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Demonstration of Key Elements of a Dual Phase Argon Detection System Suitable for Measurement of Coherent Neutrino-Nucleus Scattering

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Physics and Advanced Technologies

Demonstration of Key Elements of a Dual Phase Argon Detection System Suitable for Measurement of Coherent Neutrino-Nucleus Scattering. Final Report for a 2005 Feasibility Study LDRD

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Summary of Accomplishments

(1) Designed gas-phase prototype proportional chamber to measure scintillation and ionization properties in Argon
(2) Measured ionization and scintillation with this chamber at the 200 primary electron level (as explained in the Experimental Work section below), with a detection threshold of approximately 50 electrons. The maximum signal from coherent scatter is ten electrons. The target is expected to be achievable with cryogenic operation, which will lower the PMT dark noise seen in figure 2.
(3) Demonstrated signal enhancement through the use of a 1% nitrogen dopant in the Ar as a wavelength shifting agent.
(4) Developed an initial design for a dual phase Argon ionization detector, which is required for use in detection of coherent scatter using a nuclear reactor source.

Introduction

This feasibility study sought to demonstrate several necessary steps in a research program whose ultimate goal is to detect coherent scattering of reactor antineutrinos in dual-phase noble liquid detectors. By constructing and operating a Argon gas-phase drift and scintillation test-bed, the study confirmed important expectations about sensitivity of these detectors, and thereby met the goals set forth in our original proposal. This work has resulted in a successful Lab-Wide LDRD for design and deployment of a coherent scatter detector at a nuclear reactor, and strong interest by DOE Office of Science.

In recent years, researchers at LLNL and elsewhere have converged on a design approach for a new generation of very low noise, low background particle detectors known as two-phase noble liquid/noble gas ionization detectors. This versatile class of detector can be used to detect coherent neutrino scattering—an as yet unmeasured prediction of the Standard Model of particle physics [1]. Using the dual phase technology, our group would be the first to verify the existence of this process. Its (non)detection would (refute)validate central tenets of the Standard Model. The existence of this process is also important in astrophysics, where coherent neutrino scattering is assumed to play an important role in energy transport within nascent neutron stars.

The potential scientific impact after discovery of coherent neutrino-nuclear scattering is large. This phenomenon is flavor-blind (equal cross-sections of interaction for all three neutrino types), raising the possibility that coherent scatter detectors could be used as total flux monitors in future neutrino oscillation experiments. Such a detector could also be used to measure the flavor-blind neutrino spectrum from the next nearby (d ~ 10kpc) type Ia supernova explosion. The predicted number of events [integrated over explosion time] for a proposed dual-phase argon coherent neutrino scattering detector is 10000 nuclear recoils/kton, compared to the estimated rate in the Solar Neutrino Observatory (neutral current configuration); 200 deuteron breakup events/kton of D_2O, yielding almost a factor 50 improvement in rate [2],[3].

In a more practical vein, these detectors may also be useful for improved cooperative monitoring of nuclear reactors, as required by the Nuclear Nonproliferation Treaty. Recognizing this potential, the International Atomic Energy Agency, which administers the global reactor monitoring regime, has endorsed our research into this technology.

Coherent Scatter Detection

The inverse beta-decay process $\bar{\nu}_e + p \rightarrow n + e^+$ is commonly used to detect electron antineutrinos. By comparison, coherent antineutrino-nucleus scattering, ν + (Z,N) –> ν + (Z,N), has a factor of N^2 higher interaction probability, where *N* is the number of neutrons in the target nucleus. This gain factor is what allows construction of high-rate, kilogram scale detectors.

Reactor antineutrinos (E_ν ~ 4 MeV) interact coherently with the entire nucleus, with the resulting nuclear recoil (E_r ~ 1 keV) causing Bethe-Bloch dE/dx ionization in the target medium. Our detailed calculations and Monte Carlo simulations have shown that coherent scatter neutrinos will produce up to 10 electrons per scattering recoil from an argon target. At a standoff distance of 25 m from the reactor core, ~200 detectable ionization events are expected per day in 10 kg of Ar. Monte Carlo calculations show that argon has the largest number of measurable antineutrino-induced ionization events of all noble gases, per unit of detector mass.

These weak ionization signals are detected when an electric field pulls the electrons through the liquid, across the gas-liquid boundary, and into an electroluminescence gap [4] that amplifies the signal and converts it into light. At a field strength of ~2-3 kV/cm across the 2 cm wide gap, each drifting electron produces several hundred excited Ar atoms along its track. The de-excitation UV light is detected by an array of photomultiplier tubes.

The bulk of the detector backgrounds arise from radioactive contamination within and in the vicinity of the detector. Both electrons from beta decay of ^{39}Ar and low energy Compton electrons from background gammas will produce weak ionization events in the Ar bath. The contribution from the latter will be reduced with modest amounts of polyethylene and lead shielding around the detector [5] and the total background rate will be comparable to the neutrino signal rate. Since these aforementioned backgrounds are time independent, they can be measured during periodic reactor shutdowns and subtracted.

A key element of the coherent scatter detection problem is to determine the detection threshold of a few-electron signal in a noble gas or liquid. Recent results from the WARP collaboration in Italy indicate that this detection has been achieved in a dark matter detector prototype (See our discussion of this work below.) A second essential component of the research program is to experimentally measure the actual noise floor upon which this signal will lie, including noise sources such as sparking and corona discharge that are not captured in the Monte-Carlo simulations.

With signal and background measurements accomplished at LLNL, deployment at a reactor and measurement of the signal could proceed with a short measurement campaign, made possible by the expected high interaction rate (100s of events per day.) Our team has an important advantage in this respect, in that we have access to a power reactor through our ongoing antineutrino detection program at the San Onofre Nuclear Generating Station in Southern California.

Experimental Work

We received FY04 FS-LDRD funds to build a room temperature argon-based gas-phase detector. Using off-the-shelf or legacy equipment, we were able to complete the chamber within the budget and time scale set in our FS-LDRD. Our goal was to create a flexible test bed to examine the various contributions to the noise, including but not limited to the radiation backgrounds that we had already extensively modeled as part of earlier work for DOE NA-22.

The heart of the detector is shown in Figure 1 below. The detector consists of an active volume of one liter of STP Argon gas. The field cage is comprised of a drift region, operating at a few hundred Volts/cm, and a luminescence or gain region, operating at a bias of 500 Volts/cm or more. Electrons are generated in the drift region by Bethe-Bloch ionization from alpha, neutron or gamma sources. These are referred to as *primary electrons,* and are extracted by the electric field into the gain region, where the few electron signal is amplified via scintillation, with a gain factor of several hundred, and measured by photomultiplier tubes (PMTs). We add a few percent N to the Argon gas for for shifting the light from the deep to the near UV, thereby improving detectability with PMTs. We have seen "first light" with the gas-phase detector; x-ray emission-induced ionization from a weak Fe-55 source mounted inside the field cage (Figure 2). These measurements demonstrate that we are successful at collecting ionization events from within the target gas volume.

Based on the known energy requirement for production of electron-ion pairs in Argon, the number of electrons liberated by an Fe-55 interaction is approximately 200 (measured as 100 ADC counts in Figure 2). Using this as a calibration point and assuming linear detector response, our noise threshold due to PMT dark current is approximately 50 electrons. This is only a factor of 5 away from our upper limit of sensitivity of 10 electrons. This noise threshold will b considerably lowered by using a quieter photomultiplier tube, and by dual phase operation which requires temperatures of 85 Kelvin. Low temperature operation further lowers the PMT dark current - without significantly affecting the PMT gain and quantum efficiency.

The above work means that we are well poised to move to development of a dual phase test-bed. The fact that this detector is already constructed and operational gives us a significant head start for future development programs. Figure 3 shows an initial design of a dual phase detector for coherent scatter detection. Our 2006 Lab-Wide LDRD will focus on the construction and operation of this detector.

Aside from this work, we have also engaged in an ongoing collaboration with the XENON dark detection group led by Columbia University [6]. This collaboration is useful because there is considerable overlap in readout requirements, cryogenics, noise reduction strategies and other features of these detectors.

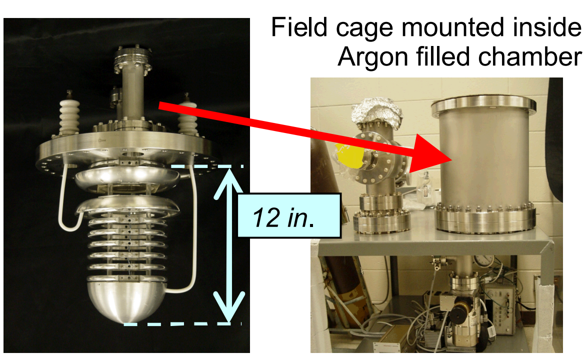

Figure 1: A photograph of the field cage for the Argon gas-phase detector, which is mounted on the inside of the top flange of the chamber shown on the right. A 50-nCi Fe-55 x-ray source is installed inside the drift region volume, generating free electrons that are subsequently drifted by the applied electric field and converted to proportional scintillation between two fine-mesh grids. This light is the detected by a photomultiplier tube.

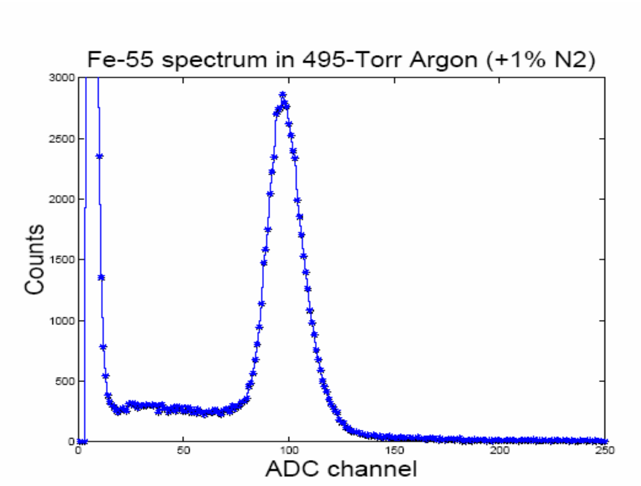

Figure 2: Spectrum from 50-nCi Fe-55 source, as measured in the Argon gas detector. The chamber pressure was 495 Torr. 1% Nitrogen was introduced in the gas to enhance scintillation in the 300-400nm range. Modest electric fields of 0.6 kV/cm and 2 kV/cm were applied across the drift and proportional gain regions of the detector, respectively. The peak of this spectrum is produced by 6 keV x-rays producing ~200 free electrons in the drift region of the detector.

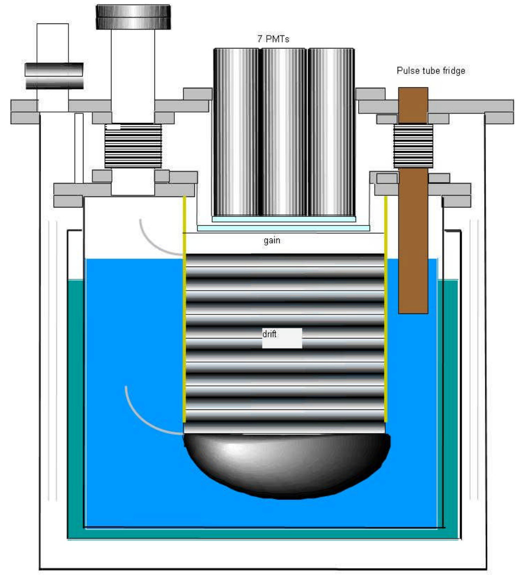

Figure 3: Layout of the 2-phase Ar detector. Upon cool-down, the Ar gas is liquefied by a LN cooled shroud. During operation, a pulse tube fridge maintains the temperature of the Ar bath at ~ 85 K.

Work by other Researchers

Using room temperature detectors like ours that rely on proportional luminescence in a noble gas, other researchers [7] have been able to resolve X-ray peaks in the 10 - 30 primary electron range, corresponding to incident X-ray energies of several hundred eV. More recently, the WARP collaboration in Italy has claimed detection threshold of a 1-10 primary electron signal in a cryogenic dual-phase argon ionization detector being built for the purpose of dark matter detection [8]. This result is an important milestone for our coherent scatter program, since it is to our knowledge the first evidence that the signal from a few primary electrons in a noble liquid can be detected. Finally, there is the prospect of using HPGe ionization detectors for neutrino detection. Both the TEXONO group [13] and the U Chicago group [12] are pushing to reduce the capacitance and thus detector energy threshold, the former by ganging together arrays of small mass (~ 10 g) Ge elements, the latter by modifying the electrode structure of the Ge diode.

Future Work

In the next stage of our research, we will use the chamber, along with lower noise PMTs, to measure the ionization signal from calibration sources at the level of a single or few electrons, as required for detection of coherent scatter. We will also directly measure the quench factor for nuclear recoils in Ar, as a function of recoil energy. Quenching in this context refers to the reduction in light output from a nuclear interaction in noble liquids (and other scintillators) compared to an electromagnetic recoil. The quench factor must be measured at low energy in order to make a definitive, well-calibrated measurement of the coherent scatter process.

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