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Inexpensive and practical sealed drift-tube neutron detector

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Abstract We describe design, construction, and performance of sealed ^{3}He drift tubes for neutron detection. The cost of the detectors is not dominated by the ^{3}He gas at pressures ranging from 25 to 300 mbar. A few percent intrinsic neutron detection efficiency is achieved by high-density polyethylene moderation. Sensitive measurement of the detector lifetime is achieved by monitoring the neutron peak positions as a function of time. The neutron peak positions show a 24-hour cycle that may be correlated to physical absorption of the gas onto the wall. The lifetime of the detectors is not limited by gas leak and therefore the design and construction method are robust and practical for applications such as fissile material detection.

Key words:
Sealed drift tubes, neutron detection efficiency, detector lifetime, gain drift.

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Introduction

Neutron emission is a ubiquitous signature of spontaneous and beam-induced nuclear fission. Fission neutrons open the door to detecting hidden fissile materials because the neutrons are only weakly absorbed by most materials and thus highly penetrating. The neutron lifetime of ~ 900 s and their motion at the thermal speed of ~2.2 km/s allow neutron detection remotely. A plethora of methods have been developed to address the basic issues such as maximizing intrinsic neutron detection efficiency (ε_i) and discrimination against background particles (cosmic rays, earth-bound energetic particles, and γ-rays) [1-4]. Maximizing the absolute neutron detection efficiency ($\varepsilon_{abs.}$) and accuracy in neutron identification at a reasonable cost is an important practical issue for fissile material detection. Other issues include ease of detector production in large quantities, detector lifetime, and stability of the gain.

We describe a practical and scalable sealed drift tube design using a gas mixture at 1 bar total pressure that contains 2.5% to 30% of ^{3}He. ^{3}He gas is widely used for neutron detection since ^{3}He is an inert gas and the reaction ^{3}He(n,p)^{3}H has a cross section of 5330 barn for thermal neutrons, one of the largest among all elements. Limited supply and high cost of ^{3}He motivated us to study low-pressure ^{3}He drift tubes that take advantage of the large albedo of thermal neutrons off of polyethylene surfaces to gain back some of the efficient, $\varepsilon_{abs,}$ lost in going to lower ^{3}He pressures. $\varepsilon_{abs.} = \frac{\Omega}{4\pi}\varepsilon_i$ for a point fission source, with Ω being the solid angle of the detector, and $\varepsilon_i = \xi\,[1- e^{-N(^3He)\sigma L}]$. $\xi \sim 1$ for gas ionization detectors. [1] Lowering the ^{3}He pressure [$\propto$N(^{3}He)] reduces ε_i. To compensate

for the reduction in ε_i, ~ one-inch thick high-density polyethylene sheets are used to surround the drift tubes. Within the polyethylene shroud, moderated neutrons can pass through the detector multiple times (that increases neutron path-length L) due to reflection and become thermalized at the same time, resulting in an increase in σ ($\propto v^{-1}$). ε_i's for single poly-moderated detectors reach a few percent, consistent with the back-of-envelope estimates and Monte Carlo simulations. ε_i's for multiple tubes are significantly higher. Furthermore, each $^3He(n,p)^3H$ reaction releases Q = 0.764 MeV of total kinetic energy, with a partition ratio of 3:1 between p (^1H) and ^3H determined by the momentum conservation. The selections of detector diameter (5 cm), the gas mixture (explained below), and the total gas pressure at 1 bar ensure that the full energy of each nuclear reaction can be absorbed by the gas, resulting in a prominent Q-value peak (Q-peak) in the pulse height spectrum. Furthermore, the wall-effects of the $^3He(n,p)^3H$ reaction are also separated from background, giving that the design can discriminate neutrons from comic rays, γ-rays, and energetic charged particles background.

Design and construction

The design of a drift tube detector is shown in Figure 1. This design has been duplicated for many tubes to make large array detectors. The aluminum body of each tube has an OD of 2" (5 cm) and wall thickness of 0.035". The tube length is variable depending on applicable specifications, usually no less than 12" to prevent detector performance from being dominated by end-effects. Detectors of this design have been built up to 6.1 m long. Both ends of the aluminum body are closed with a welded cap with a 1/8" MTP

threaded hole in the center. A Swagelok fitting is used to hold an anode wire on the central axis of the tube. The wire is made of gold-plated tungsten and 50 μm in diameter. The wire is stretched to 100 gm of tension and is held by the fittings shown in Figure 1). This fitting is a 1/16" copper tube snuggly fitted inside a polyetheretherketone (**PEEK**) tubing that is inserted into a 1/8" Swagelok feedthrough. The Swagelok seals both the Swagelok-peek and the peek-copper interfaces. The anode wire is crimped and soldered copper tubes at both ends to prevent gas leak. Vibration test are used to measure the tension of the wire based on the wire vibrational frequency. The detector is then helium leak checked and high-voltage tested before filled to one bar of total gas pressure, containing 25 to 300 mbar of ^{3}He gas. The balance of the gas mixture consists of 7.5% of C_2H_6, 2.5% of ^{4}He , 42.5% of CF_4 and 47.5% of Argon. A team of two has been able to assemble 100 detectors in one 8 hour shift, indicating the robustness of the design and construction. Excluding the cost of labor, the cost of each tube mainly comes from ^{3}He gas for the highest ^{3}He fill of 300 mbar and leverages with other material cost for lower ^{3}He pressures.

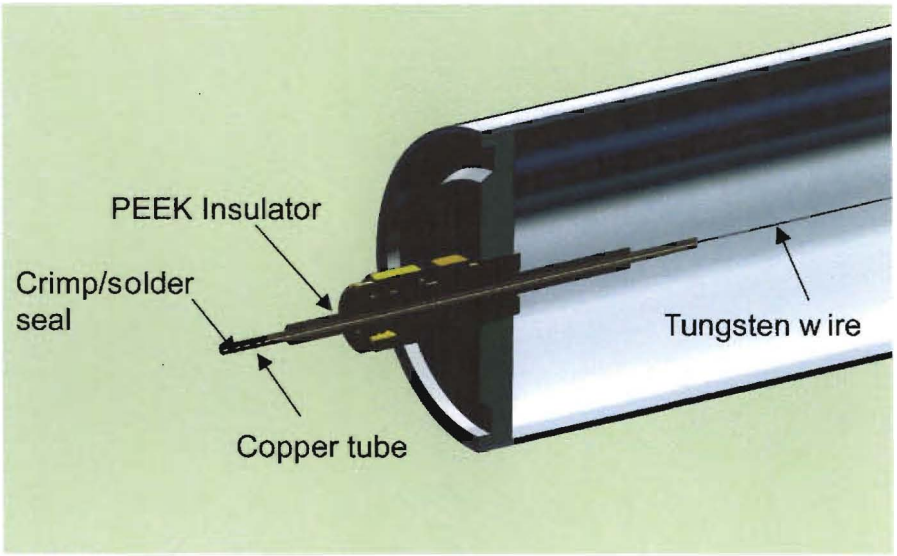

Figure 1) Schematic view of a detector construction.

Results

We use commercial pre-amplifiers (ORTEC 142 PC), shaping amplifiers (various ORTEC models and equivalent), high-voltage supplies (ORTEC 556 and equivalent), and data acquisition system (DAQ) for detector characterization and operation. The drift tube detectors operate as proportional counters when the anode wires are biased between 1400 (300 mbar ^{3}He) to 1800 volts (25 mbar ^{3}He) above the cathode body. A typical spectrum is shown in Figure 2.

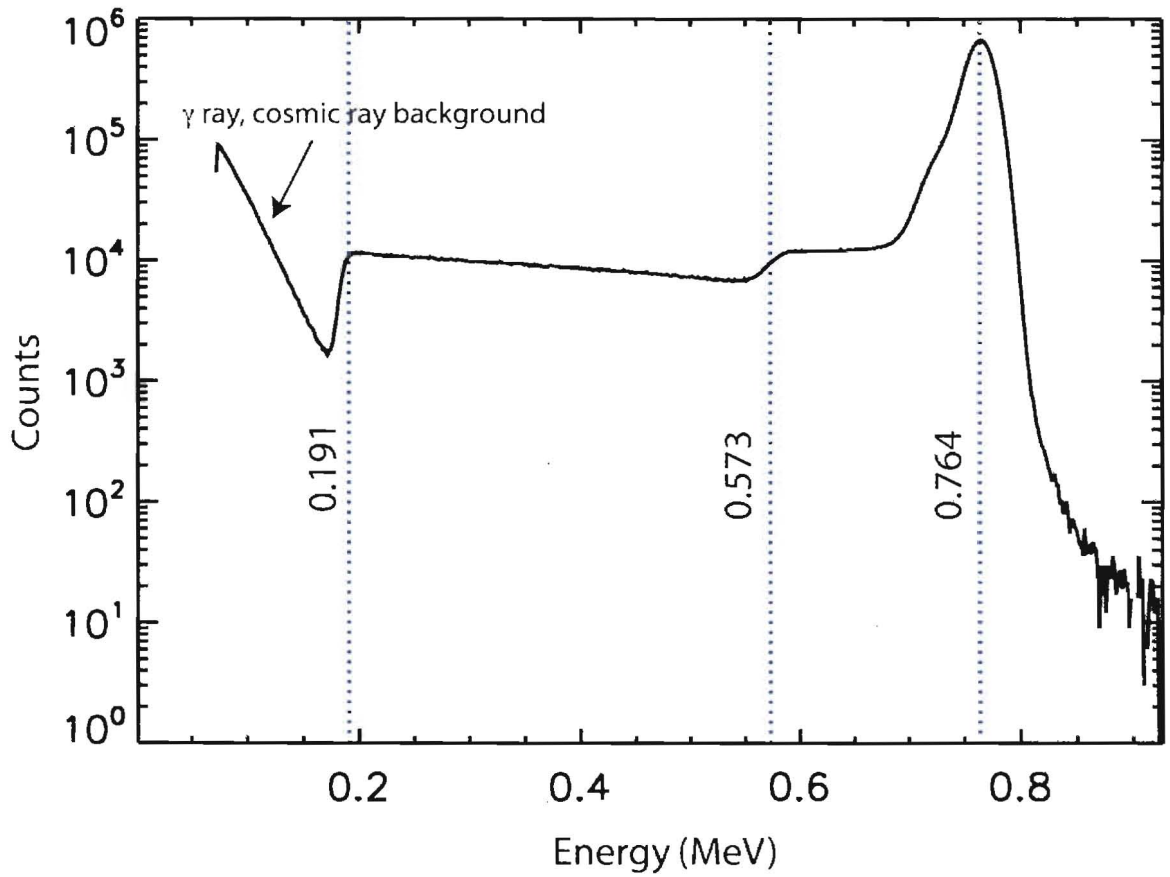

Figure 2) Pulse height spectrum of a 200 mbar ^{3}He pressure 48" long detector using a ^{252}Cf source. The detector is operating with a voltage of 1600 V. The spectra shows a peak at the ^{3}He(n,p)T Q-value of 0.764 MeV (Q-peak) as well as edges at the energies of both reaction products due to wall effects, indicated by vertical dashed lines. The energy scale is based on the Q-peak. The neutron

signals are clearly separated from the lower energy background. The background is cut off by the DAQ on the left.

The gas amplification, and consequently the pulse height, is a function of bias voltage and gas pressure. Pulse height, a measure of the total charge q_M generated by the ^{3}He(n,p)^{3}H reaction, is given by $q_M = \frac{Q}{\Delta} eM$, with Q = 764 keV, $\Delta \sim 30$ eV being the energy for ion pair production, and M being the gas multiplication factor or the gain of proportional counts. The gain M changes according to the Diethorn formulae, [2,3]

$$\ln M = \frac{V}{\ln(b/a)} \frac{\ln 2}{\Delta} \left[\ln \frac{V}{pa \ln(b/a)} - \ln K \right].$$

As expected, the total number of neutron counts does not vary with bias voltage, indicating that the efficiency of the detector is independent of the bias voltage.

The relative detector efficiency as a function of ^{3}He fill pressure is shown in Figure 3. For thermal neutrons, the efficiency increases linearly at low ^{3}He pressures. Deviation from linearity is observed at 200 mbar and above.

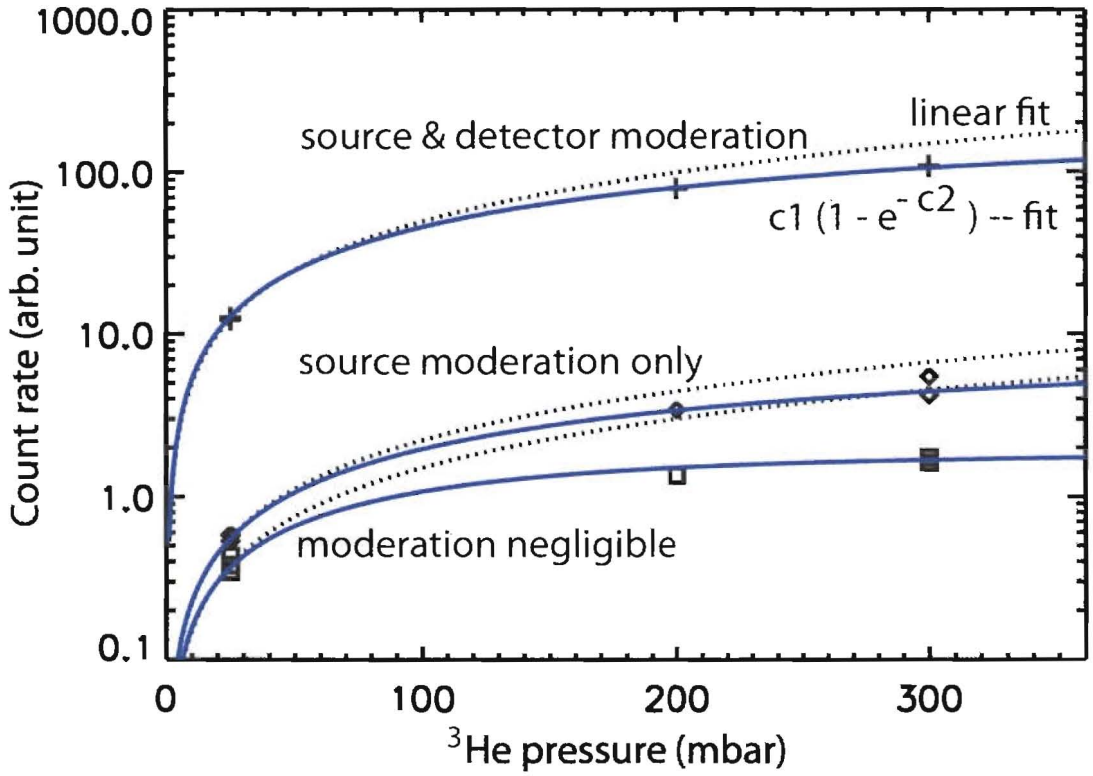

Figure 3) Relative counter rates (a measure of intrinsic efficiency) at different ^{3}He pressures, with different degrees of moderation of a ^{252}Cf source and detectors. The linear fits (dashed lines) are expected for low ^{3}He pressures (≤ 100 mbar). Deviation from linearity is observed at 200 mbar and above.

The ultimate lifetime of sealed drift tube detectors is determined by gas leaking out of the tubes; outgassing of impurities into the tube; or radiolysis and polymerization of gas components in the tube. For low neutron rates, we expect that gas leak dominates over other factors. To test this hypothesis, we monitored the Q-peak position of the pulsed height spectrum as a function of time for a few weeks. A result is shown in Figure 4. From the Diethorn formula, gas leak (p decreases) causes M and thus pulse height to increase in magnitude.

It appears that very sensitive gain measurements can be made of gas detectors using neutrons. The method can be used to monitor the tube health. [5]

For Figure 4, we only rely on the natural background (~ 0.16/s). Therefore each data point was based on accumulated counts a ~ 24 hour period.

The gain also changes with the applied voltage, anode and cathode radius (*a*, *b*), and θ in the Diethorn formula. Therefore we maintained a constant bias voltage within the specification of the ORTEC 556 HV supply. The relative position of a ^{252}Cf source to the detector is fixed, to minimize possible change of pulse height due to the non-uniform anode wire or the cathode tube radius non-uniformity. With a fixed setup, possible Q-peak shift due to the change in the stray capacitance between the detector and the pre-amp is also minimized. The linear least square fit to the slope of the gain change in Figure 4 indicates that a 100% change in gain would take ~ 44 years for this tube. We also conclude that this design and construction method can provide long term reliability

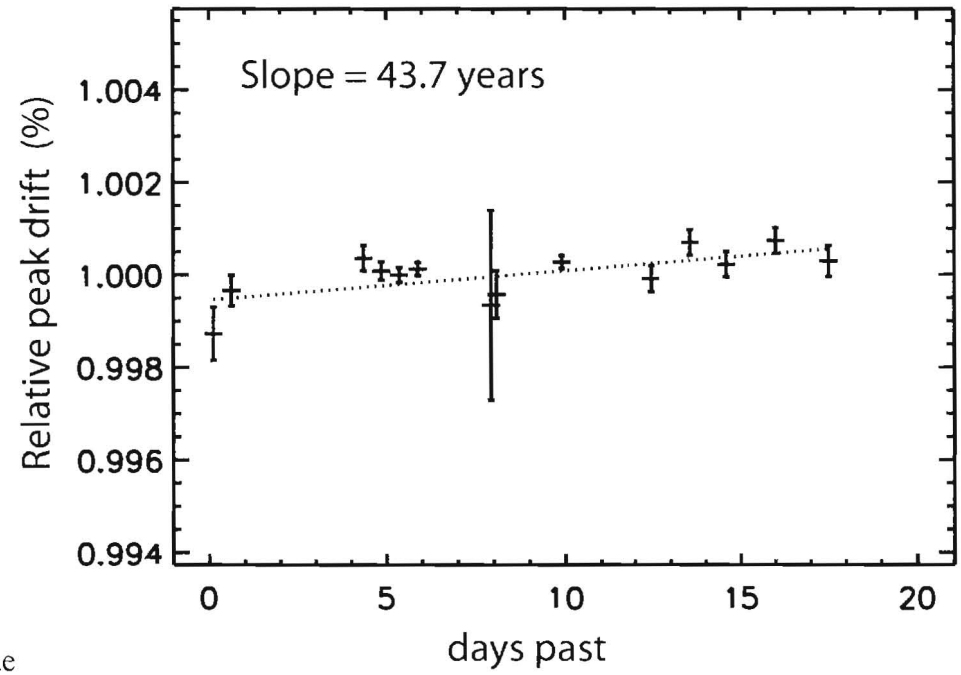

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Figure 4) Drift of the full energy peak (Q-peak) of a 25 mbar ^{3}He tube with time for over two weeks. Each data point is based on neutron pulse height spectrum accumulated for ~ 24 hours. Background neutron flux (~ 0.16/s) produces the pulse height spectrum.

Using a 252Cf source to obtain higher rates and shorter sampling times we have observed diurnal oscillations in Q-peak drift, shown in Figure 5. The 24-hour cycle of the Q-peak tracks the ambient temperature oscillations over the same period. In addition, by heating the tube to a higher temperature, the Q-peak height was found to decrease on the same time scale as the temperature change. The Q-peak height then relaxes back to the pre-heating values when the heating source is turned off. Temperature effects on drift tubes were reported before but they are different from our observation. [6,7] We can rule out thermal expansion of the tube volume as a possible cause for two reasons. The observed trend of gain change due to heating is opposite to what is expected. In addition, the thermal expansion coefficient of aluminum is 2.1-2.5 10^{-5} in/in·°C, which indicate that effect of thermal expansion is merely about 1% of what is observed. A possible explanation of the diurnal oscillation is the gas density (and the corresponding pressure) oscillation inside the drift tube due to physical absorption of the gas on the wall. [8,9] In contrast to chemical absorption with activation energies of ~ 100 kJ/mole or more, physical absorption corresponds to a typical activation energy E_d ~ 1 - 10 kJ/mol (0.01 - 0.1 eV per molecule). [8] Therefore, physical absorption or the amount of the gas on the wall is sensitive to the room temperature of ~ 0.025 eV. Physical absorption is a reversible process, thus the total amount of gas (wall + tube) remains the same. Therefore, although physical absorption causes the diurnal oscillation in gain, it does not

affect the life-time of the drift tube. The amount of absorbed gas is better described by the multi-layer absorption (BET model) than the monolayer absorption (Langmuir-like) since the tube pressure is at 1 bar total pressure and room temperature. It is possible that the relative concentration of the gas mixture on the wall is different from the volume of the tube since E_d's vary with different gases. The change in gain is

$$\frac{\delta M}{M} = -f_p \frac{\delta p}{p},$$

with $f_p = \frac{V}{\ln(b/a)} \frac{\ln 2}{\Delta}$. For the drift tubes described here, V=1.3-1.8 kV, b/a = 5 cm/50 μm, $\Delta \sim 30$ V, yielding $f_p \sim 4.3 - 6$. A 0.5% oscillation in gain, as in Fig. 5, requires 0.1% change in absorbed gas quantity, or a 6×10^{16} cm^{-2} change in surface molecule density.

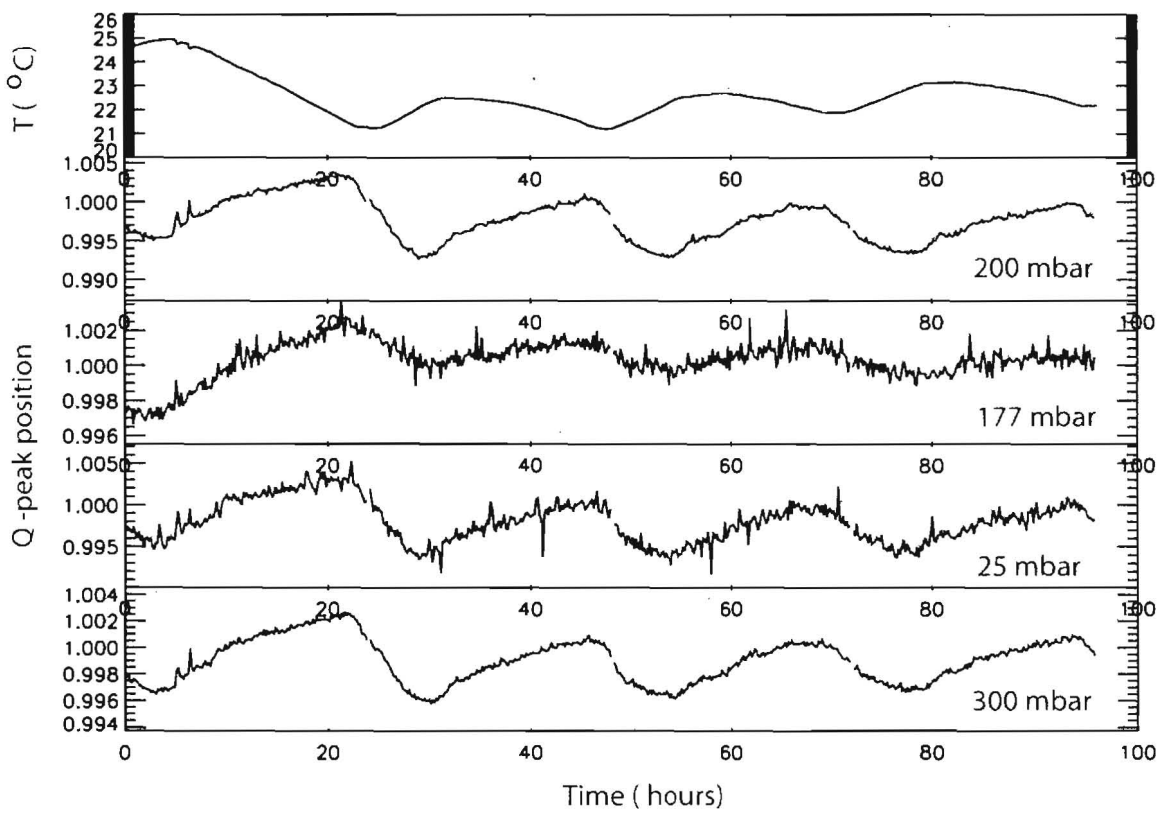

Figure 5) Q-peak positions of four sealed drift tubes at different ^{3}He pressures (as indicated) as a function of time for 96-hours (10 min per bin). Short-term fluctuations (for 177mbar and 25 mbar, in particular) are due to combined effects of Poisson statistics and electronic noises. All tubes show diurnal oscillations that track the temperature oscillations. Higher temperature corresponds to lower gain (or smaller peak amplitude).

In contrast with physical absorption that does not change the lifetime of a drift tube, outgassing due to permeated gas through the wall, chemical adsorption due to energetic electrons and UV light at the wall can potentially affect the lifetime of the drift tube. Since most of these detrimental processes involve the 'modification' of the wall conditions, which can result in change of adsorption properties accordingly, we expect that monitoring the diurnal oscillation provide a quantitative way to monitor the change of wall-adsorption conditions and thus the health of the sealed drift tubes.

Conclusions

A practical low-cost sealed-drift-tube design using low-pressure ^{3}He gas has been presented. By using 25 to 300 mbar of ^{3}He gas, the cost of ^{3}He is not the dominant factor in the total material cost of a detector. High-density polyethylene moderators increase the intrinsic neutron detection efficiency to a few percent. Sensitive measurements of the detector lifetime have been achieved by monitoring the neutron peak positions as a function of time. The neutron peak positions have a 24-hour cycle that is correlated to ambient temperature fluctuations. The lifetime of the detectors is not limited by gas leaks or wall outgassing and therefore the design and construction method are robust.

Acknowledgments

This work has been supported in part by DTRA of the Department of the Homeland Security and a CRADA agreement between LANL and Decision Sciences Corp.

Figure summary

Figure 1) Schematic view of a detector construction.

Figure 2) Pulse height spectrum of a 200 mbar ^{3}He pressure 48" long detector using a ^{252}Cf source. The detector is operating with a voltage of 1600 V. The spectra shows a peak at the ^{3}He(n,p)T Q-value of 0.764 MeV (Q-peak) as well as edges at the energies of both reaction products due to wall effects, indicated by vertical dashed lines. The energy scale is based on the Q-peak. The neutron signals are clearly separated from the lower energy background. The background is cut off by the DAQ on the left.

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