FERMILAB-LOI-1063

LETTER OF INTENT: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)

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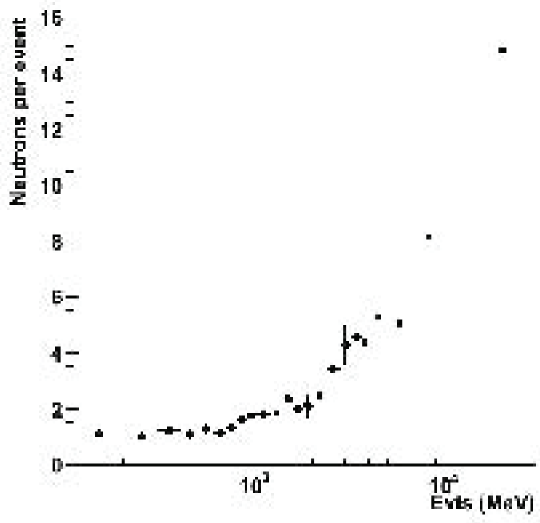


Figure 1: Measurement of neutron multiplicity in pure water versus visible energy by the Super-K collaboration [6].

transfer with higher energy interactions producing more than one neutron. However, the exact number of neutrons is determined by a variety of poorly understood nuclear processes and therefore it is not well-known.

It is not enough to identify the presence or absence of neutrons in an interaction. While the presence of neutrons can be used to remove background events, the absence of a tagged neutron is insufficient to attribute confidence to the discovery of a proton decay observation. The absence of a neutron may be explained by detection inefficiencies in the WCh detector for example. On the other hand, if typical backgrounds consistently produce *more* than one neutron, the absence of *any* neutron would significantly increase the confidence in a PDK-like event. Calculating an exact confidence for discovery will require a detailed picture of the number of neutrons produced by neutrino interactions in water as a function of momentum transferred.

The Super-Kamiokande (Super-K) collaboration has attempted to measure the final state neutron abundance. Fig 1 shows the neutron multiplicity as a function of visible energy from atmospheric neutrino interactions in water, as detected by the 2.2 MeV capture gamma in Super-K [6]. However, the Super-K analysis is limited by uncertainties on the detection efficiencies for the 2.2 MeV gammas and on the flux of atmospheric neutrinos. Additionally, neither the neutrino energy nor the momentum transfer to the nucleus can be measured precisely. Therefore, it is difficult to incorporate these data into background predictions for proton decay.

Therefore, there is a clear need for a dedicated measurement of neutron yield. Such detailed measurement of the neutron multiplicity is possible in a beam with atmospheric neutrino-like energy spectrum. We propose to build such an experiment. The Accelerator Neutrino Neu-

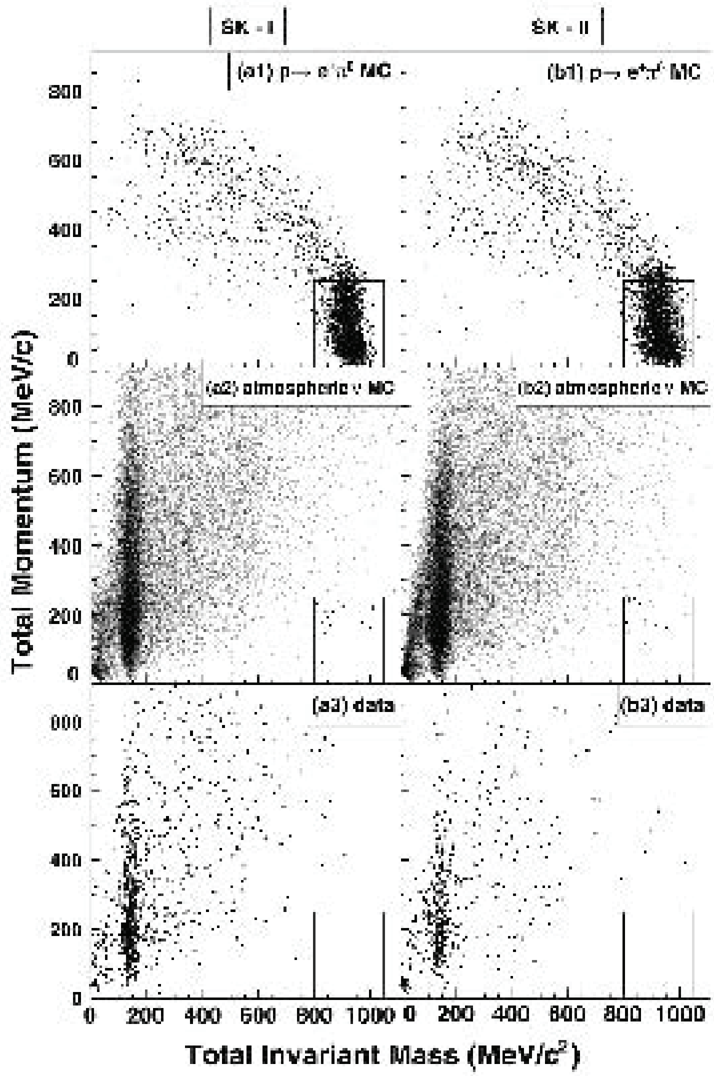
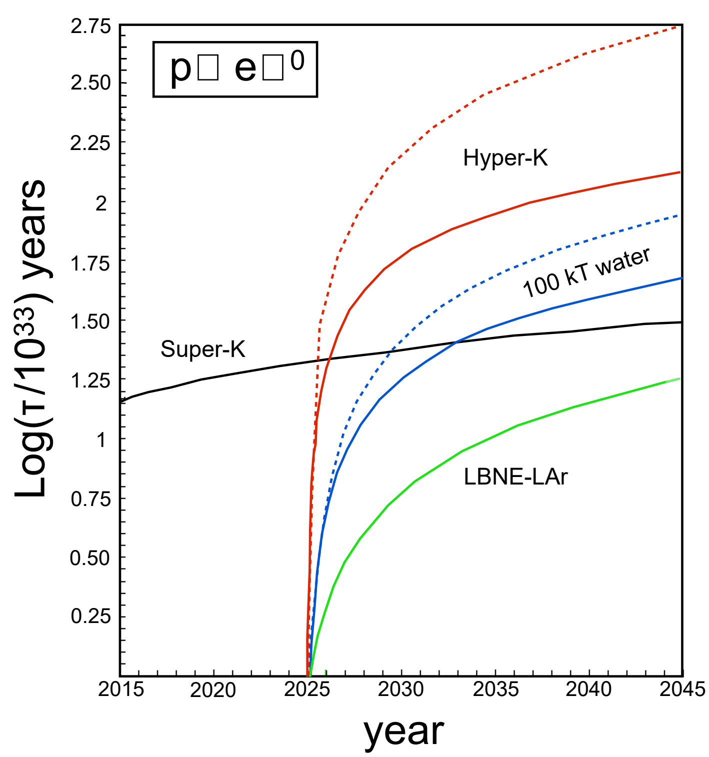


Figure 2: The reconstructed kinematics of proton decay events in Super-K Monte Carlo (a1,b1), compared with those of atmospheric neutrino Monte Carlo (a2,b2) and data (a3,b3). Atmospheric neutrino events that fall in the signal region of (a2,b2) are enlarged (Ref [8]).



p□ e□0
Hyper-K
100 kT water
Super-K
LBNE-LAr
Log(τ/10^33) years
year
2.75
2.50
2.25
2
1.75
1.50
1.25
1
0.75
0.50
0.25
2015
2020
2025
2030
2035
2040
2045

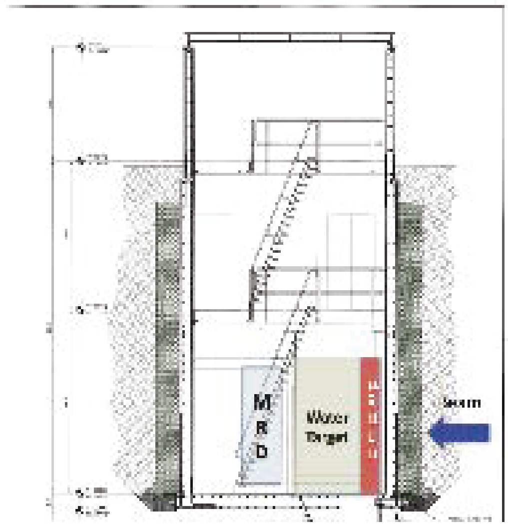


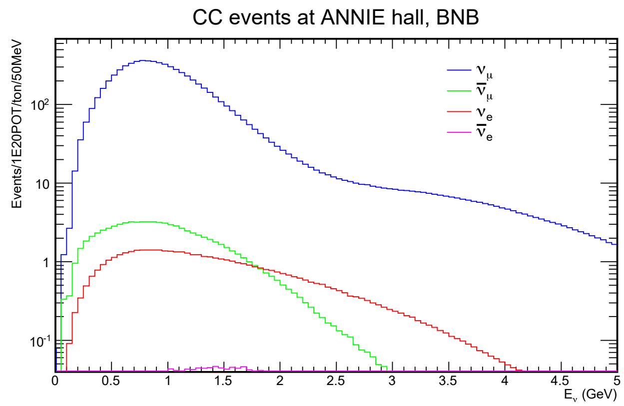
Figure 4: ANNIE in the SciBooNE Hall.

final-state neutron. High energy neutral current (NC) interactions tend to produce either protons or neutrons, proportional to the abundance of each nucleon in water.

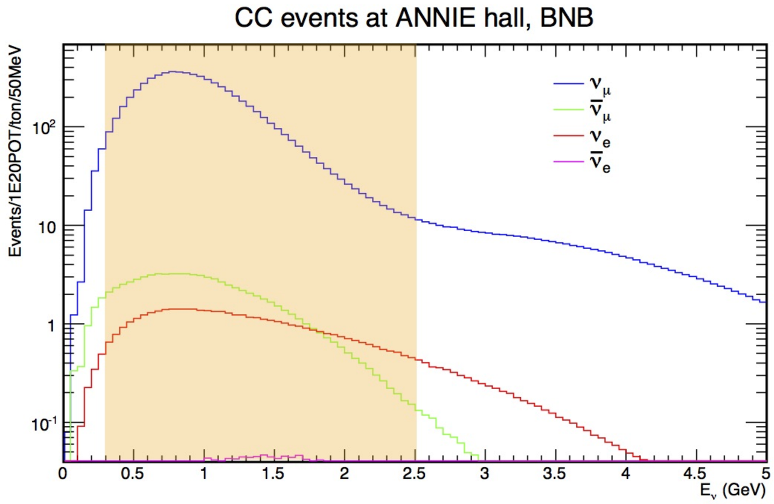
However, GeV-scale (anti-)neutrinos can produce additional neutrons through the complex interplay of higher-order and multi-scale nuclear physics:

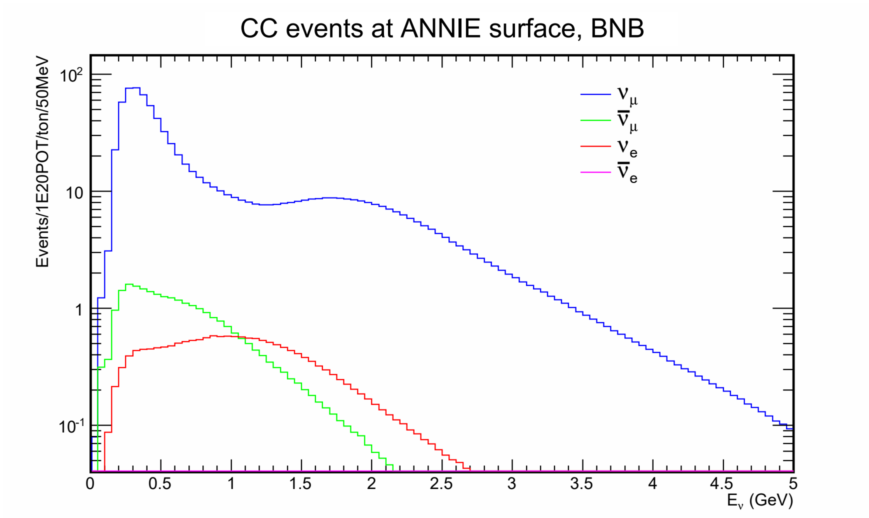
- secondary (p,n) scattering of struck nucleons within the nucleus
- charge exchange reactions of energetic hadrons in the nucleus (e.g., $\pi^- + p \rightarrow n + \pi^0$)
- de-excitation by neutron emission of the excited daughter nucleus
- capture of π^- events by protons in the water, or by oxygen 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

Consequently, neutron multiplicity distributions tend to peak at 0 or 1 with long tails. Given the highly non-gaussian shape of these distributions, parameters such as the mean neutron yield are not necessarily illuminating. At the simplest level, we want to measure P(N=0), P(N=1), and P(N>1) with particular attention to any excesses beyond tree-level expectations. These measurements, binned by interaction type and kinematics, will provide a strong handle to constrain nuclear models, even in the absence of detailed shape information beyond P(N=2).

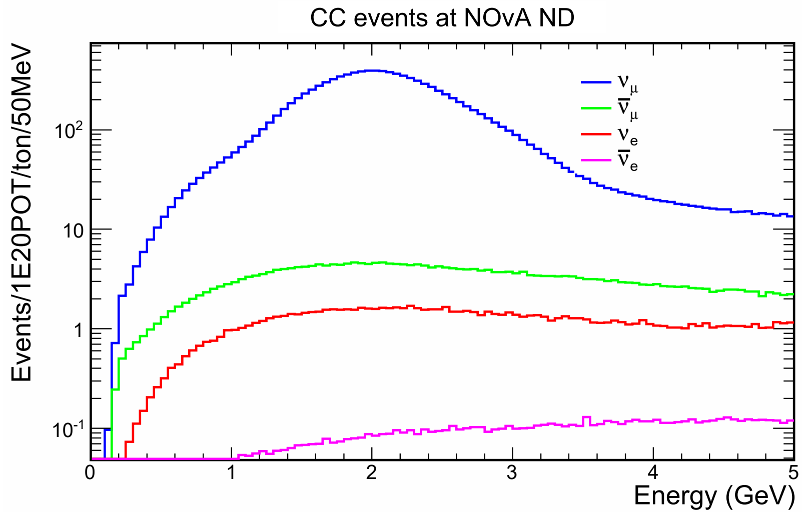


CC events at ANNIE hall, BNB
Events/1E20POT/ton/50MeV
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$

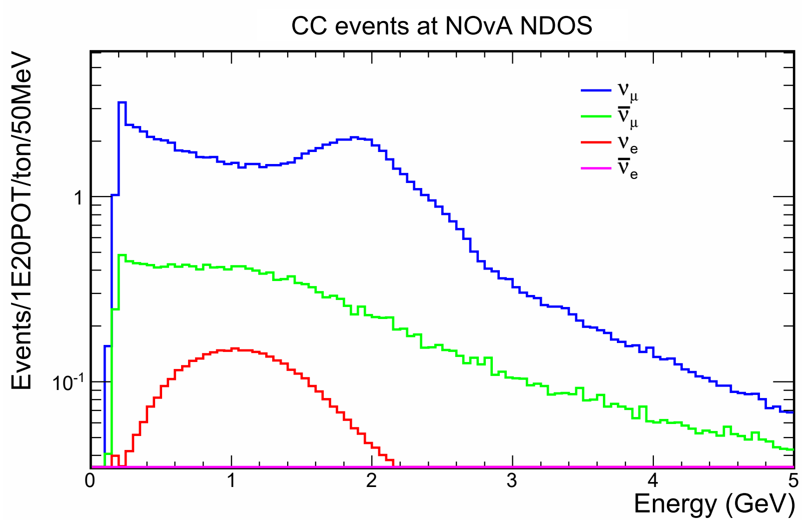

CC events at ANNIE hall, BNB
Events/1E20POT/ton/50MeV
10^2
10
1
10^{-1}
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$



CC events at ANNIE surface, BNB
Events/1E20POT/ton/50MeV
10^2
10
1
10^{-1}
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
E_ν (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$



CC events at NOvA ND
Events/1E20POT/ton/50MeV
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
10^2
10
1
10^{-1}
0
1
2
3
4
5



CC events at NOvA NDOS
Events/1E20POT/ton/50MeV
Energy (GeV)
ν_μ
$\bar{\nu}_\mu$
ν_e
$\bar{\nu}_e$
1
10^{-1}
0
1
2
3
4
5

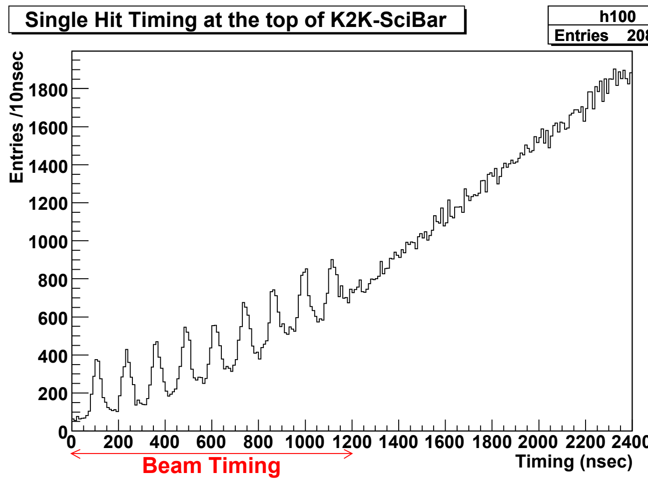


Figure 1.10: *Skyshine events in SciBar at KEK. Shown is the fine time structure of a single strip's hits in SciBar, during the K2K neutrino data runs.*

	60 m		90 m	
	beam-on	beam off	beam-on	beam-off
# spills	25,589	10,072	33,441	10,233
singles (1)	16	0	14	0
singles (2)	37	0	20	1
coincidences	5	0	4	0

Table 1.6: *BNB skyshine test results.*

1.5 Non-Neutrino Backgrounds

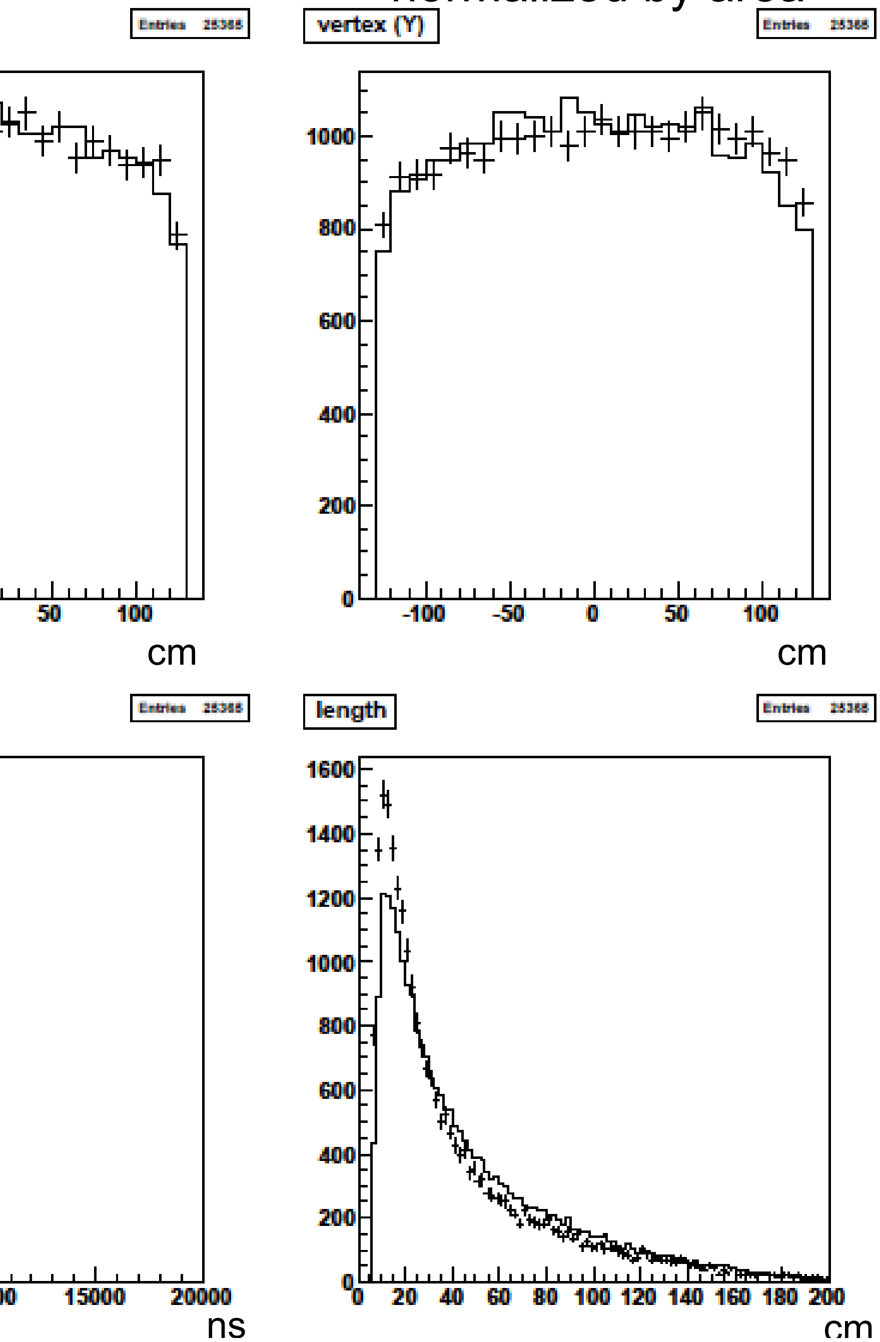
We anticipate background activity in the detector caused by sources other than neutrino interactions in the fiducial volume. They fall into two broad categories: beam related and beam unrelated backgrounds, described below.

Beam Related Backgrounds

The two most significant beam related backgrounds are dirt neutrinos and neutron skyshine. Dirt neutrinos interact in the earth around the detector hall, sending energetic particles into the detector, and skyshine is the flux of neutrons from the decay pipe or beam dump that are initially projected into the air but are scattered back toward the ground and interact in the detector. Experience with MiniBooNE indicates that dirt neutrinos form a negligible background for charged current events. The expected effect on neutral current analyses is also small due primarily to the lack of a high energy tail in the BNB flux.

rtex Distributions (on beam timing)

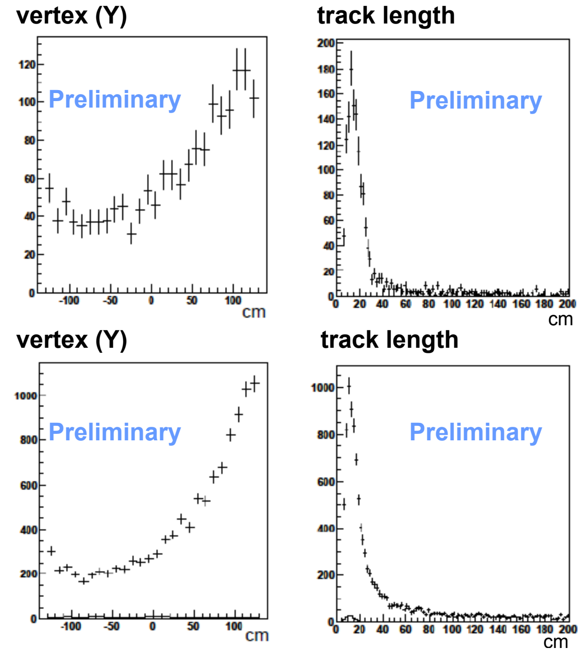
normalized by area

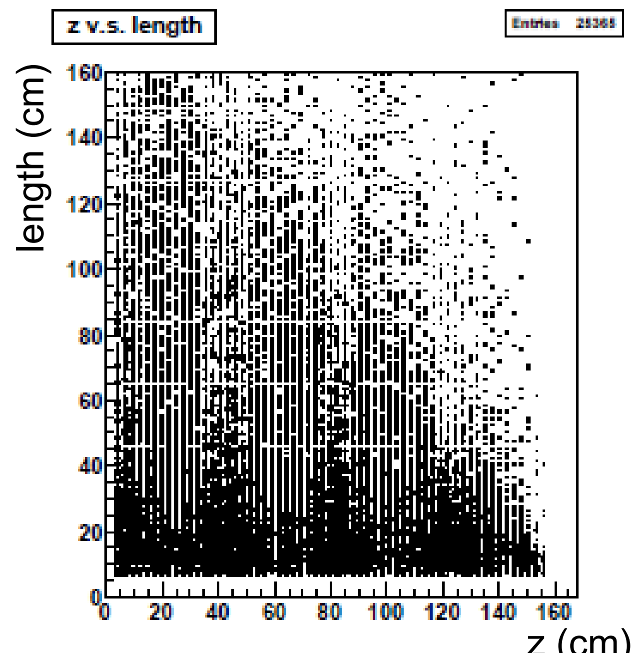


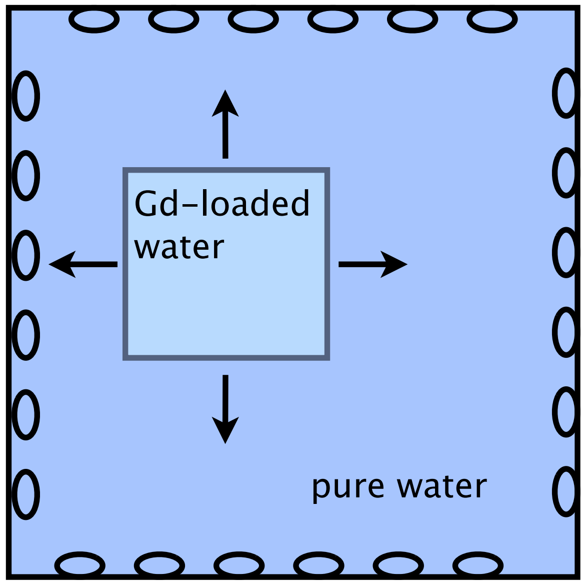
Vertex Distributions (off beam ti

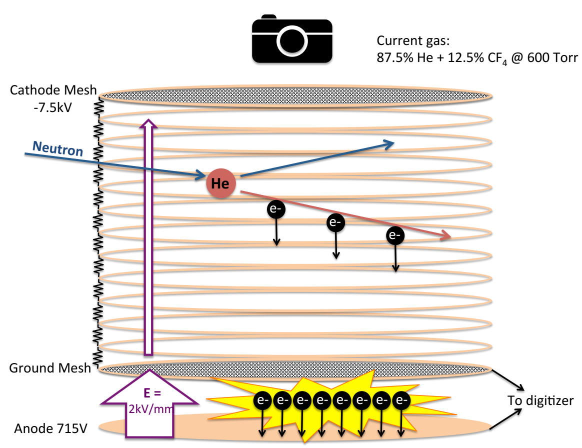
before beam
$-2 \le t < 0\ \mu s$

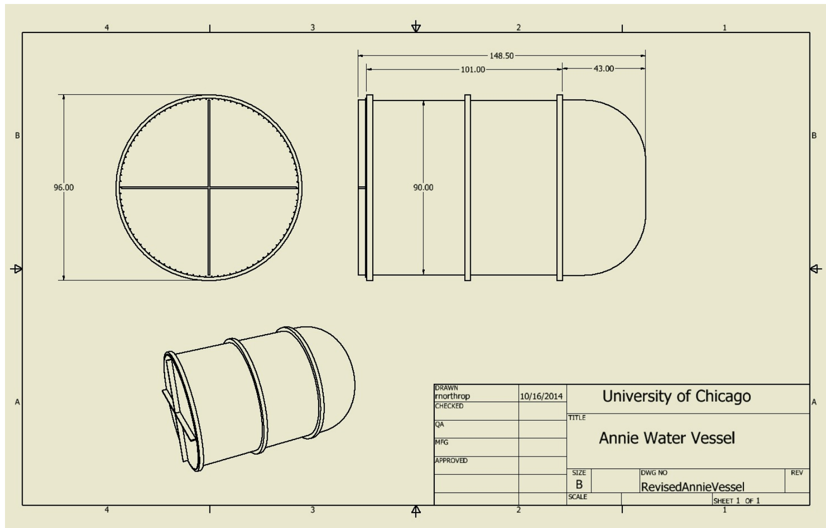
after beam
$2 < t \le 20\ \mu s$

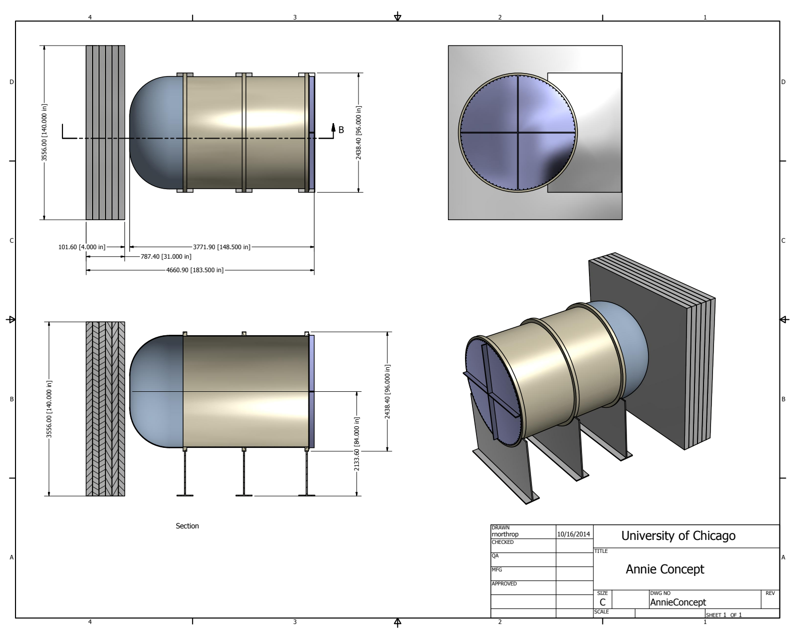


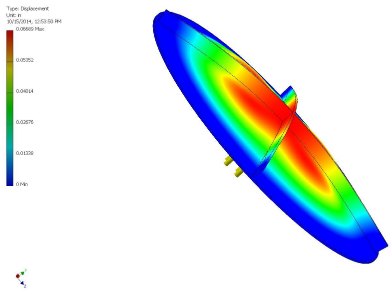


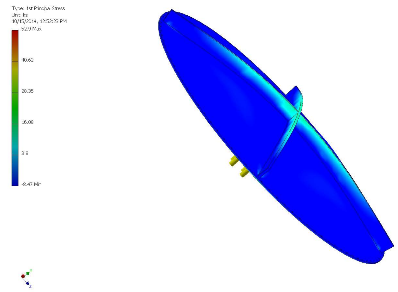

Gd-loaded water
pure water


Current gas:
87.5% He + 12.5% CF_4 @ 600 Torr
Cathode Mesh
-7.5kV
Neutron
He
e-
Ground Mesh
E =
2kV/mm
Anode 715V
To digitizer


148.50
101.00
43.00
96.00
90.00
DRAWN
rnorthrop
10/16/2014
CHECKED
QA
MFG
APPROVED
University of Chicago
TITLE
Annie Water Vessel
SIZE
B
DWG NO
RevisedAnnieVessel
REV
SCALE
SHEET 1 OF 1


3556.00 [140.000 in]
2438.40 [96.000 in]
101.60 [4.000 in]
3771.90 [148.500 in]
787.40 [31.000 in]
4660.90 [183.500 in]
2133.60 [84.000 in]
Section
DRAWN
rnorthrop
10/16/2014
CHECKED
QA
MFG
APPROVED
University of Chicago
TITLE
Annie Concept
SIZE
C
DWG NO
AnnieConcept
REV
SCALE
SHEET 1 OF 1


Type: Displacement
Unit: in
10/15/2014, 12:53:50 PM
0.06689 Max
0.05352
0.04014
0.02676
0.01338
0 Min
Y
Z


Type: 1st Principal Stress
Unit: ksi
10/15/2014, 12:52:23 PM
52.9 Max
40.62
28.35
16.08
3.8
-8.47 Min
Y
Z

$$\overline{\sqrt{\qquad}}$$

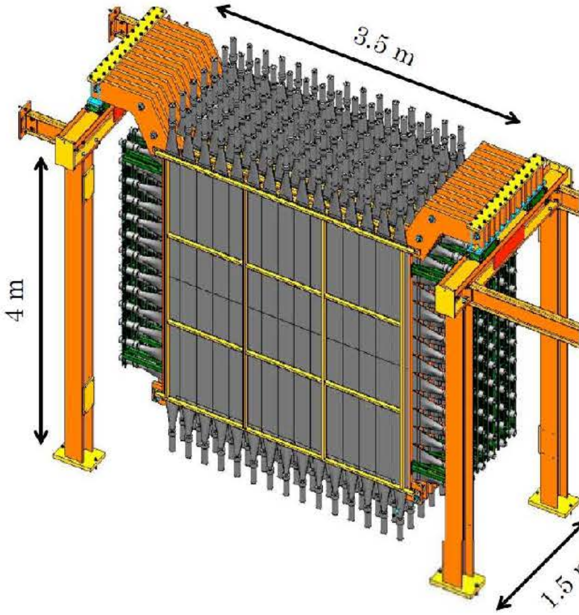
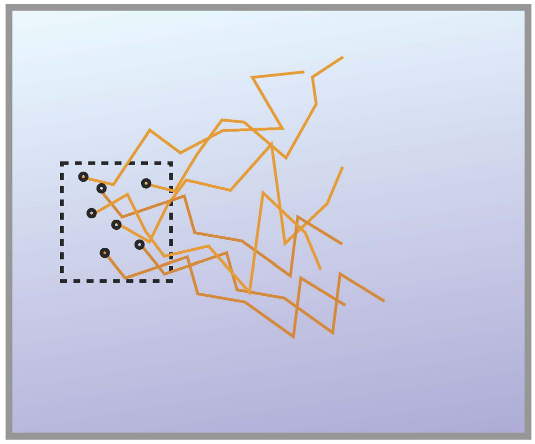
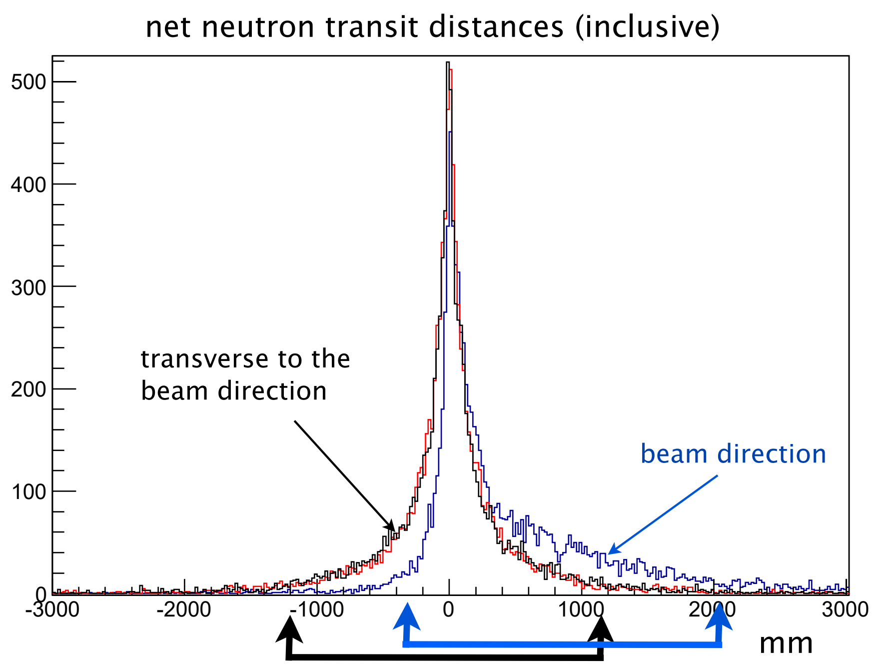
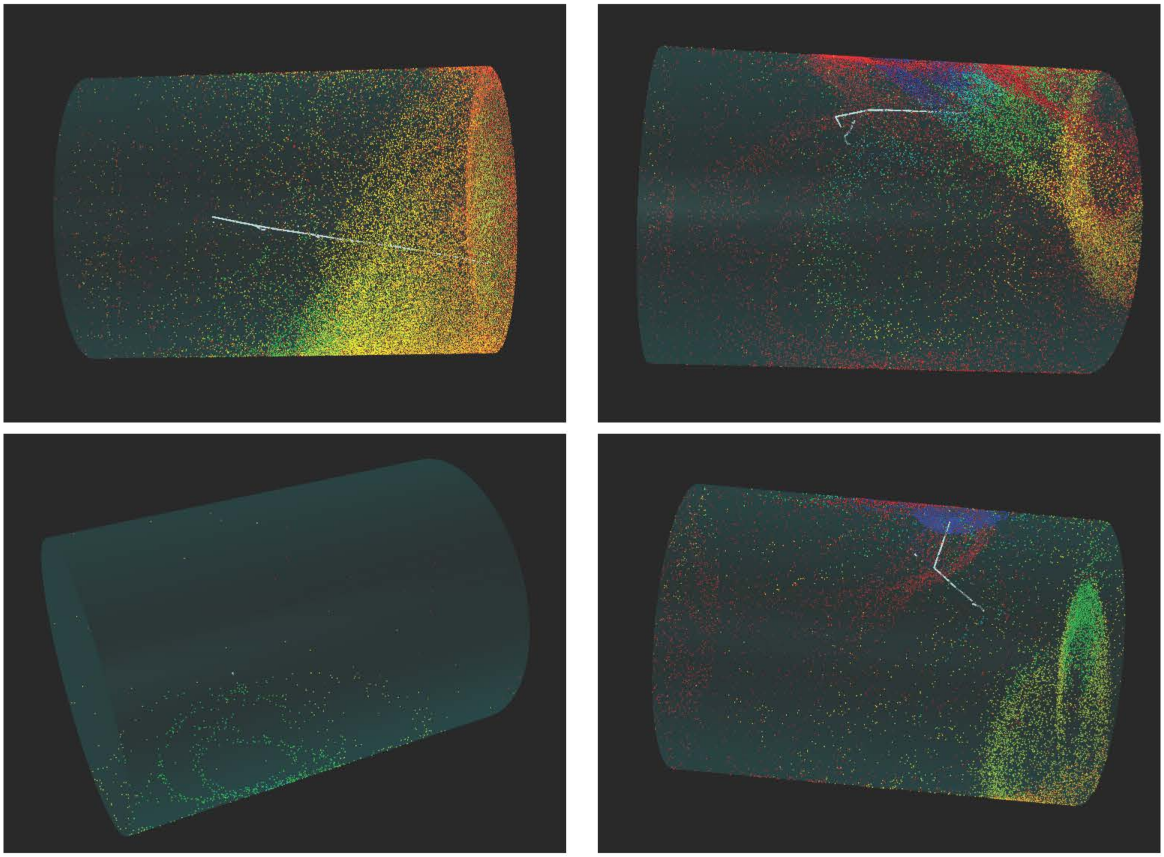


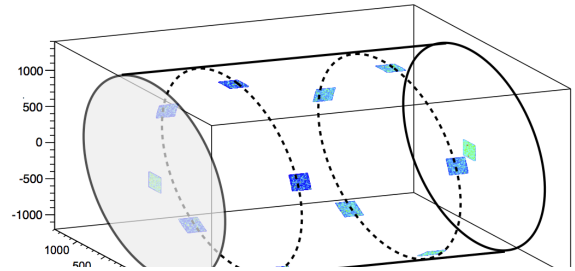
Figure 3.7: The MRD is installed downstream of the EC. It has 12 iron plates with thickness of 5 cm and 13 plastic scintillator planes with thickness of 6 mm.





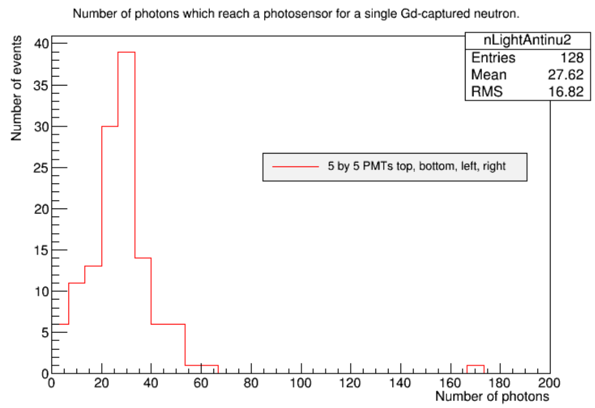
net neutron transit distances (inclusive)
500
400
300
200
100
0
-3000
-2000
-1000
0
1000
2000
3000
mm
transverse to the beam direction
beam direction



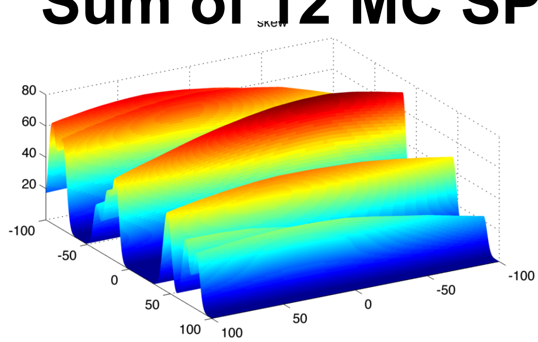


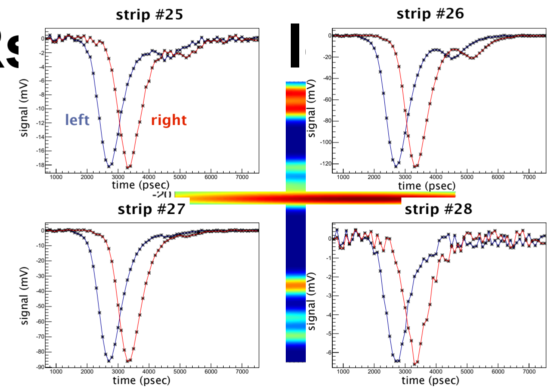
Neutron Capture Light Yield

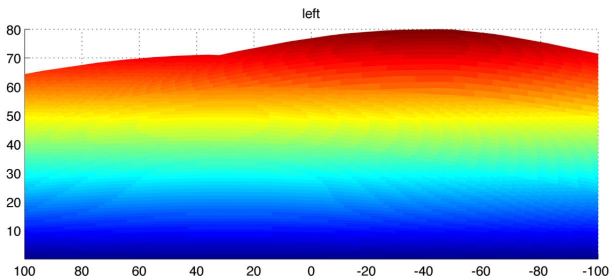
- **Config. 2)** 5 x 5 grid of 8” PMTs
  - Top + Bottom + Left + Right
  - 100 PMTs total

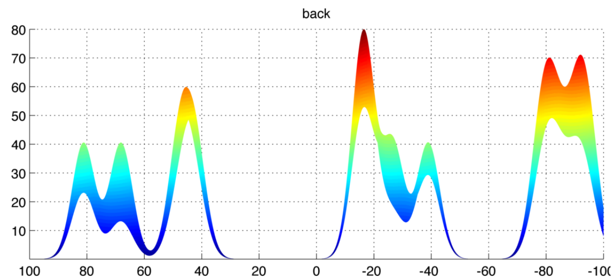


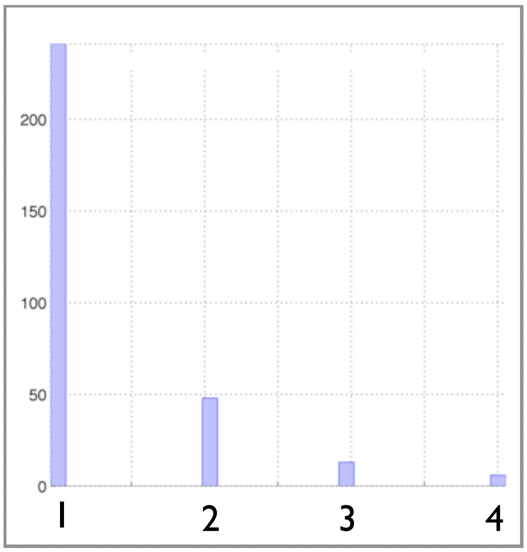
Sum of 12 MC SPRs

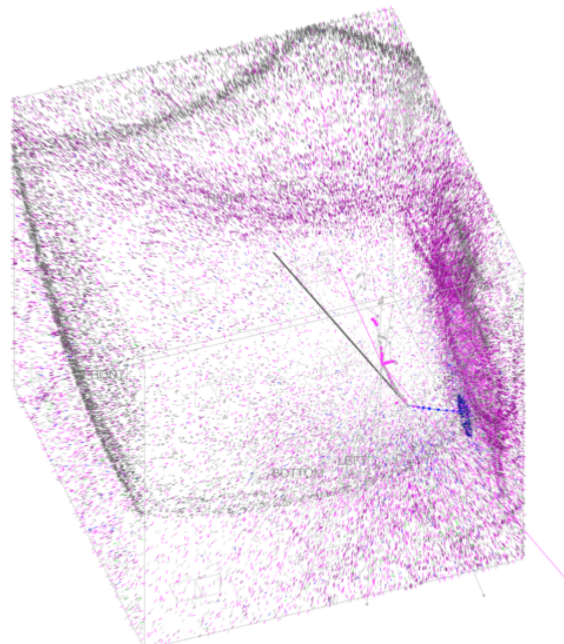












Number of hits per LAPPD (1000 evts)