Multi-wire proportional chamber for ultra-cold neutron detection

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\textbf{1. Introduction}

The interaction of neutrons with materials is typically determined by the material’s nuclear potential. At sufficiently low energies, the neutron wavelength is long enough that the material surface acts as a potential barrier, given by the Fermi potential, \( V_F \) \cite{1}:

\[ V_F = \frac{2\pi h^2}{m N a}. \]

where \( m \) is the neutron mass, \( N \) is the number density of the material, and \( a \) is the coherent nuclear scattering length. Therefore, these neutrons can be trapped in material bottles, as long as the scattering length is positive. Neutrons with kinetic energies below the \( V_F \) of the trapping material are referred to as ultra-cold neutrons (UCNs). \(^{58}\text{Ni}\) is often used as a trapping surface due to its large \( V_F \) of 342 MeV.

The ability to transport, store, and manipulate the spins of UCN has led to a broad experimental program that has been reviewed by Ignatovich \cite{2}, and by Golub et al. \cite{3}. Recently, new technologies have been developed for producing UCN that promise sources with higher intensities and fluxes than have been obtained from reactor-driven sources \cite{4–7}. In this paper we describe UCN detectors that have been developed and that are in use at the UCN source at the Los Alamos Neutron Science Center (LANSCE).

\textbf{2. Design}

Little is published on the design and construction of proportional chambers for detecting UCN. The idea of using gas-filled detectors for thermal neutrons goes back to Fermi \cite{8}. We have developed robust and simple multi-wire proportional detectors to monitor the UCN flux from the Los Alamos UCN source. The first detectors used \(^{10}\text{BF}_3\) as the fill gas in a proportional detector. Thermal neutrons are absorbed by the reaction \(^{10}\text{B}(n,t)\text{Li}^7\), releasing 2.79 MeV of kinetic energy in the charged particles that ionize the gas. The resulting electrons are collected and amplified in the high electric field around a small diameter anode wire that is placed at several kV of potential relative to the tube that contains the gas.

\(^{3}\text{He}\) provides a safer alternative to \(^{10}\text{BF}_3\) through the reaction \(^{3}\text{He}(n,\alpha)^{4}\text{He}\), with a Q-value of 0.764 MeV. \(^{3}\text{He}\) gas does not have...
the stopping power of BF$_3$, so detectors are often filled with an additional stopping gas that produces higher ionization energy loss and stopping power for the energetic ions produced in the neutron capture reaction. After the reaction, the triton has an energy of 191 keV and the proton has 573 keV. Fluorocarbon stopping gases are ideal because they provide high stopping power and small neutron absorption cross-sections. At 1 bar of pressure and temperature 20°C, the sum of the ranges in CF$_4$ of the two charged particles is 0.48 cm compared to 1.60 cm in argon and 6.0 cm in $^3$He. In order to obtain the best signal-to-noise, the detector must have active detector volume dimensions that are largely compared to the ranges in order to reduce the fraction of events, where energy is lost in the detector walls rather than in the active gas volume.

The thermal neutron cross-section for the reaction $^3$He(n,p)$^3$H is $\sigma=5.333$ kb. At low energies the lifetime ($\tau=1/(\rho v)$, where $\rho$ is the $^3$He number density), is independent of neutron velocity because the cross-section varies like $1/v$ with neutron velocity, $v$. For gas mixtures where the neutron absorption is dominated by capture on $^3$He the lifetime is $\tau=(3.55 \times 10^{-3})/P$ s, where $P$ is the $^3$He pressure in bars. Neutrons with $v=5$ m/s have a mean free path of $l=vt$ of 9 mm with 20 mbar of $^3$He pressure. The detector must be several mean free paths thick in order to optimize the detector efficiency and the mean free path needs to be larger than the charged particle range to minimize the wall effects.

We have designed a detector, shown in Fig. 1, which is approximately planar. The detector incorporates two cathodes held at ground, the entrance window and a copper circuit board. At the approximate center is an anode plane which is held at high voltage. The active volume is determined by the distance between the two cathode planes, 5 cm. Grid planes, spaced 2.5 mm from the anode, ensure uniform fields in the anode region even though the entrance window is held by a flange, and is bowed by the gas pressure.

The anode planes were constructed on a FR-80 frame with 20 $\mu$m gold-plated tungsten wires spaced by 2 mm and wound at 50 g of tension. The wires were epoxied to the plane and soldered to the copper tabs. The ends of the wire plane were terminated with 75 $\mu$m beryllium–copper guard wires wound at 100 g m of tension. The grid planes were of similar construction with 2.5 mm spaced 75 $\mu$m gold-plated copper-clad aluminum wire also at 50 g m of tension.

For detecting UCN, one must use low absorption materials for the entrance windows. We used aluminum alloy windows (6061 T6) which are strong, robust and provide relatively low losses. The window in the detector presents both a potential barrier and introduces UCN losses due to absorption and scattering. With the detector mounted 1 m below the beam line (using gravity to accelerate the UCN), we have measured the transmission of UCN falling through a 0.025 cm-thick window to be 50%. Monte Carlo modeling suggests that about half of the losses are absorption in the material and half are due reflections off of the non-specular surface.

Recently, we have measured the strength and transmission of UCN through zirconium metal foils. Zirconium, 50 $\mu$m, is capable of robustly supporting >4 bar of pressure with about 80% transmission. We hope to try this as a detector foil soon.

### 3. Results

We present a typical spectrum obtained for UCN from the LANSE source with one of these detectors mounted after a fall of 1 m into the detector in Fig. 2. The detector was operated with 2600 V on the anode and 390 V on the grid planes. The pulses were amplified with an Ortec 142PC pre-amplifier and shaping amplifier and read into a peak-sensing ADC. The detector gain at this voltage is ~6. The cosmic and gamma ray backgrounds are low in this set up so that the edges due to wall effects are apparent in the histogram. The typical resolution was 3% for the five detectors that were tested.

In an earlier work, we used detectors of a similar construction in ion chamber mode. In the laboratory this mode of running provides similar resolution and high gain stability, but was much more susceptible to both electronic and microphonic noise. Maintaining good resolution in detectors with gas gain required...
tighter dimensional tolerances (we achieved ~100 μm precision in wire spacing and plane spacing), but reduced the susceptibility of the electronic and the microphonic noise to negligible levels.

The relative detector efficiency as a function of 3He fill pressure, for both thermal and ultra-cold neutrons is shown in Fig. 3. For thermal neutrons the efficiency is linear with 3He pressure, but for UCN the efficiency saturates at relatively low 3He pressure as expected. The solid curve through the UCN data is a calculation of the UCN efficiency assuming that the mean velocity of neutrons in the detector is 4.4 m/s due to the 1 m drop to the detector and the lifetime given by the 3He absorption cross-section.

In Fig. 4 we plot the relative full energy efficiency for thermal neutrons as a function of stopping gas pressure. For both thermal neutrons and UCN, the efficiency is observed to plateau at about 1 bar of CF₄. Therefore, we have chosen a conservative combination of 0.025 cm 6061 T6 aluminum window with 1 bar of stopping gas pressure.

4. Conclusions

A simple and robust design for a multi-wire ³He ultra-cold neutron detector has been presented. The performance has been measured for both thermal and ultra-cold neutrons. The pulse-height resolution was measured to be 3%. The full energy efficiency is 80% for neutrons that make it through the entrance window. Transmission through the window for neutrons that are dropped 1 m into the detector was measured to be 50%. We hope to significantly improve this transmission by using zirconium windows in future.

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