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Alpha and beta particle induced scintillations in liquid and solid neon

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Abstract

Scintillations induced by alpha and beta particles in liquid and solid neon are studied and their light yield measured. Charged particle scintillation in neon is primarily in the extreme ultraviolet (EUV). We detect this EUV light by converting it to blue using a wavelength shifting fluor and detecting the blue light with a photomultiplier tube. It is observed that liquid neon is a somewhat less-efficient scintillator than liquid helium for both alpha and beta radiation while the light yield in solid neon is greater than in liquid helium. Based on our measurements of the relative light yields of liquid and solid neon to liquid helium whose absolute light yield has previously been determined, we find that an alpha source in liquid neon produces up to 5900 photons per MeV while a beta source produces up to 7400 photons per MeV. In solid neon, we find that an alpha particle produces up to 9300 photons per MeV while a beta particle produces up to 17,000 photons per MeV. We observe a significant dependence of the scintillation efficiency on temperature. The decay of the fluorescence from the scintillation is observed over time. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Scintillations in the liquefied noble gases due to ionizing radiation have been studied both for their theoretical and practical significance. Cryogenic liquid noble gas scintillators such as argon, krypton, and xenon have been investigated for their potential use as calorimeters in high-energy

physics facilities. Their fast response time and high photon yield make them attractive candidates for this use [1]. The study of scintillations in liquid helium has a long history. The investigation of excitations in superfluid helium produced by radioactive sources and intense electron beams has provided a wealth of information about the excited helium dimer [2–4]. Observation of scintillations in liquid helium has been used to detect the beta decay from magnetically trapped ultracold neutrons as a means toward determining the neutron lifetime [5]. In addition, a solar neutrino

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detector has been proposed (HERON) that would observe scintillations in liquid helium along with phonons and rotons produced by neutrino-electron scattering events [6].

Liquid neon has not been investigated as thoroughly as the other condensed rare gases. This is due, in part, to the difficult combination of cryogenics and light detection techniques involved compared with the other noble gases. Recently, a neutrino detector (CLEAN) has been proposed that employs either liquid helium or liquid neon as a scintillator to detect neutrino-electron scattering events and thus measure in real time the low-energy solar neutrino flux [7]. In this detector, the neon or helium acts both as gamma-ray shielding and as a scintillator. Scintillation photons are wavelength shifted to visible blue light for detection with photomultiplier tubes. Liquid helium and liquid neon are attractive choices for such a detector because their low boiling points and weak interactions with surfaces allow them to be purified very efficiently using distillation and cold traps. In addition, unlike other scintillators, there are no long-lived radioactive isotopes of helium or neon that could create a background in the detector. Because the electron density in liquid neon is a factor of eight higher than in liquid helium, neon is a much more effective gamma-ray shield. Also, because of the higher electron density, a desired neutrino-electron scattering event rate would require a smaller active volume with neon than with helium. For these reasons, a neon-based version of CLEAN could be made significantly smaller than a similar helium-based detector [7]. While the spectrum of light from excitations in liquid and solid neon has previously been measured [8], to our knowledge the light yield has not. Knowledge of the light yield from neon is necessary to determine how it can be used as a scintillator. This paper describes measurements of the light yield of liquid and solid neon from alpha and beta particle induced scintillations.

Scintillations in liquid rare gases are a result of excitations produced in the liquid. When high-energy electrons or alpha particles, for example, are stopped in the liquid, numerous ions and excited atoms are produced. These may combine

with nearby ground state atoms to form excimer molecules (the molecular ions that are formed quickly recombine with their electron to form neutral molecules) [9]. The excimer molecules decay to the dissociative two atom ground state through the emission of a photon. For liquid helium, the spectrum of the emitted light has a peak centered at 80 nm (with FWHM = 15 nm) [10,11]. In liquid neon, the spectrum of the emitted light contains a peak centered around 77.4 nm (with FWHM = 3 nm) [8]. In both cases, the energy of the emitted photon is below that required to produce the first excited state of the atom, and thus liquid helium and liquid neon are transparent to their own radiation, making them possible candidates for use in a large detector. In solid neon, there is an additional sharp emission peak at 74.3 nm. The integrated intensity of this peak is approximately twice that of the 77.4 nm peak in the solid [8]. The wavelength of this peak is very close to the lowest frequency transition in the atomic neon spectrum and thus it has been suggested that this feature is due to the decay of excited neon atoms which do not react to form excimer molecules [12].

The excimer molecules (as well as the excited atoms) produced by ionizing radiation may be in either singlet or triplet spin states. Transitions from the excited singlet dimer state to the dissociative two atom singlet ground state occur very quickly (on the order of a few nanoseconds) creating a “prompt” component to the fluorescence [13]. Transitions from the triplet molecular state to the two-atom singlet ground state are forbidden. The lifetime of the triplet molecules is, therefore, long compared to that of the singlets, and the decay of triplet molecules creates a long-lived component to the fluorescence. For example, the lifetime of the triplet state in liquid xenon is tens of nanoseconds, in liquid krypton hundreds of nanoseconds, and in liquid argon about a microsecond [14]. In liquid helium, the triplet molecular state has been observed to have a very long lifetime of approximately 13 s [15]. Measurements on the spectrum of liquid neon reveal a triplet molecular state with a lifetime of several microseconds [12]. We have made measurements on the light yield from both liquid and solid neon due to ionizing

radiation from alpha and beta sources and compared it to liquid helium whose absolute light yield has previously been measured [16]. It is found that the light yield depends on the neon temperature. We have also observed the decay of the fluorescence over time and determined a time constant for decay that agrees qualitatively with the previously measured lifetime of the triplet molecular state.

2. Experimental apparatus

A diagram of the experimental apparatus used in the scintillation measurements is shown in Fig. 1. The experimental cell containing the neon or helium and the radioactive source consists of an OFE copper (alloy 101) tube connected via an indium seal to a thin stainless-steel tube hung vertically from a standard metal cryostat. The cell is 22.9 cm long, 6.4 cm in outer diameter, and has a 1.0 cm thick wall. Neon is liquid over only a small temperature window (24.5–27.1 K) so it is important that we be able to maintain a uniform temperature across the cell. Because OFE copper

has high thermal conductivity, it was chosen to satisfy this demand. A copper cap closes the bottom of the cell. Surrounding the cell is a large stainless-steel (alloy 304) cylinder with an inner diameter of 12.4 cm with a 0.2 cm thick wall. A stainless steel disc is welded to the bottom of this cylinder. The cylinder and disc serve to thermally isolate the experimental cell when the cryostat is filled with liquid helium. The temperature of the cell is controllable over a wide temperature range by placing a small amount (typically ~ 1 kPa) of helium exchange gas into the space between the experimental cell and the surrounding stainless-steel cylinder. The exchange gas keeps the cell in weak thermal contact with the liquid helium bath to provide cooling. Nichrome heating wire (~ 30 m) is wrapped around the experimental cell. A similar length of nichrome is also wrapped around the stainless-steel tube. By running a variable current through the heating wire, we are effectively able to maintain the experimental cell at constant temperature (to better than 0.1 K). This temperature is monitored using four silicon diode thermometers [17]. One thermometer is placed on the stainless-steel tube directly above the copper experimental cell; the other three are placed at the bottom, middle, and top of the cell. A radioactive source is placed at the bottom of the cell a variable distance from a glass window (3.8 cm diameter, 0.4 cm thick) on whose surface is thermally evaporated a thin layer of tetraphenyl butadiene (TPB). TPB is a wavelength shifting fluor that efficiently converts EUV light to blue light [18]. The prompt (< 20 ns) photon-to-photon conversion efficiency from EUV to the blue has been measured to be approximately 100% while the total conversion efficiency is approximately 135% [18,19]. Because the EUV light is at similar wavelengths for helium and neon, the conversion efficiency should be virtually identical (thus allowing us to accurately compare the light yield of neon to helium). The glass window is pressed against an acrylic PMMA light pipe (3.8 cm diameter) that is centered in the stainless-steel tube connected to the copper cell. During the experiment, scintillations from the helium or neon surrounding the source produce EUV light. Nearly half of this light (depending on the solid angle subtended by the

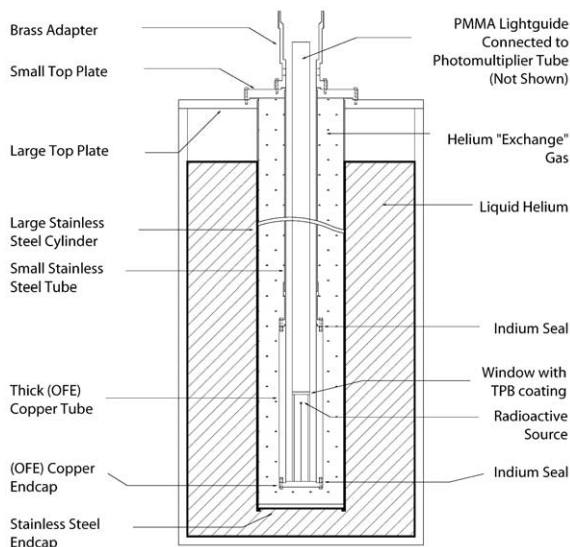


Fig. 1. Apparatus used to measure light yield from scintillations in helium and neon.

window as determined by the position of the radioactive source) strikes the TPB and is converted to blue. This blue light travels up the light pipe to a photomultiplier tube at room temperature¹ (not shown) connected to a brass adapter at the top of the cryostat. To maximize light collection, the light pipe is wrapped with highly reflective Tyvek paper. We measured the efficiency of the light pipe to be approximately 10% (with most of the loss presumably due to scattering from surface imperfections). The output of the PMT is sent to a charge preamp and shaping amplifier and then to a multichannel analyzer (MCA) board inside of a PC for data collection.

3. Measurements with an alpha source

We first made measurements using a 1 kBq ²¹⁰Po source. ²¹⁰Po emits alpha particles with an energy of 5.305 MeV. This source is placed approximately 3 mm from the TPB-coated glass window. Before running the experiment, the gas handling system and experimental cell are pumped out for a period of approximately three days using a turbomolecular pump. This is done to achieve maximum cleanliness. High-purity (99.999%) helium gas is condensed into the experimental cell after passing through a thin (0.5 cm ID) copper tube (not shown). Inside of this copper tube is a fine copper mesh² to increase the surface area in contact with the gas. This tube is wrapped around the experimental cell and serves as an internal cold trap to further purify the gas entering the cell. In order to condense the helium gas into the cell, it is necessary to lower the temperature of the helium bath in the cryostat below the normal boiling point. This is done by pumping on the helium bath to cool it to ~2 K. The total volume of liquid accumulated in the cell during the course of the experiment is approximately 200 cm³ with the condensing taking approximately 8 h. Initially, as the cell is filling with liquid, we observe scintilla-

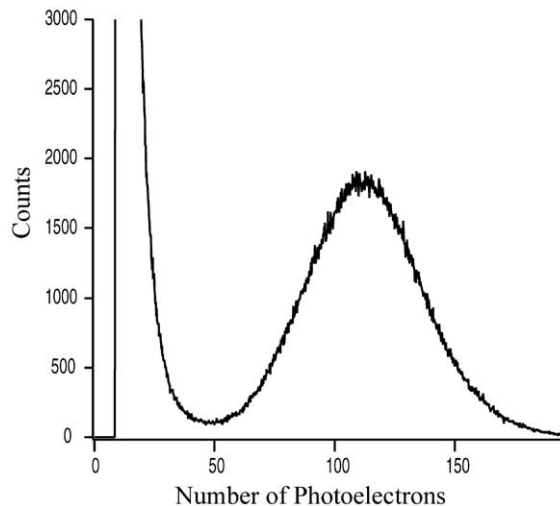


Fig. 2. Photoelectron peak from helium gas at 4.2 K due to scintillations induced by a 1 kBq ²¹⁰Po alpha source (5.305 MeV). Note, the pressure of the gas is approximately 100 kPa (atmospheric pressure).

tions from the helium gas. Data from a typical 1000 s run is shown in Fig. 2. The alpha particles create excitations in the gas that produce light collected by the PMT as described above. The peak in the MCA data is due to charge accumulated by the preamp from multiple photoelectrons produced in the PMT during the shaping time of the amplifier (6 μ s). The position of this peak is thus indicative of the light yield during this time. When the cell is filled with liquid helium, displacing the helium gas, we observe a shift in the position of the photoelectron peak. The position of the peak in liquid helium is used for comparison with that in liquid and solid neon.

After the measurements with helium, we warm the cell to remove all of the condensed liquid and pump out the system for another 3 days before repeating the experiment with neon. For the measurements with neon, we again pass high-purity gas (99.999%) through the copper mesh cold trap into the cell. Condensation takes approximately 8 h, as with the helium, and again, we initially observe a peak in the photoelectron spectrum due to scintillations from neon gas. After the cell is filled with liquid, we observe a peak

¹Burle model 8850 with a quantum efficiency of 0.20 at 420 nm.

²The mesh used has 40 \times 40 lines per cm². The total mesh area is 900 cm².

shifted to considerably lower photoelectron number. The position of this peak is observed to depend on the temperature of the liquid which we gradually lower from 27 to 24.5 K. The temperature is lowered in half-degree intervals taking approximately half an hour to go down each half degree. The temperature is then held constant for another half an hour during which it is verified that the photoelectron peak position is constant (indicating that the temperature is no longer changing). After observing scintillations in the liquid, we lower the temperature of the cell to gradually allow the neon to solidify. This is done over the course of approximately 2 h while keeping the cell temperature about 24 K. Measurements of the photoelectron peak position in 1° intervals are made down to 15 K. Initially, there is a sharp decline in the light yield from the solid at temperatures slightly below the freezing point. Below 18 K, however, the light yield increases dramatically and eventually becomes greater than the liquid (and comparable to that of the gas). The heaters are then turned off completely, and the neon cooled for several more hours (overnight) to a final temperature of 5 K. The neon is then melted and reheated to 27 K. The position of the photoelectron peak is consistent to within 5% compared with the initial cooling cycle. Fig. 3 shows the light yield from neon compared to liquid helium as a function of the neon temperature. The accuracy of the light yield measurement was limited mainly by our ability to resolve the position of the single photoelectron peak from the photomultiplier with the MCA. Uncertainty in the solid angle subtended by the TPB-coated window due to differential thermal contraction also contributed to the error bars on the light yield. The accuracy of our temperature measurements was set by the silicon diode thermometers used in the experiment [17].

4. Measurements with a beta source

After performing the measurements with the alpha source, we repeat the experiment with a beta source. The source is 0.5 kBq of ^{113}Sn (which emits electrons through internal conversion with an

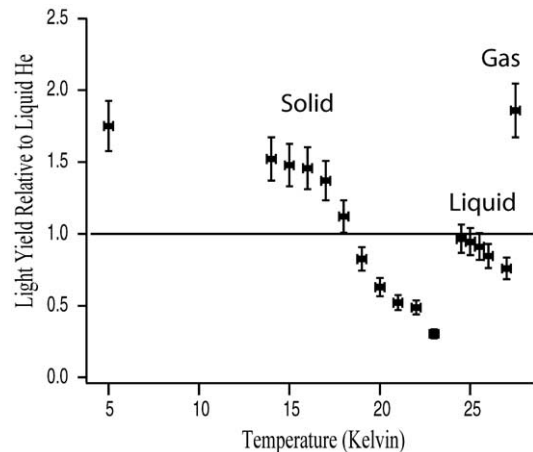


Fig. 3. Light yield from alpha particle induced scintillations in solid, liquid, and gaseous neon relative to liquid helium at 4.2 K as a function of temperature. Note, the pressure of neon gas for the gaseous data point is approximately 100 kPa (atmospheric pressure). The alpha source in liquid helium produces ~ 6300 photons/MeV [16].

energy of 364 keV). This energy is chosen to mimic the energy of electrons scattered by low energy solar neutrinos in the proposed neutrino detector mentioned above [7]. We again first investigate scintillations in helium. The source is placed 1 cm from the TPB coated window. We place the beta source further away than in the experiments with the alpha source because the electron in liquid helium deposits its energy over a distance up to 8 mm [20] (whereas the alpha particle deposits its energy over a length less than 0.1 mm). Because the path length of the electron in helium gas is several tens of centimeters, we are not able to observe a photoelectron peak from the gas as the cell fills (as we are with the alpha source). When the cell is filled, we observe a photoelectron peak due to scintillations in the liquid. As expected, this peak is at a much lower photoelectron number than with the higher energy alpha source. Again, the position of the helium peak is used for comparison with the neon.

After the helium measurement is performed, we reposition the beta source closer to the window (about 3 mm away) before measuring the scintillation efficiency of neon. The greater solid angle subtended by the window when the source is closer

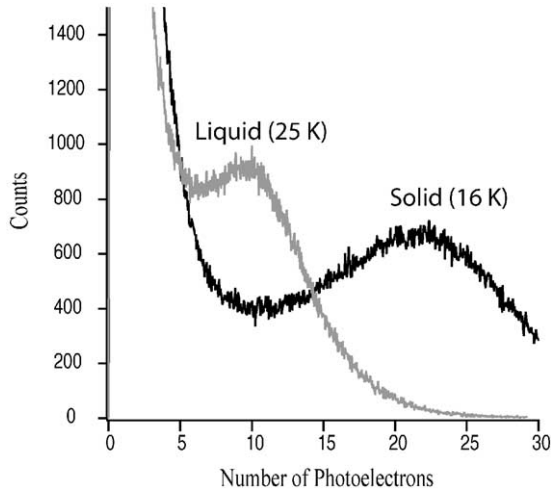


Fig. 4. Photoelectron peak from liquid neon (left) at 25 K and solid neon (right) at 16 K due to scintillations induced by a 0.5 kBq ^{113}Sn beta source (364 keV).

creates a larger signal. This is necessary because we find that the scintillations from liquid neon are somewhat weaker than from helium, and our system is not sensitive enough to resolve a peak in the photoelectron spectrum when the source is 1 cm away from the window as in the experiments with helium. We repeat our measurements at different temperatures in both the liquid and the solid and observe that, as with the alpha source, the light yield is temperature dependent (although there does not seem to be as much structure to this temperature dependence as with the alpha). As with the alpha source, the peak position was consistent to within 5% upon thermal cycling. In Fig. 4, we show the photoelectron peaks from the liquid at 25 K and the solid at 16 K. Again, it is found that the light yield is higher at lower temperatures in both the liquid and the solid. In Fig. 5, we show the light yield from the beta source in neon compared to liquid helium as a function of the temperature. Note, between 24 and 22 K the light yield in the solid is too low to create a resolvable photoelectron peak. We also observe the time decay of the fluorescence from the scintillation. This is done by connecting the output of the photomultiplier tube to a multichannel scaler (MCS). The MCS trigger threshold is set so

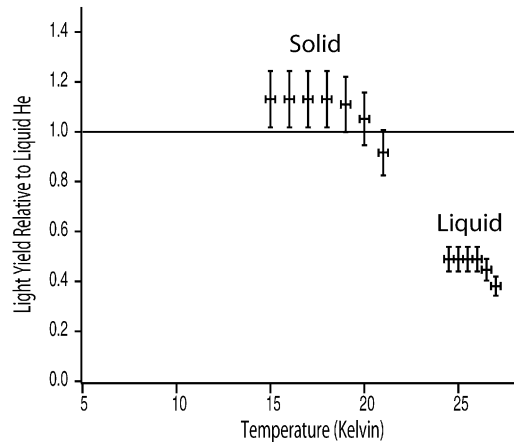


Fig. 5. Light yield from beta particle induced scintillations in solid and liquid neon relative to liquid helium at 4.2 K as a function of temperature. The beta source in liquid helium produces $\sim 15,000$ photons/MeV [16]. Note, between 24 and 22 K, the light yield in the solid was too low to create a resolvable photoelectron peak.

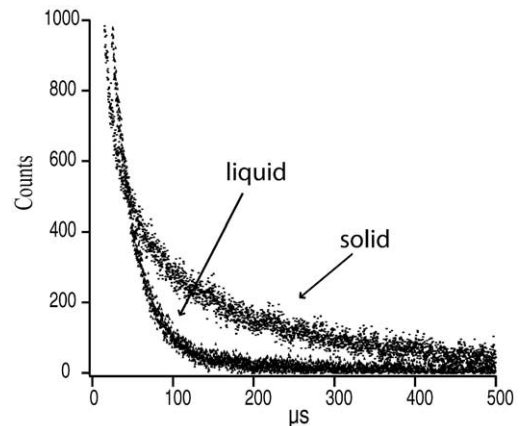


Fig. 6. Decay of fluorescence observed from 60,000 beta decays in liquid (25 K) and solid (16 K) neon.

that it triggers on the large (many photoelectron) signal from the prompt singlet decay that marks each beta event. Single photoelectron counts from the longer lived triplet state are then binned in time for a period up to 2.5 ms after. Data from 60,000 beta decay events in both the liquid and the solid is shown in Fig. 6. At early times, the decay is exponential with a lifetime of $3.9 \pm 0.5 \mu\text{s}$ in the liquid and $3.3 \pm 0.3 \mu\text{s}$ in the solid. These lifetimes

agree roughly with a previously measured lifetime for the excited triplet neon dimer in liquid and solid (2.9 and 3.9 μs , respectively) [12]. In the solid, we also see that there is a significant long time component to the decay with a lifetime of several hundred microseconds (although this decay does not seem to be purely exponential). Previous spectroscopy of excitations in solid neon detected lines due to transitions from excited states of the neon atoms. The intensities of these lines were found to decay with a lifetime of 560 μs in the solid while in the liquid, these lines showed non-exponential decay and disappeared within several microseconds.

5. Discussion and conclusions

We have made measurements of the scintillation properties of helium and neon using both alpha and beta sources. To calculate the absolute scintillation efficiency of neon (photons per MeV) we use the value from [16] for the absolute light yield from liquid helium scintillations. Here, it is found that an alpha particle in liquid helium produces ~ 6300 photons per MeV while a beta particle in liquid helium produces $\sim 15,000$ photons per MeV. These values compare well with what we calculate in our apparatus based on our knowledge of the conversion efficiency of TPB, the measured transmission of our light guide, and the solid angle subtended by the TPB-coated window. Using these values and the efficiencies relative to liquid helium that we measure in our experiment, we can calculate the absolute scintillation efficiency of neon. At 25 K, we find that an alpha source in liquid neon produces ~ 5900 photons per MeV while a beta source produces ~ 7400 photons per MeV. In solid neon at 15 K, an alpha source produces ~ 9300 photons per MeV while a beta source produces $\sim 17,000$ photons per MeV.

We find a large difference in scintillation efficiencies in liquid neon compared to solid and gaseous neon. Also, it is interesting that liquid neon is a somewhat weaker scintillator than liquid helium. Considering that it takes less energy to ionize the heavier noble gases, one might naively expect the heavier condensed noble gases to be

more efficient scintillators. This is the case with Ar, and Xe which have been found to produce more than twice as much light per MeV of ionizing beta radiation as liquid helium [9]. In neon, however, we observe that scintillations in the liquid from the beta source are only half as strong as in helium. As mentioned above, there is evidence that a significant fraction of the light yield in solid neon is due to the decay of excited atoms (rather than excimer molecules). It has been suggested that the formation of dimer molecules may be somewhat inhibited by some feature of the neon–neon atomic potential [12]. Another possibility is that due to the long vibrational relaxation time of excited neon molecules, these molecules decay non-radiatively before they have a chance to emit a photon [21]. We might further speculate that the greater density of the liquid compared to the gas favors non-radiative quenching of the excited state. Perhaps the lower temperature and more regular structure of the solid make various quenching reactions less favorable compared to the liquid and thus account for the greater light yield observed in the solid. A more detailed study would be required to confirm or reject any of these speculations.

Although the absolute efficiency of liquid neon is not as high as liquid helium, there is still a large number of photons produced per MeV of electron energy in liquid neon. This means that liquid neon shows promise for use as a scintillator in the CLEAN neutrino detector mentioned earlier [7]. Solid neon with its higher light yield may also be considered for use. As previously noted, the smaller detector size makes neon preferable to helium for use in this detector. Future work will investigate the absorption and scattering lengths of light in the neon to determine what issues need to be addressed in employing a large volume of neon in a detector.

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