Development of ^{16}N and ^{17}N Sources for Calibration of a Large Gd-Doped Water Cherenkov Detector

K. Ogren (AIT-WATCHMAN Collaboration)
University of Michigan
I. Jovanovic, ijov@umich.edu
Consortium for Monitoring, Technology, and Verification (MTV)

NUCLEAR ENGINEERING & RADIOLOGICAL SCIENCES
UNIVERSITY OF MICHIGAN

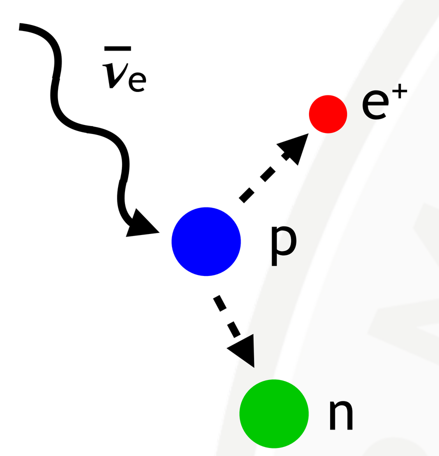
ABSTRACT - The detection of antineutrinos from nuclear reactors is of great interest for nuclear security and nonproliferation, as antineutrino signatures are impossible to shield and may provide information on the presence of undeclared reactors or the operation of known reactors, which would be useful for verification applications. One prominent detector design, now under consideration by the WATCHMAN-AIT collaboration, relies on a multi-kiloton tank of gadolinium-doped water to detect inverse beta-decay (IBD) events caused by antineutrino interactions. The gadolinium, added to the water at the part-per-thousand level, enhances the signature from the neutron generated by the IBD interaction. In such large-volume detectors, calibration is a considerable challenge, and carefully designed sources are needed which can both mimic the expected response to IBD events and be easily moved to different locations inside the detector volume. One proposed calibration source is ^{16}N, which emits a beta-correlated gamma-ray with energy of 6.1 MeV. The ^{16}N gamma-ray is interesting because it is near the high-energy range of the gamma-ray cascade produced by neutron captures on gadolinium, and the correlated beta particle allows the gamma-rays to be time-tagged. Current designs for the ^{16}N calibration source are based on the Sudbury Neutrino Observatory (SNO) design, where ^{16}N was produced by irradiating CO_2 gas with 14.1 MeV neutrons from a DT generator, then transferred to a small decay chamber inside the detector volume. Another little-considered feature of this design is that by substituting CO_2 gas enriched with ^{17}O, ^{17}N can be produced using the same mechanism. ^{17}N may also be interesting as a potential calibration source, as it emits beta-correlated delayed neutrons. We present initial studies on producing and characterizing ^{16}N using large NaI(Tl) detectors, as well as Monte Carlo simulations of the expected ^{16}N and ^{17}N production rates for various source design configurations.

Introduction and Motivation

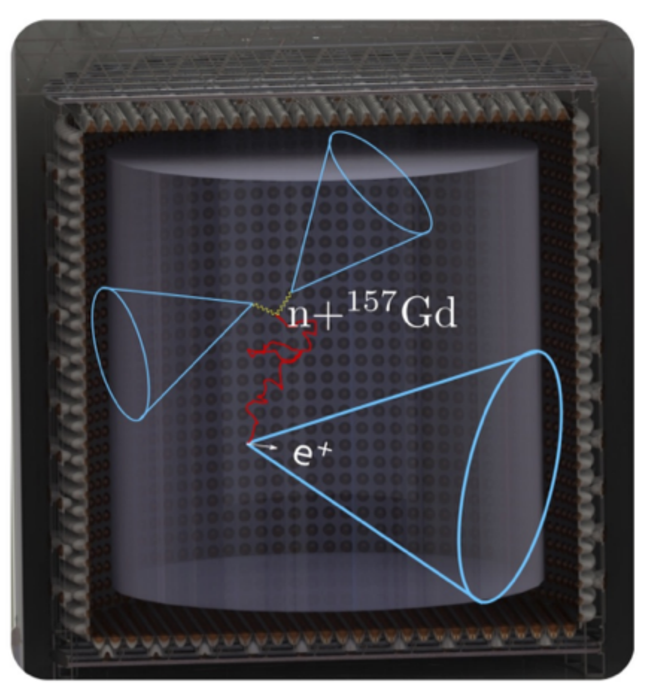
Antineutrino detection can allow for reactor monitoring or discovery.

Antineutrinos can be detected through inverse beta-decay (IBD) events in large water-based detectors.

Inverse Beta Decay



Preliminary WATCHMAN Detector Design



M. Askins, arXiv:1911.06834v2 (2019)

In IBD, an electron antineutrino interacts with a proton to produce a positron and a neutron.

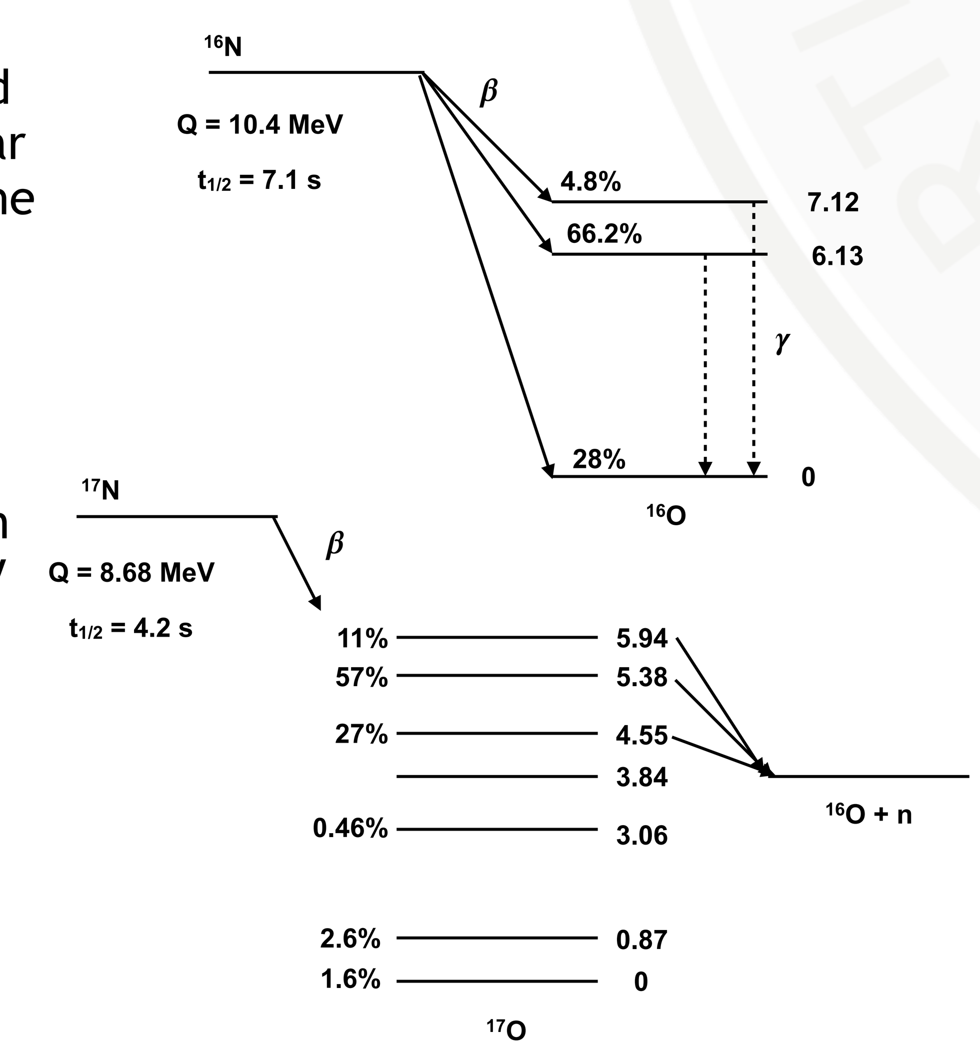
Positrons and high-energy gamma-rays from neutron capture on Gd produce Cherenkov radiation in water.

Calibration Source Design

^{16}N emits a beta-correlated gamma-ray at 6.1 MeV, near the high energy range of the Gd capture cascade.

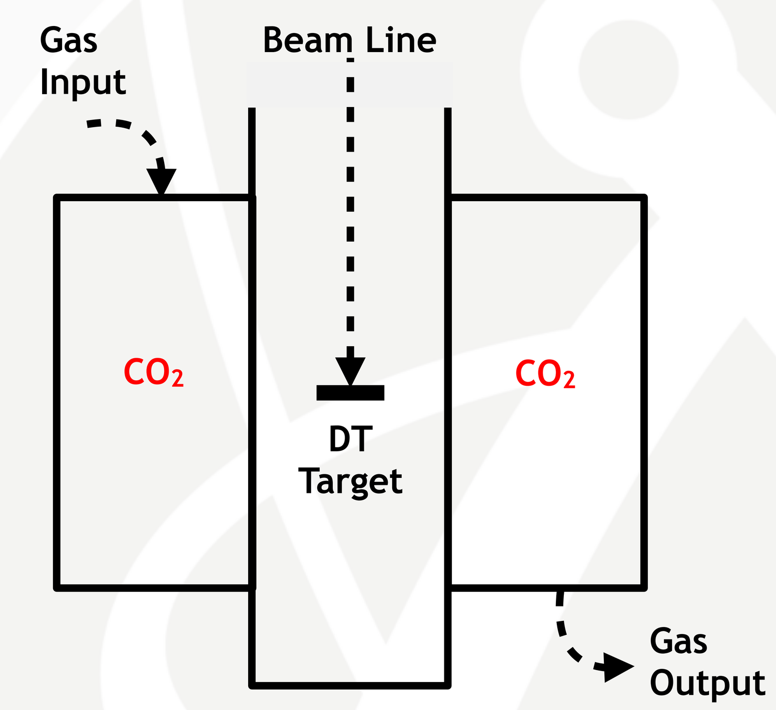
^{17}N emits beta-correlated delayed neutrons (discrete energies).

Nearly identical production cross-sections for 14.1 MeV neutrons.

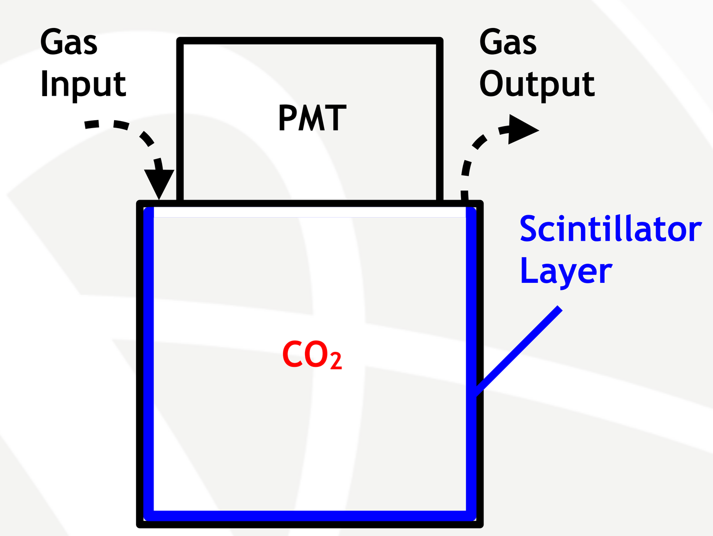


Source Delivery System

Simplified Target Chamber Design Cross-Section



Simplified Decay Chamber Design Cross-Section



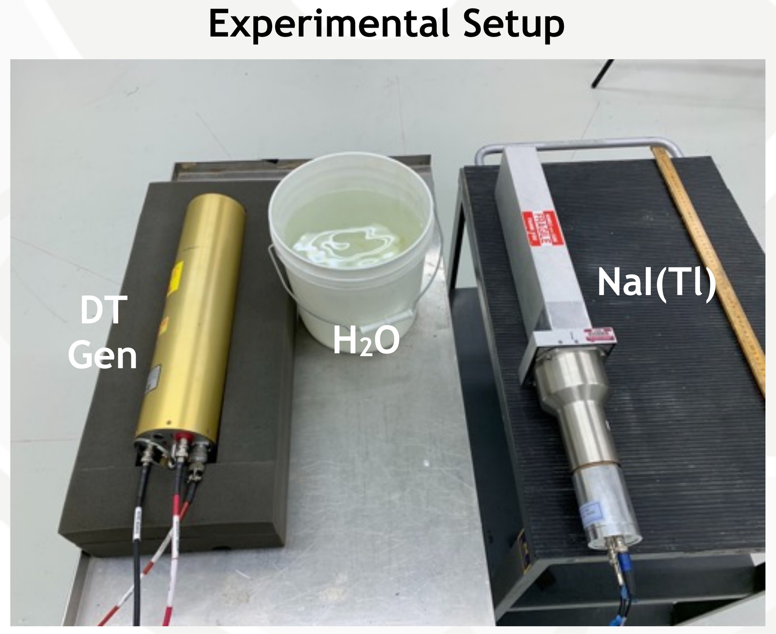
Delivery system based on design used for SNO.

Separation of ^{16}N production outside of detector from ^{16}N decay within detector.

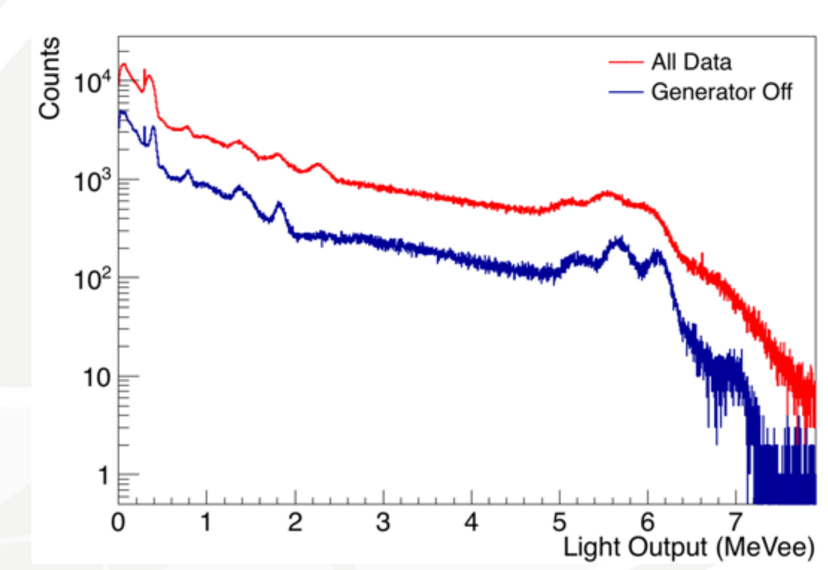
Gas must circulate fast enough to limit decay losses in transit, while allowing long enough dwell time in decay chamber

Preliminary ^{16}N Production & Testing

Experimental Setup



Light Output Spectrum for H_2O Irradiated by DT Generator

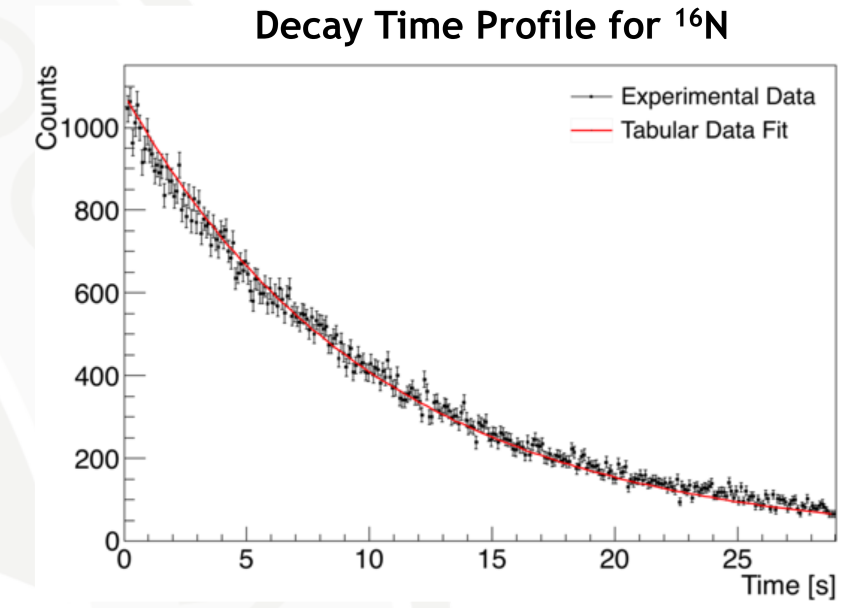


Preliminary test experiments have been conducted to produce ^{16}N in water using a DT generator in 60 second on/off cycles.

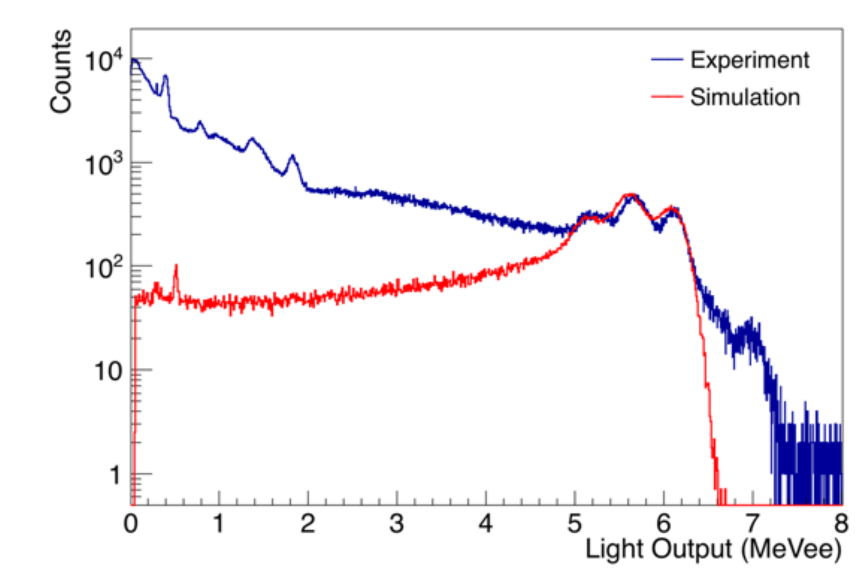
Photopeak, single-escape, and double-escape features for 6.1 MeV ^{16}N gamma-rays were clearly observed, and the less-intense 7.1 MeV photopeak is also visible.

Modeling & Simulation

Decay Time Profile for ^{16}N



^{16}N Simulated vs Experimental Spectrum



Time profile of ^{16}N experimental data matches well with the expected decay profile calculated from the known time constant.

Simulations of NaI(Tl) detector response agree with experimental data.

^{17}N production simulations indicate a measurable delayed neutron signature with ~1 g of 60% ^{17}O-enriched water or ~1 L of 18% enriched CO_2 gas, both of which are commercially available.

MTV Impact

Work on this project directly supports the WATCHMAN-AIT Collaboration in both nonproliferation and scientific R&D goals.

This project includes US and UK collaborators, including the University of Michigan, University of Sheffield (UK), LLNL, and other partners.

Collaboration work includes planned assignments at Boulby Underground Laboratory (UK) and LLNL, as well as student exchange between Michigan and Sheffield.

Conclusion & Next Steps

This preliminary work supports the development and characterization of a prototype ^{16}N source for large water Cherenkov detectors.

Next steps include procurement of ^{17}O-enriched samples for experimental testing of ^{17}N production, ^{16}N production tests using CO_2, and continued collaboration with UK partners on the design and construction of the source delivery system.

This work was funded in-part by the Consortium for Monitoring, Technology, and Verification under Department of Energy National Nuclear Security Administration award number DE-NA0003920

National Nuclear Security Administration