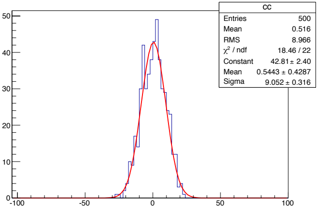
- secondary (p,n) scattering of struck nucleons within the nucleus
- charge exchange reactions of energetic hadrons in the nucleus (e.g., $\pi^- + p \rightarrow n + \pi^0$)
- de-excitation by neutron emission of the excited daughter nucleus
- capture of π^- events by protons in the water, or by oxygen nuclei, followed by nuclear breakup
- Meson Exchange Currents (MEC), where the neutrino interacts with a correlated pair of nucleons, rather than a single proton or neutron.
- secondary neutron production by proton or neutron scattering in water

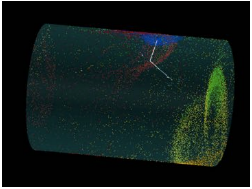
Simulations

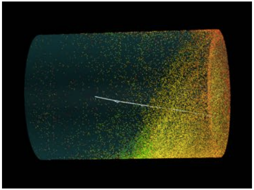
We've developed a fast MC for studying detector optimization - now used by ANNIE and some Hyper-K collaborators

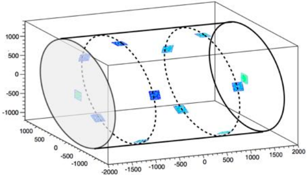
Studies of vertex resolution are underway

We're developing a strategy for managing the basic physics with low (<15) LAPPD coverage



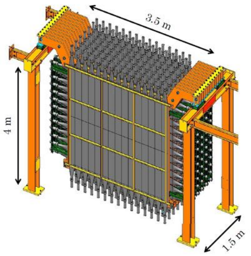






MRD

Muon Range Detector



Not needed for year 1. Exploring 2 options:

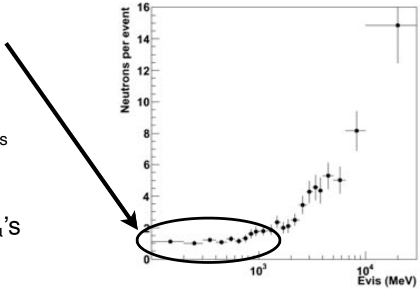
- Refurbish SciBooNE MRD
  - Structure and steel has been transferred from Morgan Wasco
  - Needs PMTs
- ANL digital HCAL group has joined ANNIE and are offering their RPC based system as an MRD (possibly magnetizable).

Did SuperK measure neutron yields?

Measurement published 2011 conference proceeding:

Neutron yields as a function of E_{vis} from atmospheric neutrino interactions.
Neutrons were detected from capture on pure water (efficiency ~19%)

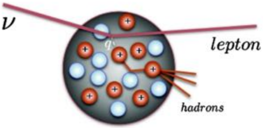
Neutron yields at the energies of interest are just on the edge of being useful.



Neutrino energy is approximated from E_{vis} alone, since direction is not known. Moreover, these yields average over neutrino and anti-neutrino interactions, ν_μ's and ν_e's.

We really need a controlled beam experiment, where we can use more detailed kinematic variables, and where we can identify neutron production for different flavors and interaction types.

Neutrino Interactions



Studies of neutrino-nucleon interactions are interesting in their own right!

- To turn neutrino physics into a precision science we need to understand the complex multi-scale physics of neutrino-nucleus interactions.
  - Dominant source of systematics on future long baseline oscillation physics
  - Source of uncertainty and controversy in short baseline anomalies
- The presence, multiplicity and absence of neutrons is a strong handle for signal - background separation in a number of physics analyses
- ANNIE is a final-state $X + Nn$ program to complement $X + Np$ measurements in LAr

Water Cherenkov detectors and Gd doping I

- Even moderately energetic neutrons ranging from tens to hundreds of MeV will quickly lose energy by collisions with free protons and oxygen nuclei in water.
- Once thermalized, the neutrons undergo radiative capture, combining with a nearby nucleus to produce a more tightly bound final state, with excess energy released in a gamma cascade.
- Neutron capture in pure water typically produces around 2.2 MeV in gamma particles (γ). However, these low energy photons produce very little optical light and are difficult to detect in large WCh tanks.
- The introduction of Gadolinium (Gd) salts dissolved in water is proposed as an effective way to improve the detection efficiency of thermal neutrons.
- With a significantly larger capture cross-section (49,000 barns compared with 0.3 barns on a free proton), Gd-captures happen roughly 10 times faster, on the order of tens of microseconds.

Water Cherenkov detectors and Gd doping II

- In addition, the Gd-capture produces an 8 MeV cascade of typically 2-3 gammas, producing sufficient optical light to be more reliably detected in large volumes.

Proton Decay (PDK)

- Possible grand unification of strong & electroweak forces not directly testable due to energy scale involved ($\sim 10^{15}$ GeV)
- One key prediction of GUT is the generically called *proton decay* (although neutrons in nuclei are included)
- The main background on PDK experiments arises from atmospheric neutrino interactions
- These interactions almost always produce at least one final-state neutron, whereas proton decays are expected to produce neutrons less than 10% of the time

Supernova Neutrinos

- Supernova explosions throughout the universe left behind a diffuse supernova background of neutrinos that may be detected on Earth.
- The flux and spectrum of this background contains information about the rate of supernova explosions as well as their average neutrino temperature.
- The main detection channel for supernova relic neutrinos in water Cherenkov detectors comes from positrons emitted by inverse β decay reactions.
- Above ~ 20 MeV, the dominant background is due to the decay of sub-Cherenkov threshold muons from atmospheric neutrino interactions.
- This could be greatly reduced by tagging the neutron that accompanies each inverse β reaction.
- A 200-kton detector loaded with gadolinium and at sufficient depth may be within reach of detecting this neutrino flux. In order to achieve this, understanding neutron yields can be used to help statistically discriminate among various radiogenic, spallation and neutrino backgrounds.

Installation notes

- UC Irvine has 180 spare 8" Hamamatsu PMT spares from Super-K and IMB.
- The 60 necessary for Run 1 are ready for immediate use.
- Welded steel tank: it can be lowered into the hall ready-built, it does not require any additional support structure (beyond the concrete floor), and it is amenable to welding additional fixtures as needed
- Tank interior will be plastic lined, with the photosensors attached to a wireframe structure within the liner.
- UC Davis water purification system available for long term loan.
- 50 kg of Gd-sulfate
- WATCHBOY detector's PMT readout and HV system
- Incom Inc confirmed plans to have an LAPPD production line by mid 2016.
- Prototype MCPs and LAPPDs likely available sooner, in small numbers.

Time Line: Phase I

- Phase one: technical development and background characterization
  - Approved and active!
  - Begin Installation Summer 2015
  - Run Fall 2015 - Spring 2016
  - ANNIE will aim to characterize neutron backgrounds.
  - Initial runs will be done with 60 Type-S PMTs rather than LAPPDs until these become available.
  - Test prototype LAPPDs.
  - A movable, smaller volume of gadolinium doped water will be used to measure rates of neutron events as a function of position inside the tank.

Time Line: Phase II

- Phase two: ANNIE physics run I
  - Proposed
  - Installation Summer 2016

  - ANNIE will begin this phase when sufficient LAPPDs are acquired.
  - Use a full gadolinium-doped water volume, 60 Type-S PMTs, a small but sufficient number of LAPPDs, and the refurbished MRD.
  - The first measurement will be of neutron yield as a function of momentum transfer and visible energy.
  - This phase aims to demonstrate full DAQ, successfully operation of LAPPDs for tracking, successfully operation of the MRD for tracking, and complete timing calibrations.

Time Line: Phase III

- Phase three: ANNIE physics run II
  - Proposed
  - Run Fall 2017 or upon completion of phase II until Fall 2018

  - This stage represents the full realization of the ANNIE detector.
  - LAPPD coverage will be at over 10% isotropically which corresponds to 50-100 LAPPDs.
  - During this stage, detailed reconstruction of kinematics will be possible, and therefore, measurements of neutron yield for event classes determined by final state particles.
  - Phase III will designed to identify PDK-backgrounds based on simulations and data from Phase I and II.