Liquid Helium and Liquid Neon - Sensitive, Low Background Scintillation Media For The Detection Of Low Energy Neutrinos

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The use of liquid helium and neon as scintillators for neutrino detection is investigated. Several unique properties of these cryogens make them promising candidates for real-time solar neutrino spectroscopy: large ultraviolet scintillation yields from ionizing radiation, transparency to their own scintillation light, and low levels of radioactive impurities. When neutrinos scatter from electrons in liquid helium or neon, ultraviolet light is emitted. The ultraviolet scintillation light can be efficiently converted to the visible with wavelength shifting films. In this way the neutrino-electron scattering events can be detected by photomultiplier tubes at room temperature. We conclude that the solar neutrino flux from the $\mathrm{p}+\mathrm{p} \rightarrow \mathrm{e}^{+}+\mathrm{d}+\nu_{\mathrm{e}}$ reaction could be characterized and monitored versus time using a 10 ton mass of liquid helium or neon as a scintillation target.

I. INTRODUCTION

The observed deficit in solar neutrino flux at the Earth's surface is now well established; the neutrino detection rates measured in the Homestake [1], SAGE/GALLEX [2,3], and Kamiokande/Super-Kamiokande [4,5] experiments are each significantly less than predicted by the Standard Solar Model (SSM), but taken together are also logically incompatible with any current solar model. Resolution of this problem remains a tantalizing goal. It is plausible that the correct model explaining the observed neutrino detection rates involves flavor oscillation of massive neutrinos. The several scenarios for flavor conversion will most likely be discriminated through measurement of the solar neutrino flux, including temporal variations, at all energies and for all neutrino species. Distortions of the predicted solar neutrino energy spectra could indicate neutrino flavor oscillations, as could daily or seasonal variation of the detected neutrino flux. With these motivations, it is no surprise that real-time detection of neutrinos is rapidly becoming more sophisticated, with many new detectors either in development or recently implemented.

One of the most daunting experimental challenges in neutrino observation is the real-time measurement of the full flux of low energy neutrinos from the solar reaction $\mathrm{p}+\mathrm{p} \rightarrow \mathrm{e}^{+}+\mathrm{d}+\nu_{\mathrm{e}}$. This "pp" reaction is the most intense source of solar neutrinos, and initiates the chain of fusion reactions in the sun. The emitted pp neutrinos range in energy from 0 to 420 keV and have a precisely predicted flux of $5.94 \times 10^{10}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$ at the Earth [6]. Despite this high flux, the pp neutrinos have proven difficult to characterize in real time; low energy neutrinos yield low energy scattering events, and these are difficult to detect and discriminate from radioactive backgrounds. In order to characterize and monitor the pp neutrino flux, a detector is needed that has a high signal yield for neutrino-induced events, a high rate of such events, and a low background rate from intrinsic radioactivity. We are familiar with several approaches to the real-time detection of pp neutrinos: bolometric detection of helium atoms liberated by rotons from a liquid helium bath (HERON) [7], measurement of electron tracks generated in a pressurized He (HELLAZ) or CF_4 (SUPER-MuNu) gas-filled time projection chamber [8,9], and the use of a low energy neutrino absorbing nuclide that follows absorption with a delayed gamma emission(LENS) [10]. Here we propose a detector that uses liquid helium or neon as a scintillation target. This scheme offers the advantages of high scintillation yield, high neutrino detection rate, low intrinsic radioactivity, and simplicity.

II. EXPERIMENTAL OVERVIEW

Detection of neutrinos in our proposed experiment is based on neutrino-electron elastic scattering, $\nu_{\mathrm{x}}+\mathrm{e}^{-} \rightarrow \nu_{\mathrm{x}}+\mathrm{e}^{-}$, where x = (e, μ, τ). For pp neutrinos, the scattered electron can range in energy from 0 to 260 keV. The scattering cross-section for electron neutrinos is about $1.2 \times 10^{-45}\,\mathrm{cm}^2$ (about 4 times larger than for μ or τ neutrinos) [11]. This small cross-section leads to the need for a large detector. With 10 tons of active scintillator (3×10^{30} electrons), a total solar neutrino scattering rate of roughly 27 per day will occur with about 18 of these from p-p neutrinos (according to the SSM) [6]. This mass of liquid helium (neon) fills a 5.1 (2.6) meter diameter sphere.

We have diagrammed our proposed experiment in Figure 1. The design characteristics are similar to those used currently in the Borexino experiment [12], with crucial differences arising from the choice of scintillator and associated cryogenics. A spherical geometry is chosen for conceptual simplicity (a cylindrical volume, for example, could be used instead).

In the center of the experiment is an active region (10 tons) of liquid helium or neon. Surrounding the active region is a thin shell of transparent material. On the inner surface of this shell is evaporated a layer of tetraphenyl butadiene (TPB), a wavelength shifting fluor. Around the active (inner) region is a shielding (outer) region filled with either liquid neon or liquid helium. If neon is used as a shielding medium, it should be about 2 meters thick, while if the shielding region is liquid helium, this region should be 5 meters thick. These liquids are held in a large transparent tank (or 2 separate tanks, see below).

Surrounding the central tank(s), separated by vacuum, is another transparent tank filled with pure liquid nitrogen. Outside the cryogens, at room temperature, is a large array of low-activity photomultiplier tubes, all facing the interior and fitted with light concentrators. Around the entire assembly is a stainless-steel tank, filled with water.

Detection of solar neutrinos is via scintillation originating from neutrino-electron scattering that occurs in the active region. These events cause intense emission of extreme ultraviolet light (EUV), centered at a wavelength of approximately 80 nm [13,14]. This light is absorbed by the TPB waveshifter, causing fluorescence in the blue (~ 430 nm). The blue light travels through the shield region, through the transparent acrylic walls and liquid nitrogen, and is detected by the photomultipliers at room temperature. Detection electronics are triggered by multiple photomultiplier coincidence, indicating a potential neutrino scattering event.

There are several aspects of this geometry that lead to important advantages. EUV light that originates in the active region will hit the TPB film and be converted into blue light, but EUV light that originates outside the active region will simply be absorbed and will not contribute to the background. The liquid nitrogen acts both as black-body radiation shielding and gamma ray shielding, while the tank of deionized water outside the photomultipliers acts as further shielding.

The entire experiment will be located deep underground to reduce cosmic ray events. Muon events will be actively vetoed. Vetoing could be done using a set of photomultipliers to detect Cerenkov light in the water tank.

III. SIGNAL

A relatively clear model of scintillations in liquid helium and neon can be elucidated from the numerous experimental characterizations of charged-particle-induced scintillation in condensed noble gases [13–19]. When an energetic charged particle passes through the liquid, numerous ion-electron pairs and excited atoms are created. The ions immediately attract surrounding ground state atoms and form ion clusters. When the ion clusters recombine with electrons, excited diatomic molecules are created. Similarly, the excited atoms react with surrounding ground state atoms, also forming excited diatomic molecules. 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 state (two separated atoms) and the first atomic excited state for any given noble gas. The scintillation target is thus transparent to its own scintillation light, and a detector based on a condensed noble gas can be built to essentially arbitrary size without signal loss from reabsorption.

Liquid helium scintillations have been more quantitatively studied than neon scintillations. It has been found that conversion of electron kinetic energy into prompt scintillation light is highly efficient; about 24% of the energy of an energetic electron is converted into prompt EUV light [20], corresponding to 15,000 photons per MeV of electron energy. Recent work towards detection of ultracold neutrons trapped in liquid helium [21], has resulted in the characterization of efficient wavelength shifting fluors that convert EUV light into blue visible light [22]. This blue light is well matched to the peak sensitivity of available photomultiplier tubes. TPB is the fluor of choice, having a (prompt, < 20 ns) photon-to-photon conversion efficiency from the EUV to the blue of at least 70% (and a total conversion efficiency of 135%) [22,23]. The prompt scintillation component from the combined liquid helium-waveshifter system has been measured to have a 20 ns width, allowing the use of coincidence techniques to reduce background [19]. (In liquid argon and liquid xenon, the prompt ultraviolet photon yield has been measured to be even larger; Doke *et. al.* have measured yields of 40,000 and 42,000 photons/MeV respectively [24]. This indicates that it is likely that neon has a comparable yield.) Given a scintillation yield of 15,000 photons per MeV, a waveshifting efficiency of 70%, a photomultiplier covering fraction of 70%, and a bialkali photocathode quantum efficiency of 20%, a total photoelectron yield of about 1500 per MeV could be achieved from the prompt component. With this expected photoelectron yield, the energy of a 100 keV neutrino-electron scattering event could be measured with an average of 150 photoelectrons, attaining 16% energy resolution.

Liquid neon can be expected to be a similarly fast and efficient scintillation medium, with properties similar to those found in liquid helium. Packard et. al. have found that the electron-excited emission spectrum of liquid neon peaks at 77 nm [14]. Liquid neon should also have an intense afterpulsing component due to the extreme ultraviolet radiation of triplet molecules. In liquid helium, the lifetime of this slow component has been measured to be 13 seconds [25], close to the radiative lifetime of the ground state triplet molecule [26]. But the theoretically predicted lifetime of ground state triplet neon molecules [27] is only 11.9 μs. In liquid neon, the ground triplet molecular lifetime has been measured to be 2.9 μs [28]. Intense afterpulsing following neutrino scattering events could be used to positively identify events within the active neon, and could also be added into the prompt signal to improve pulse height resolution. However, our detection scheme does not necessarily require the use of this afterpulsing signal.

IV. CRYOGENICS

We describe here the cryogenic and structural requirements for a low energy neutrino detector whose active region is a 10-ton reservoir of liquid helium or neon. We consider three cases. The backgrounds due to construction materials are discussed in section V.

Case A: Liquid neon active region, liquid neon shielding region. Here the transparent tank holding the shielding and active regions would be constructed of a copper grid and a transparent, low radioactivity material, such as quartz or acrylic. Copper is used to give the tank walls high thermal conductivity and structural rigidity, while the quartz or acrylic allows scintillation light through to the photomultipliers. Given a total surface area of $\pi(6.6\,\mathrm{m})^2 = 137\,\mathrm{m}^2$ and a conservatively estimated emissivity [29] of 1, a total of 270 W is absorbed by the tank walls and routed through a copper heat link to a closed-cycle helium gas refrigerator outside the shielding. If the copper grid covers 20% of the tank surface, has a bulk thermal conductivity of 15 W cm^{-1} K^{-1}, and this copper is 10 cm thick, then the power absorbed from 77 K blackbody radiation results in a temperature difference across the tank of no more than 2 degrees. The use of copper to maintain a low thermal gradient is necessary because of the narrow temperature window at which neon is liquid ($24.5 - 27.1$ K) and the poor thermal conductivity ($\sim 10^{-3}$ W cm^{-1} K^{-1}) of liquid neon. The cryogenic constraints on this tank may be relaxed if convection in the liquid neon is found to play an appreciable role in the flow of heat through its volume. The active and shielding regions are separated by a thin ($\sim$ 0.1 mm) shell of transparent plastic or quartz. This shell simply floats in the neon and is held in place by nylon strings connecting the shell to the copper tank. The shell may have small holes in it to allow liquid neon to flow freely between the active and shielding regions.

Case B: Liquid helium active region, liquid neon shielding region. As in case A, the active and shielding regions are held in a copper grid composite tank. The tank must however be of larger diameter (9.1 m instead of 6.6 m) to accomodate the larger active region. Also, the active and shielding regions must be separated by a vacuum space because of the different temperatures of the liquid neon and liquid helium. The separation of the active and shielding regions must be accomplished with as little material as possible so as to minimize radioactive backgrounds. Appropriate separation may be possible using a 1 mm thick Kevlar-acrylic composite shell, with shielding and active regions held apart using small acrylic pegs.

Case C: Liquid helium active region, liquid helium shielding region. Liquid helium is not an effective enough gamma ray absorber to protect the active region from copper activity. Therefore the tank must be made from a transparent, low radioactivity material such as acrylic. The heat load from 77 K is large (1430 W), but by cooling the helium through its superfluid transition temperature (2.2 K) to achieve high thermal conductivity, the temperature of the helium may be made constant throughout its volume. The high thermal load on the helium may be handled with a large pumped helium system outside the stainless steel tank. As in Case A, the active and shielding regions may be separated with a thin sheet of plastic or quartz.

General Considerations. The liquid nitrogen shielding may be held in either a copper grid composite or acrylic tank. The nitrogen should be thick enough (1-2 m) to sufficiently absorb gamma rays from the photomultipliers and stainless tank. Acrylic is a low activity, transparent, strong material. At low temperatures, acrylic remains strong and tough. The yield strength of acrylic increases significantly as temperature is lowered, while the fracture toughness remains roughly constant [30]. Nevertheless, any acrylic containers will have to be designed carefully to avoid unnecessary thermal and mechanical stresses, as the cryogens are of larger scale than is common in low temperature work.

V. BACKGROUNDS

Condensed noble gases have an important advantage over organic scintillators: they have no ^{14}C contamination. But among the condensed noble gases, only liquid neon and liquid helium can satisfy the strictest requirements of low radioactive contamination [31]. Natural argon is contaminated by the two long-lived isotopes ^{39}Ar and ^{42}Ar, and natural krypton contains ^{85}Kr that precludes its use in low background detectors. Liquid xenon would need to be cleaned of Ar and Kr, and double beta decay of ^{136}Xe would have to be addressed. In addition, while liquid xenon has been put to increasing use in searches for dark matter, its high price (at least $1,000,000 per ton) makes liquid xenon unattractive for use in a large low energy neutrino detector.

Helium and neon have no unstable naturally occuring isotopes and therefore no inherent radioactive backgrounds. They do however need to be cleaned of dissolved Ar and Kr, as well as possible low-level contamination by K, U, and Th, but their low boiling temperatures allows for simple and effective solutions to these problems. Distillation can effectively remove argon and krypton, and by passing the helium or neon through a cold trap, the non-noble radioactive contaminants can be frozen out. In neon one remaining possible radioactive contaminant is tritium. If it is found that commercially available neon is contaminated with low levels of tritium, then it can be easily removed by chemical means. Impurities within the helium or neon are therefore not expected to be a significant source of background. Helium and neon are also relatively inexpensive [32].

Because liquid helium and neon are easily cleaned of radioactive isotopes, the limiting backgrounds are expected to arise from the various construction materials. Copper (used in cases A and B) has been shown to possess low levels of radioactive impurities [33]; an estimate of the activity of copper stored underground for a year [7] gives .02 events kg^{-1} $minute^{-1}$. Possible impurity levels of other necessary materials can be estimated from the results of the BOREXINO [34] and SNO [35] collaborations. It is found [36] that acrylic is commercially available with U and Th levels of less than 10^{-13} g/g. Photomultiplier assemblies can be constructed with U and Th levels of 10^{-8} g/g. Gamma rays emitted from the copper, acrylic, photomultipliers, stainless steel tank, and heat link will Compton scatter in the nitrogen and shielding regions, producing Cerenkov light that can be detected by the photomultipliers. There will be a significant rate of such events; for example, the BOREXINO group reports a gamma flux of $2 \times 10^6\,\mathrm{day}^{-1}\,\mathrm{m}^{-2}$ from their photomultiplier assembly. Fortunately, the light yield from gamma Compton scattering events should be relatively small. Cerenkov light should result in no more than 10 photoelectrons per MeV [35], and visible scintillation light should contribute even less. In liquid helium scintillations, the visible light output has been measured to be 500 times less intense than the extreme ultraviolet output [13,37]. Furthermore, the visible output is concentrated in wavelengths greater than 640 nm, where photocathode responsivities can be chosen to be low. In liquid neon, the visible light emissions are similarly weak, with wavelengths that are shifted even further into the infrared [28]. As a result, the outer neon region, without exposure to an ultraviolet waveshifter, will yield an insignificant amount of visible light from gamma scattering events within its volume. However, even with these effects the high rate of gamma scattering events in the shielding will produce significant background at low photoelectron number. This will therefore set a low energy threshold for neutrino events of roughly 20 keV. This leaves only 10% of solar neutrinos undetected. With a 2 (5) meter thick liquid neon (helium) shielding region, the rate of gammas entering the active volume should be less than 1/day, compared to the predicted 27/day solar neutrino counting rate. Also, gamma rays that penetrate the shielding region will have relatively high energies and are likely to deposit most of their energy in the active region, allowing energy cuts to further reduce background. The background levels arising from events in the shielding regions can be independently tested by running the experiment without any waveshifter.

A variety of other effects may help to decrease background counts. The three-dimensional photomultiplier arrangement will allow rough determination of the event location. Events in the active volume will be more evenly spread over the photomultipliers than events in the liquid nitrogen and shielding volume. Also, the light concentrators affixed to the photomultiplier tubes will restrict their immediate field of vision to the active volume. The expected intense ultraviolet afterpulsing from the active liquid neon (see section III) could also provide an important test against background events.

Radioactive contamination requirements of the materials separating the active and shield regions are stringent. However, very little of these materials are necessary. If clear plastic is used as a divider between the active and shielding regions, radioactive background from U and Th should be insignificant (given U and Th levels of less than 10^{-13} g/g.) However, ^{14}C contamination is a serious issue. In the BOREXINO experiment, ^{14}C levels were demonstrated to be less than 1.9×10^{-18} ^{14}C/C in organic scintillator synthesized from petroleum [34]. The theoretical estimate for ^{14}C/C in old petroleum is $\sim 5 \times 10^{-21}$, and the higher measured value is presumed to arise during scintillator synthesis or later handling. A 1.9×10^{-18} ^{14}C/C level in a 100 μm thick plastic divider would result in roughly 80 (30) events per day if helium (neon) is used as the active medium. This would obscure the expected 27 neutrino events per day. However, the fact that very little material is required ($\sim$ 10 kg of plastic compared to 100 tons of organic scintillator used in the BOREXINO experiment) suggests it is reasonable to expect that the ^{14}C concentration could be held to an acceptable level. In scheme B, a strong, largely transparent material is needed to separate the liquid helium and liquid neon shielding regions. Because the amount of plastic needed is larger than in cases A and C, a lower level of radioactive impurities is necessary.

A second option is to use thin quartz sheet as a substrate. If old silicon is used (older than 50,000 years), then ^{32}Si and ^{14}C are not a problem [38]. But, of course, ^{238}U, ^{40}K, ^{232}Th, ^{3}H and ^{22}Na must be shown to contribute less than 1 event per day in the energy range of interest. This should be possible because cleanliness levels of less than 10^{-12} g/g are routinely achieved in pure Si through zone-refining techniques [39]. By converting this clean Si into silane (SiH_4) gas, ridding the silane gas of radioactive impurities, and then oxidizing, sufficiently clean SiO_2 could be produced. Again, the fact that very little quartz is needed makes this contamination level a reasonable requirement. Contamination requirements on the TPB are not so stringent, as only $0.2\,\mathrm{mg\,cm}^{-2}$ is necessary for efficient wavelength shifting [22].

Muons are another potential source of background. Muons will pass through the experiment at a rate of about $25\,\mathrm{day}^{-1}\,\mathrm{m}^{-2}$ (at Gran Sasso). These prompt events can be eliminated through active vetoing. One way to do this is to detect the Cerenkov radiation in the ultrapure water tank using a second set of photomultipliers [12]. In addition, muons that pass through the active region will produce extremely bright, easily distinguishable scintillation pulses.

In the neon experiment, neutrons and radioactive species can be produced by muons stopping in the active volume. With only a small fraction ($\sim .008$) of muons stopping [40], and with 40% of these stopped muons absorbed by neon nuclei [41], a rate of muon radiogenesis of about 0.5 per day follows. Most of these events result in the production of ^{19}F, a stable isotope. Prompt muon coincidence rejection and energy cuts will reduce background due to the remaining events (e.g. prompt gammas from neutron absorption, decay of long-lived nuclei) to negligible levels. Muons can also lead to the production of neutrons in the surrounding rock. These neutrons, as well as those emitted from fission products and (α, n) reactions, will be moderated and absorbed in the ultrapure water tank, possibly with the help of boric acid dissolved in the water [7], and are not expected to constitute a significant source of background.

VI. CONCLUSION

There are several other experimental programs currently underway to develop real time detectors of pp neutrinos. We believe the method described above compares favorably to all of these. However, making exact technical comparisons with HELLAZ, SUPER-MuNu, and LENS is beyond the scope of this paper. Because the HERON experiment also uses a liquid cryogen it is possible to make a few simple comparisons. The HERON program uses liquid helium as a neutrino scattering medium, and bolometers to detect helium atoms liberated by rotons from the liquid helium surface [7]. The possible event rate achievable with HERON is similar to that possible using our proposed scintillation technique with helium as the active scintillator. If liquid neon is used, however, the event rate is 8 times larger for a given active volume. Our design is technically simpler because it requires temperatures of only 27 K (2 K) for liquid neon (helium), while HERON requires 30 mK superfluid helium to avoid roton scattering. HERON has the requirement (not present in our proposed design) that the helium be isotopically pure to avoid ^{3}He-roton scattering centers. The added effort and complexity of isotopic purification of 10 tons of helium is significant. A significant technical requirement present in our proposed experiment and not in HERON is the need for large, strong clear plastic tanks at low temperatures. Also, unlike HERON, our proposed experiment relies almost entirely on high purity shielding materials to reduce background, obviating the need for precise event reconstruction for background reduction but requiring additional materials processing.

The use of liquid helium or neon as a scintillation medium is a promising method for the detection of low energy neutrinos. First, the background level should be very low because of the extreme cleanliness possible in the active region. All other materials (with higher levels of contamination) can either be well shielded from the active volume or are present in such small amounts that their contribution may be made negligible. Second, the photoelectron output from neutrino scattering events should be high because of the intense extreme ultraviolet scintillation yield. Detection with standard PMTs is made possible by the availability of efficient wavelength shifters. Third, the rate of detected neutrino scattering events will be comparable or larger than those expected in other experimental techniques. Finally, this experiment uses only existing technologies; a small “proof of principle” apparatus could be constructed and tested in relatively little time.

Along with the calibration and monitoring of the pp neutrino flux, this detector will be sensitive to other neutrino sources. For example, the relative and absolute intensities of the ^{7}Be and pep solar neutrino lines might be measured using this sort of detector, yielding a good diagnostic test of what happens to neutrinos after they are emitted [42]. Whether these line intensities could be measured over radioactive background (and other neutrino spectra) must be tested by Monte Carlo methods.

We conclude that liquid helium and neon are intriguing possible detectors for solar neutrinos. An efficient real-time neutrino detector based on this technique could be used to calibrate the pp neutrino flux from the sun, look for time variation signatures of neutrino oscillations, and provide detailed energy information over the entire solar neutrino spectrum.

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FIG. 1. Diagram of the proposed experiment: (1) Active region, containing 10 tons of ultrapure liquid helium or liquid neon. (2) Sheet of transparent material, coated on its inside surface with TPB waveshifter. In case B there would also be a vacuum region separating the active and shielding regions. (3) Shielding region, filled with ultrapure liquid neon or liquid helium.(4) Transparent copper grid composite or acrylic tank (5) Ultrapure liquid nitrogen (6) Photomultipliers (7) Ultrapure water (8) Stainless steel tank (9) Thermal link to refrigerator. Dimensions assume case A (liquid neon active region and liquid neon shielding region.)