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Detecting ionizing radiation in liquid helium using wavelength shifting light collection

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Abstract

Detectors for counting low energy (less than 1 MeV) ionizing events in liquid helium are developed and characterized. These devices employ wavelength shifting fluors to convert extreme ultraviolet (EUV) helium scintillation light to the visible, allowing transport of signal light to room temperature. Three technological approaches are developed and tested: wavelength shifting fiber, composite acrylic tube, and diffuse reflecting tube of expanded teflon. The tube-based detectors have been used to detect magnetically trapped neutrons. All of the technological approaches have utility in other experiments, such as a more sensitive measurement of the neutron electric dipole moment and the monitoring of the low-energy solar neutrino flux.

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1. Introduction

Liquid helium is a fascinating medium, famous for its quantum fluid characteristics at low temperatures. Less widely known is its high efficiency as a scintillator. However, there is an abundance of literature on this topic, mostly dating from the 1960s and early 1970s. Helium scintillations were first detected in 1959 by Thorndike and Shlaer [1] and Fleishman et al. [2]. They found strong helium scintillations in the ultraviolet, with a wavelength less than the

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LiF cutoff at 121 nm. This scintillation could be detected using wavelength shifting fluors to convert the scintillation light to the visible. The physics of scintillation was not fully understood until later, when several groups used electron beams and radioactive sources to investigate the spectrum of the scintillation. The radiation was found to be centered around a wavelength of 80 nm, in the technically difficult extreme ultraviolet (EUV) region [3–5]. Work with wavelength shifters to convert the EUV light to the visible allowed detection of individual ionizing radiation events, and found that the scintillation pulse height due to alpha particles varied with helium temperature below the λ point, unlike that from energetic betas which did not [6–8].

At present there is a moderately complete model of scintillations in liquid helium. The scintillation process starts when an energetic charged particle passes through the liquid, creating numerous ion–electron pairs and excited atoms. The ions quickly attract surrounding ground state atoms and form ion clusters. The ion clusters recombine with electrons, producing excited diatomic molecules. Similarly, excited atoms combine with ground state helium, also forming excited diatomic molecules, including singlet $\text{He}_2(A^1\Sigma_u^+)$ and triplet $\text{He}_2(a^3\Sigma_u^+)$. Fluorescence in condensed noble gases is observed to be almost entirely composed of a wide continuum of EUV light, emitted when these excited diatomic molecules decay to the monoatomic ground state. The energy of emission is less than the difference in energies between the ground and the first atomic excited state. The scintillation target is thus transparent to its own scintillation light, and a detector based on a condensed noble gas can be built to large size with little signal loss from reabsorption.

Recently, interest in liquid helium as a scintillator has revived due to proposals to measure the neutron electric dipole moment [9], measure the neutron beta decay lifetime [10], and detect low energy solar neutrinos [11,12]. In the neutron experiments, superfluid helium is used because it does not absorb neutrons and can be used as an ultracold neutron production and storage medium. Superfluid helium has the advantage of extremely low levels of radioactive impurities,

a potential advantage for neutrino detection. These new experiments have spurred the investigation of liquid helium scintillations. For example, studies by Adams et al. indicate that approximately 35% of the energy from high-energy electrons is emitted in a fast pulse of EUV light [13,14]. In addition, a considerable amount of light is emitted slowly from the decay of triplet molecules. In a previous publication, we reported that after removing a radioactive source from liquid helium, a single photoelectron rate was observed to decrease exponentially with time, with a lifetime of 13 s. This exponential decay was identified as the radiative decay of $\text{He}_2^*(a^3\Sigma_u^+)$ molecules [15]. Combining the light intensity from both singlet and triplet decay, over half of the kinetic energy carried by relativistic electrons in liquid helium is converted to EUV scintillation light.

In this paper, we describe work and findings on liquid helium as a scintillator. Our particular motivation for these studies is the goal of detecting scintillation light from the beta decay of magnetically trapped neutrons residing in liquid helium [16,17]. Thus, several key constraints guided the development of our detection systems. First, the system must allow a cold neutron beam to enter the center of the detection region. Second, the physical components must not activate when exposed to cold neutrons because energetic particles emitted from activated materials in the detector could compete with the neutron decay signal. Third, the system must operate in a high magnetic field. Finally, the system must have efficient transport of light out of the long narrow bore of a superconducting magnetic trap. We have investigated three different designs, one using wavelength shifting fibers, one using an acrylic tube, and one using a tube of expanded teflon. This paper describes these systems with emphasis on the amount of signal achieved with each system. All three systems have in common the use of tetraphenyl butadiene (TPB) as an EUV waveshifter. TPB is the fluor of choice, having a conversion efficiency from the EUV to the blue of 135% [18]. This blue light is well matched to the peak sensitivity of available photomultiplier tubes.

2. Wavelength shifting fiber-based detector

The first cells built for detecting neutron decays in liquid helium are constructed using both TPB and wavelength-shifting fibers. The basic idea is that the TPB will convert the EUV helium scintillation light into blue light, and then the fibers will convert the blue light to green light. The green light is transported out of the cryogenic apparatus through the fibers.

The first generation detection cells are 15 cm long, and consist of a Gore-tex sheet,⁴ three boron nitride (BN) rods, and two wavelength shifting optical fibers⁵ (as shown in Fig. 1). The fibers are coiled into a double helix and held in position using three 3 mm × 3 mm × 150 mm rods of boron nitride (not shown in figure), with 24 holes drilled in them (one every 6 mm). Thus, each fiber has 12 loops of 32 mm diameter. The Gore-tex is coated on the inner surface with evaporated TPB and wrapped around the fiber as a tube.⁶ This detection tube assembly is slid into a G-10 tube of 38 mm inner diameter.

The results of a series of tests on this fiber-based design are summarized in Table 1. Tests 1–6 use a 12 cm diameter vertical helium dewar with a narrow neck, filled directly with 4.2 K liquid helium from a storage dewar. A ¹³⁷Cs source can be raised and lowered vertically within the cell, allowing comparison of signals with and without helium excitation in the detection region. The ¹³⁷Cs source emits betas with an endpoint energy of 514 keV. Using a pancake counter,⁷ its activity is measured to be $\approx 2830 \text{ s}^{-1}$. Results with the ¹³⁷Cs source are not normalized per unit of energy deposition, as ¹³⁷Cs is an intense gamma as well as

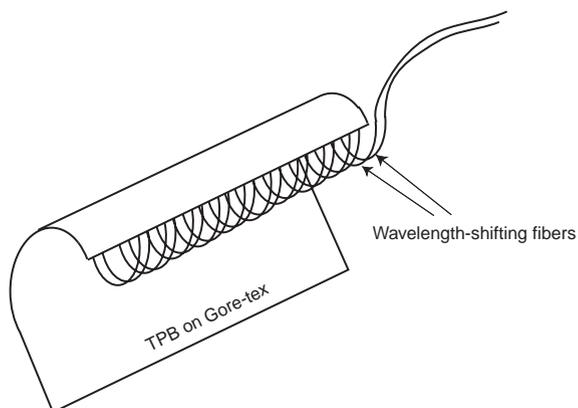


Fig. 1. A fiber cell is built with a pair of wavelength shifting fibers and a sheet of Gore-tex with TPB evaporated on its inside surface. The fibers are held in place with boron nitride rods (not shown).

beta emitter, and many gammas escape the helium without depositing their energy in the helium.

The cell tube is constructed such that the bottom is open to allow liquid helium to enter the detection region. One end of each fiber exits the dewar and is pushed up against the front window of a single 19 mm diameter PMT⁸ with heightened long wavelength response (quantum efficiency of about 12% at 500 nm). The PMT signal is sent to a fast discriminator, whose threshold was set to trigger on single photoelectron signals. The trigger rate is then recorded for different detector configurations.

It is seen that TPB works better than DPS (diphenyl stilbene, another fluor used for wavelength shifting EUV light), and that a 6 mm coil spacing works better than a 12 mm coil spacing. By doing one run without any TPB on the Gore-tex, we observe that the liquid helium from the storage dewar fluoresces in the visible with an intensity of about 10% of that observed with the TPB present. We hypothesize that frozen air impurities in the helium are responsible, as fluorescence from impurities in liquid helium was seen in previous work [19].

Tests 7–9 on the table are performed using a ³⁶Cl source in a tall 12.7 cm diameter dewar. In this apparatus (see Fig. 2), the G-10 tube is closed

⁴Certain trade names and company products are mentioned in the text or identified in illustrations in order to adequately specify the experimental procedure and equipment used. In no case does such identification imply recommendation of endorsement by the National Institute of Standards and Technology, nor does it imply that the products are necessarily the best available for the purpose.

⁵0.8 mm diameter double-clad Y11(250) fibers from Kuraray.

⁶Gore-tex gasketing material purchased from Big River Rubber and Gasket, Owensboro, KY (800) 626-7030 (www.bigriverrubber.com).

⁷Calibrated to within 10%.

⁸Burle 8644.

Table 1

Results for a variety of tests using wavelength shifting fiber-based cells. Tests using the ^{137}Cs source could not be normalized per unit of energy deposition, as ^{137}Cs is an intense gamma as well as beta emitter. Here, ℓ denotes the length of each fiber and σ denotes the TPB density on the Gore-tex sheet. Descriptions of the tests are described in the text

| Test | ℓ (m) | σ ($\mu\text{g}/\text{cm}^2$) | PMT type | Source | Count rate (s^{-1}) | Counts per 250 keV β | Remarks |
|------|------------|--|----------|-------------------|--------------------------------|----------------------------|----------------|
| 1 | 0.9 | 55 | 8644 | ^{137}Cs | 17881 | — | |
| 2 | 0.9 | 60 | 8644 | ^{137}Cs | 13507 | — | DPS used |
| 3 | 0.9 | 58 | 8644 | ^{137}Cs | 16281 | — | |
| 4 | 0.9 | 0 | 8644 | ^{137}Cs | 1493 | — | |
| 5 | 0.8 | 95 | 8644 | ^{137}Cs | 25158 | — | $d = 12$ mm |
| 6 | 0.9 | 173 | 8644 | ^{137}Cs | 28578 | — | |
| 7 | 2.8 | 143 | 8644 | ^{36}Cl | 2976 | 3.25 | |
| 8 | 2.8 | 240 | R943-02 | ^{36}Cl | 2613 | 2.83 | Through window |
| 9 | 2.8 | 231 | R943-02 | ^{36}Cl | 3597 | 3.89 | Ball lens |
| 10a | 3.9 | 160 | R943-02 | ^{36}Cl | 2153 | 2.33 | PMT 1 |
| 10b | | | R943-02 | | 1796 | 1.94 | PMT 2 |
| 10c | | | | | 457 | 0.50 | Coincidence |

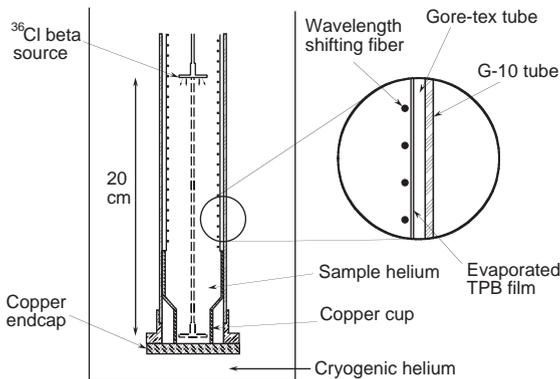


Fig. 2. Diagram of the cryogenic apparatus used to test fiber-based detection cells.

at the bottom with a copper flange. The fibers traveled up through the tube to Swagelok feedthroughs [20] and exit the cryogenic apparatus. The G-10 tube can be filled with helium from the surrounding helium bath or highly purified helium from a gas bottle. In the latter case, the temperature of the helium surrounding the detection cell can be lowered by pumping. This allows helium to be condensed in the cell. The temperature of the cell can be as low as 1.8 K. The ^{36}Cl source's beta decay spectrum (average energy 252 keV, maximum energy 710 keV) closely mimics the neutron's. The source has a beta intensity of 920 s^{-1} (measured using a pancake counter),

and can be lowered or raised within the cell using a motion feedthrough at the top of the apparatus. The source can be “turned off” by lowering it into a copper housing at the bottom of the tube.

Test number seven is performed with the 19 mm photomultiplier, whereas later tests are performed using a photomultiplier with better response in the green⁹ and cooled to achieve low dark counts.¹⁰ Unfortunately, this PMT has a recessed GaAs photocathode, making it more difficult to effectively couple it to the fiber. At first we simply send the fiber light through an acrylic window, but later we use a 10 mm ball lens.

The number of photoelectrons detected for each scintillation event can be expressed as

$$N = YF(1 - S)C e^{-\ell/\ell_{\text{att}}} R^{1/S} Q,$$

where Y is the EUV photon yield of the liquid helium, F is the fluorescence efficiency of the wavelength shifting fluor, S is the fraction of the wall surface covered by the wavelength shifting fiber, C is the conversion and capture efficiency of the wavelength shifting fiber, ℓ is the length of the fiber, ℓ_{att} is the attenuation length of the fiber, R is the reflectivity of the fluor coating, and Q is the quantum efficiency of the light detector. The factor

⁹Hamamatsu R943-02, with a quantum efficiency of 19% at 500 nm.

¹⁰Peltier cooler purchased from Products For Research.

$R^{1/S}$ takes into account the probability that a blue photon emitted by the wavelength shifting fluor is absorbed by the wall surface before reaching the wavelength shifting fiber. In using this factor, we assume that $S \ll 1$ and that the photon, on average, reflects $1/S$ times before being captured by the fiber.

With a TPB concentration of about 0.2 mg cm^{-2} we detect an average signal of 3.9 phototelectrons per β particle. This can be explained using the following input parameters:

- $Y = 8200 \pm 1000$ EUV photons for a 250 keV beta.¹¹
- $F = 1.35 \pm 0.1$ for TPB [18].
- $S = 0.12 \pm 0.01$ for fiber coils spaced 6 mm apart.
- $C = 0.025 \pm 0.002$ for the conversion and capture efficiency of the Y11 fiber¹² (one end).
- $\ell = (2.5 \pm 0.2) \text{ m}$ (the total fiber length from the center of the detector).
- $\ell_{\text{att}} = (2.9 \pm 0.2) \text{ m}$ (the attenuation length of the wavelength shifting fiber (see footnote 12)).
- $R = 0.85 \pm 0.05$ (estimated reflectivity of TPB).
- $Q = 0.13 \pm 0.02$ (quantum efficiency of the R943-02 multiplied by optics efficiency).

These values predict a total collection of $3.5_{-1.4}^{+2.2}$ photoelectrons per 250 keV beta. The dominant contributor to this uncertainty is the knowledge of the reflectivity of the TPB coating.

A cell of this type was used in our first attempt to detect trapped neutrons. This cell was 30 cm long (twice as long as the cells initially tested), with two fibers wrapped in helices of opposite sense. Two sets of 15 cm long BN rods (6 rods total) and two Gore-tex sheets were used. Each boron nitride rod had 24 holes, and each fiber was wound through both sets of BN rods (a total of 24 coils). All four fiber ends exited the cryogenic apparatus and were connected to a single Hamamatsu R943-02 photomultiplier. We soon found, however, that the neutron trapping apparatus suffered from a

large quantity of neutron-induced luminescence. To minimize this background, coincidence detection was introduced, and we began running in coincidence, with the two ends of each fiber fed into its own PMT.

After approximately 1 month of beam time and failing to observe trapped neutrons because of this luminescence background, we tested the efficiency of the larger cell. This test (number 10 in the table above) revealed that the light yield in each PMT was decreased significantly by the increased fiber length. The decrease in light yield is consistent with the 2.9 m light attenuation length in the wavelength shifting fibers. We found that only about half of the decay events were detectable in coincidence. Altogether, the fiber-based cells of the type used in the attempt to detect trapped neutrons yielded 4.27 photoelectrons per ^{36}Cl decay (summing the yield in the two photomultipliers). Since a large fraction ($33\% \pm 10\%$) of the photoelectrons came from triplet $\text{He}_2^*(a^3\Sigma_u^+)$ decay, this photoelectron yield must be multiplied by $66\% \pm 10\%$ to find the total number of photoelectrons in the prompt pulse. This fraction is estimated from separate measurements of the intensity of triplet molecule decay. Assuming a PMT quantum efficiency of $19\% \pm 1\%$ and a light collection efficiency of $40\% \pm 10\%$ for transport of the light from the fiber coils, through the 1.5 m of fiber between the coils and the photomultiplier, into the ball lens, and onto the PMT photocathode, one finds that the fiber cells yielded (224 ± 60) photons MeV^{-1} .

While the fiber-based cells never were demonstrated to have very high light collection efficiencies, this design may be useful for other experiments. Since the fiber has a small cross-section, it can be snaked out of an apparatus without physically interfering with other aspects of the experiment. The fiber design was used initially in the neutron trapping experiment because it was felt that the neutron beam should not be stopped within the apparatus, so as to minimize activation and heat load from neutron absorption. With the removal of this constraint, we turned to a second detector design using acrylic tubes to transport the light out of the detection region.

¹¹This value calculated assuming 35% efficiency in creating the fast component [14], and half of this efficiency in creating the slow triplet component [15].

¹²Fiber properties provided by Kuraray America, Inc., New York, NY 10166.

3. Acrylic tubes

The second type of detector insert developed for the neutron trapping experiment is based on acrylic tubes whose inside surfaces are coated with TPB-doped polystyrene. This mixture was tested independently using a fluorescence efficiency measuring device (see Ref. [18]) and found to have good EUV-to-visible conversion properties (fluorescence efficiency of 40%). Polystyrene doped with TPB is transparent and can be index matched to light guides, allowing efficient transportation of visible light out of the detection region. In tests with a movable alpha source in an acrylic tube filled with argon gas, it is found that acrylic tubes coated with the polystyrene-TPB mixture have less light attenuation than tubes coated with evaporated TPB (see Fig. 3).

The TPB-polystyrene coating converts the EUV scintillation light to blue light, with about half of the blue light trapped in the tube walls. A fraction of this light makes it to the end of the tube, passes into a solid acrylic light guide, and travels up to room temperature. The light is then detected using a photomultiplier tube¹³ at room temperature.

To optimize the design of the tube-based detector inserts, an apparatus (see Fig. 4) is used to test how varying detector parameters (such as tube wall thickness and TPB concentration) affected light output. The cell is mounted inside a G-10 tube, suspended along the vertical axis of a liquid helium dewar. A brass flange is attached to the bottom of the G-10 tube; the tube can then be closed by fastening a copper flange to the bottom with an indium seal. The detection cell is a 40 cm long, 3.8 cm diameter, transparent acrylic tube. Its wall thickness is 3.2 mm, and its inner surface is coated with TPB-doped polystyrene. Centered in the acrylic tube, held from below by a stainless steel rod, is a radioactive source; this can be either an α source (^{210}Po or ^{241}Am) or a β source (^{113}Sn). Mating with the acrylic tube from above is a 3.8 cm diameter solid acrylic light guide that extends to room temperature. A 5.1 cm diameter acrylic plug stands above the top of the light guide,

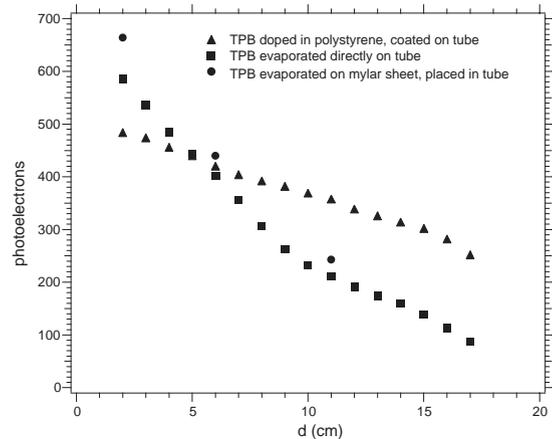


Fig. 3. Variation in pulse size versus position d of an ^{241}Am alpha source in a 5 cm diameter acrylic tube filled with argon gas at a pressure of 1 atm. The distance d is measured with respect to the end of a solid acrylic light guide. Data are shown for tubes coated on the inside surface with TPB-polystyrene mixture, with TPB evaporated directly on the tube, and for TPB evaporated on a mylar sheet inserted in the tube.

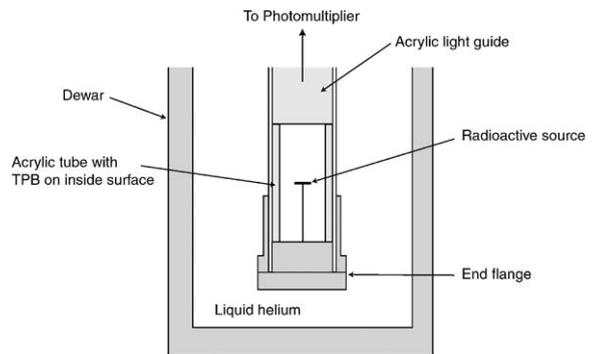


Fig. 4. Apparatus used to measure the relative efficiencies of detection inserts based on TPB-coated acrylic tubes. (Not to scale.)

and an O-ring vacuum seal is made against the plug. Above the plug, index matched using optical grease, is a PMT facing down into the light guide. The photomultiplier was enclosed within a metal housing to protect it from helium gas which can diffuse into the PMT, cause it to afterpulse, and eventually destroy it.

The G-10 tube is initially filled with high purity helium gas¹⁴ using the same techniques described

¹³ Burle 8850 photomultiplier tube, Burle, Inc., Lancaster, PA.

¹⁴ Helium content 99.999%. The helium is also passed through a liquid helium-cooled tube filled with copper mesh before entering the cell.

Table 2

Results for a variety of tests using acrylic tube-based cells. All tests used the Burle 8850 photomultiplier. Specifics of each test are described in the text

| Test | Date | Source | Excitation | Peak signal (p.e.) | Remarks |
|------|---------|-------------------|------------------|--------------------|-------------------------------|
| 1 | 6/20/98 | ^{210}Po | 5.3 MeV α | 177 | HMI cell, 40% TPB |
| 2 | 6/22/98 | ^{210}Po | 5.3 MeV α | 73 | 40% TPB, center blocked |
| 3 | 6/24/98 | ^{210}Po | 5.3 MeV α | 112 | 4% TPB |
| 4 | 6/26/98 | ^{210}Po | 5.3 MeV α | 146 | TPB on Gore-tex |
| 5 | 9/20/98 | ^{241}Am | 5.5 MeV α | 147 | 12% TPB |
| 6 | 9/20/98 | ^{241}Am | 5.5 MeV α | 112 | 4% TPB |
| 7 | 2/5/99 | ^{241}Am | 5.5 MeV α | 145 | 8% TPB |
| 8 | 2/5/99 | ^{241}Am | 5.5 MeV α | 144 | 8% TPB, dewar helium |
| 9 | 2/11/99 | ^{241}Am | 5.5 MeV α | 40 | 2% TPB, center blocked |
| 10 | 2/13/99 | ^{241}Am | 5.5 MeV α | 72 | 30% TPB, center blocked |
| 11 | 2/23/99 | ^{113}Sn | 364 keV β | 18.5 | 40% TPB |
| 12 | 2/24/99 | ^{113}Sn | 364 keV β | 5.5 | Neutron cell [16,17]; 40% TPB |
| 13 | 2/28/99 | ^{241}Am | 5.3 MeV α | 62 | 40% TPB, center blocked |
| 14 | 3/6/99 | ^{113}Sn | 364 keV β | 8.5 | 40% TPB, center blocked |

in the previous section. Once the source is covered with liquid helium, scintillations induced by the radioactive source can be detected by the photomultiplier at room temperature. The PMT signal is fed to a charge preamp¹⁵ and then to a scintillation amplifier¹⁶ and multichannel analyzer. By comparing the scintillation pulse height with the size of the one photoelectron pulse height, the average number of photoelectrons made by scintillation events can be determined. The construction of the acrylic tube is then varied in an attempt to maximize the light collection efficiency.

The acrylic tubes are coated with TPB-doped acrylic using the following procedure. First, the acrylic tube (ultraviolet transmitting grade, UVT) is cut to length (40 cm) and its ends polished. Then a mixture of research grade toluene, crystalline TPB, and polystyrene pellets is stirred and heated within a beaker. When the mixture is dissolved and warm, the acrylic tube is lowered about 1 cm into the liquid. The top of the tube is covered with a rubber plug with a hole in the center. Leading from the hole is a rubber hose with a valve midway through its length, and the far end of the hose terminated at a pump. By carefully throttling the

valve, the liquid can be sucked up into the acrylic tube. After a few seconds, the pump is shut off and the liquid level allowed to slowly drop (over a 20 s period). The tube is then set aside to dry. When dry, the tube is wrapped with Tyvek paper¹⁷ to protect the outer surface.

A variety of tests are performed on the acrylic tube-based detector inserts. These tests are summarized in Table 2. Most of the early tests were performed using a high-energy alpha source, so as to have a large scintillation signal. It is found that a TPB concentration of 30–40% (TPB to polystyrene mass fraction) yielded the highest signals, though TPB concentrations as low as 8% gives as much as 80% of the optimal signal. Attempting to achieve more than 40% TPB concentration generally results in TPB crystallization, spoiling the optical properties of the tube. It is also found that blocking the central region of the end of the tube drops the signal yield by 60%, showing that most of the light does not travel inside the tube walls.

Tests are also performed using ^{113}Sn , a conversion beta source with a line energy of 364 keV. This source is chosen because 364 keV is a comparable energy to that released in neutron beta decay and because a monoenergetic line is

¹⁵Canberra 2005.

¹⁶Shaping width 1 μs .

¹⁷DuPont Chemical Corporation.

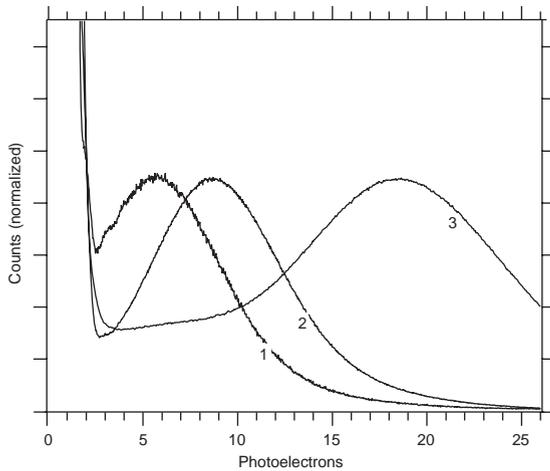


Fig. 5. Three calibration runs of acrylic tube-based scintillation detectors. An ^{113}Sn source, emitting β particles at 364 keV, is used to create pulses of EUV light in the liquid helium. Curve 1 shows the response of a cell used to detect trapped neutrons [16] in April–May 1999. Curve 2 shows the response of a similar cell tested in a cell testing rig. As in the cell used to detect trapped neutrons, only light traveling through the acrylic wall is allowed to pass; the rest is blocked by a black neutron beam stop. Curve 3 shows the response without the center blocked.

more easily identified in a pulse-height spectrum than a broad beta decay spectrum. Data from three of these tests are shown in Fig. 5. Depending on whether the center of the cell is blocked with a black neutron beam dump, either 8.5 or 18.5 photoelectrons can be detected per ^{113}Sn decay event. When this type of cell is placed within the neutron trapping experiment [16,17] along with the ^{113}Sn source (Test 12), an average of 5.5 photoelectrons are detected. The decrease in average pulse size is due to a more complicated, less efficient, set of optics for transporting the light to room temperature.

The intensity of the scintillation signal is also measured as a function of source position along the length of the tube. The pulse height as a function of position is shown in Fig. 6 and exhibits a roughly linear dependence.

The efficiency of the light guide in the test apparatus is measured using an organic scintillator with a beta line source embedded. This light source is alternately positioned at the end of the light guide and directly to the PMT itself. It is found that the light guide is 31% efficient. Given that the

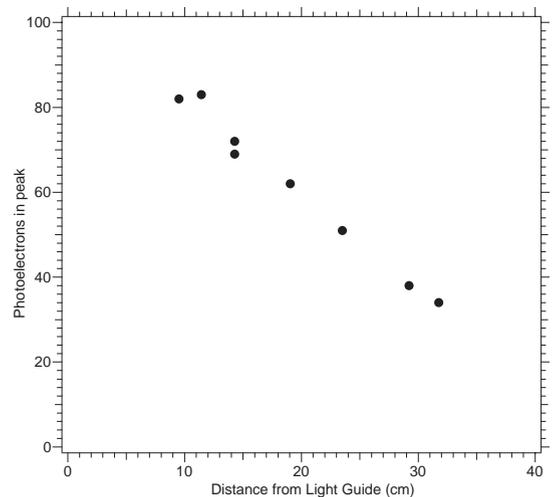


Fig. 6. Variation in pulse size versus position of an ^{241}Am alpha source immersed in liquid helium at 4.2 K. Position is measured from the end of the light guide, with the 3.8 cm diameter acrylic tube extending from 0 to 40 cm. The central region of the end of the acrylic tube is blocked.

Burle 8850 has approximately a 20% quantum efficiency for detecting blue light,¹⁸ it follows that about 140 photons per ^{113}Sn beta event are released from the end of the acrylic tube if its center is blocked, and about 300 photons if it is not. Given the high EUV yield of liquid helium (22,000 photons per MeV for β particles) it follows that only 3.8% of the EUV photons released in the liquid helium result in a blue photon exiting upward into the light guide, and this number drops to 1.8% if the center is blocked. This low yield of blue photons is a combination of the fluorescence yield of TPB doped polystyrene (approximately 25%) and the transmission of the acrylic tube (6.9% in the tube wall, 8.3% down the center). Of course these numbers would be different for a different acrylic tube; a larger wall thickness or shorter tube would increase these numbers significantly.

Result number 4 in Table 2 revealed that a cell built using a sheet of Gore-tex rolled into a tube, with TPB evaporated on its inside surface, could also perform well as a detector. However, since there is no tube wall, all the light extracted from a

¹⁸Burle Industries, Inc., Lancaster, PA.

Gore-tex cell must come down the center. Therefore, a beam dump that is black to visible light makes the use of a Gore-tex cell impossible. However, after 1999, we put significant effort into developing a transparent beam dump, one that could both absorb the neutron beam and pass scintillation light. Eventually we chose to use a cylinder of high purity boron oxide B_2O_3 as a beam dump.

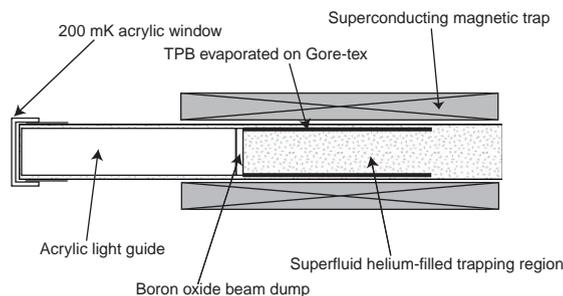


Fig. 7. The neutron detection cell.

4. Expanded PTFE tube-based detector

The third type of detector insert uses a tube of expanded PTFE teflon (Gore-tex). A sketch of this insert and associated optics is shown in Fig. 7. The detector insert is located in the center of the trapping region and surrounds the region where neutrons beta-decay. It is made from two sheets of TPB coated Gore-tex rolled into tubes and placed end-to-end.¹⁹ The resulting tube is 35 cm long and 8.4 cm in diameter. Each sheet [17.5 cm × 28 cm] is placed in an organic evaporator and coated with TPB. The TPB density is measured by concurrently evaporating TPB onto 2.5 cm × 6.3 cm glass slides placed in the evaporator alongside the Gore-tex. The density of TPB on the Gore-tex is not uniform and is estimated to be between 200 and 400 $\mu\text{g cm}^{-2}$.

Blue photons, after being emitted by the TPB, on average reflect several times from the TPB coated Gore-tex before escaping out through one of the two tube ends. Some of the light is absorbed by the TPB coating, which is not a perfect reflector. The reflectivity and specularity of TPB-coated Gore-tex has not been measured, and thus it is difficult to estimate the fraction of blue light emitted by the TPB that finally escapes the tube.

In order for the TPB luminescence to be collected by light guides and transported to room temperature, it must pass through an optically transparent, neutron-absorbing disc of boron oxide located directly after the trapping region. This beam dump allows most of the scintillation light through.

Following the beam dump is a UVT acrylic light guide of diameter 8.7 cm and length 40.7 cm that transports light from the Gore-tex tube to the end of the experimental cell.²⁰ The beam dump is attached to the light guide using FEP teflon tape.²¹ The light guide is wrapped in a 175 μm thick layer of Tyvek, a paper that protects the light guide from scratches and increases its light transport efficiency.²² The light guide slides inside the experimental cell, and is surrounded by tubes of graphite and boron nitride, which are required to shield luminescence light and absorb scattered neutrons, respectively.

Scintillation light that passes out of the light guide and through the 200 mK acrylic window must pass through acrylic and quartz windows at 4 K. After the 4 K window is a second light guide, this one of larger diameter (11.4 cm) than the first. This acrylic guide transports scintillation light from 77 to 300 K, and is 35 cm long. The 77 K end of the light guide is heat sunk to the 77 K flange using strips of aluminum foil. A vacuum seal is formed around the second light guide using a Viton o-ring seal. A metal clamp fastens tightly around the light guide and prevents it from moving.

At room temperature, the light guide is coupled to a photomultiplier tube by optical grease.²³ The detector was calibrated by placing an ^{113}Sn source

²⁰ UVT acrylic material purchased from Boedeker Plastics, Shiner, TX (www.boedeker.com). All light guides polished by Universal Plastics, Akron, OH, USA.

²¹ McMaster-Carr, New Brunswick, NJ, USA.

²² Tyvek is a paper made from filaments of polyethylene, made by DuPont.

²³ RX-6 optical grease purchased from Rexon, Inc., Beachwood, OH (www.rexon.com).

¹⁹ Unembossed GoreTex GR gasket material, Gore Corporation (www.gorefabrics.com).

in the center of the liquid helium-filled trapping region and measuring the pulse-height spectrum of the helium scintillations. A Burle 8854 photomultiplier was placed at the end of the light guide. An average of 34.5 photoelectrons was detected from the ^{113}Sn source. The value of 34.5 photoelectrons was derived by dividing the channel position of the 364 keV beta peak by the channel position of the single photoelectron peak. The calibration peak is shown in Fig. 8.

5. Discussions

Table 3 shows the efficiencies of the three detector technologies for turning helium scintillation events into detector photoelectrons, as well as the inferred visible photon yield of the cryogenic cell. Each detector technology employs a cryogenic cell in which helium scintillations are converted to visible

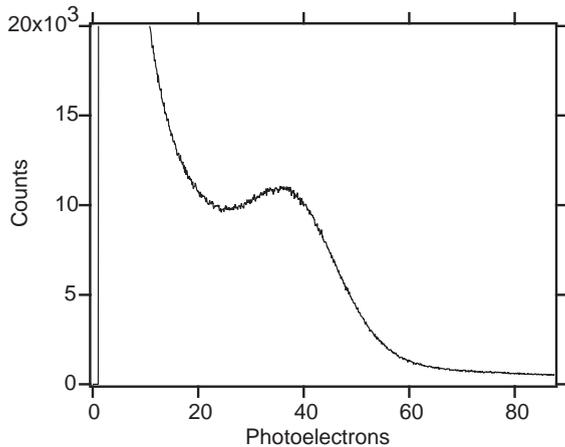


Fig. 8. The calibration pulse height spectrum for an expanded PTFE cell, taken with an ^{113}Sn source.

Table 3

Summary of detector efficiencies. The detector designs include a fiber-based cell of length 150 mm and diameter 38 mm, acrylic tube-based cells (with center either blocked or open) of length 400 mm and diameter 38 mm, and a Gore-tex tube-based cell of length 350 mm and diameter 84 mm

| Detector type | Optics (%) | QE (%) | P.E./MeV | Photons/MeV |
|-------------------------------|------------|--------|------------|-------------|
| Wavelength shifting fibers | 40 ± 10 | 19 ± 1 | 17 ± 2.6 | 224 ± 60 |
| Acrylic tube (center blocked) | 31 ± 3 | 20 ± 2 | 23.4 ± 1.4 | 377 ± 57 |
| Acrylic tube (center open) | 31 ± 3 | 20 ± 2 | 50.8 ± 1.4 | 819 ± 116 |
| TPB evaporated on Gore-tex | 49 ± 5 | 17 ± 2 | 96 ± 8.0 | 1150 ± 203 |

light and then transported through a first set of optics components at low temperature to a second set of optics components at a higher temperature. The “Optics” column specifies the measured efficiency with which photons pass through the second set of optics to a detector at room temperature. The “QE” column specifies the quantum efficiency for the photomultiplier used in that measurement, as published by the photomultiplier vendor. The “P.E./MeV” column specifies the measured efficiency for turning a single beta excitation in the liquid helium into prompt photoelectrons in the detector. The “Photons/MeV” column specifies the estimated number of photons that escape the cryogenic cell, calculated from the data of the previous three columns. The visible photon yields of the cryogenic cells are much less than the initial 22,000 EUV photons/MeV because many photons are lost before they can be extracted from the cryogenic cell. For example, for the three “tube-based” cells, half of the visible light leaves the end of the tube opposite the window at low temperature. Also, much light is presumably lost through scattering and absorption before it reaches the window.

By performing tests with both alpha and beta sources, measurement of a “quenching factor” could be performed. Comparing acrylic tube cell tests 13 and 14, which were performed using the very same detector, one finds that

$$f = \left[\frac{62 \text{ photoelectrons}}{8.5 \text{ photoelectrons}} \right] \left[\frac{0.364 \text{ MeV}}{5.3 \text{ MeV}} \right] = 0.50 \pm 0.10$$

where f is the ratio of detected photons from alpha excitation to detected photons from beta excitation per unit energy deposition. The

uncertainty in the derivation of f is a function of how much the properties of the cell changed between tests 13 and 14, and how the two different radiation sources might have shielded the TPB wavelength shifter differently from the EUV scintillation light. Based on the repeatability of past detector tests and geometric calculations of the self-shielding fraction, we estimate the uncertainty from these two sources to be 20%.

6. Conclusion

In conclusion, we have demonstrated that liquid helium, combined with wavelength shifting light collection can be used as an effective detector for ionizing radiation. Several sorts of detectors have been described, each with relative advantages and disadvantages. Uses of liquid helium as a detector abound, especially in fundamental physics experiments. This work was supported by NSF grant PHY-0099400.

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