Abstract

This paper outlines one facet of the research and development of a novel eBubble neutrino detector: the ejection of charge from a LHe-He interface using acoustic pulses.
1  Introduction & Theory

1.1  The Standard Model

The Standard Model (SM) (See Fig. 1) describes the fundamental buildingblocks that comprise the universe and the laws that govern their interaction. In the SM, matter is composed of force mediating vector bosons (particles with integer spin) and fermions (particles with $\frac{1}{2}$ integer spin). In addition, each particle has a corresponding antiparticle (although a few particles, such as the photon, are their own antiparticle).

The vector bosons mediate 3 of the 4 fundamental interactions. The gluon (g) mediates the strong force between particles containing strong (color) charge. The photon ($\gamma$) mediates the electromagnetic force between particles containing electrical charge. The W and Z bosons mediate the weak force between particles containing weak charge. The SM does not account for gravity.

Fermions are divided into two groups (quarks and leptons) and three generations. The first generation consists of a quark pair (up and down) and a lepton pair (electron and electron neutrino). In general, higher generations are unstable, more massive versions of the first generation. Quarks have not been observed by themselves, but rather bind together via the strong force to form hadrons. Leptons do exist by themselves; electrons and neutrinos are pervasive in matter. The accuracy of the Standard Model’s predictions for particle interactions is astonishing but unfortunately it is an incomplete model.

Figure 1: A diagram of the Standard Model consisting of 6 quarks, 6 leptons and 4 force mediating bosons. Note that antimatter is not shown in the diagram. Retrieved from reference [1].
1.2 Neutrino Detection

The neutrino (meaning ‘little neutral one’) was first postulated by Pauli in 1930 to save conservation of energy in beta decay. After observing that electrons emitted in nuclear beta decay possess a spectrum of energies instead of the predicted fixed energy, Pauli postulated that a third, unobserved particle carries away some of the energy. [2] This nearly massless particle has no color charge and no electrical charge; it only interacts via the weak force. There are two known types of neutrino interactions: charged current (CC) where a neutrino exchanges a electrically charged $W^\pm$ boson, and neutral current (NC) where a neutrino exchanges a electrically chargeless $Z^0$ boson. One specific interaction, electron scattering (ES), occurs when an electron neutrino interacts with an electron in either a CC or NC interaction. (See Fig. 2)

![Diagram of Charged Current (CC) and Neutral Current (NC)](image)

Elastic Scattering (ES)

Figure 2: Elastic scattering of an electron with an electron neutrino is mediated by either a W or Z vector boson. [3]

There are three main sources of neutrinos. High energy neutrinos (10 MeV - 100 GeV) can be made in particle accelerators by aiming a proton beam onto a target. Lower energy (≈ 4 MeV) anti-neutrinos are produced from the decay of neutron rich fission fragments in nuclear reactors. The main source of neutrinos, the sun, produces an energy spectrum of neutrinos (0 eV - 100 MeV) from the pp fusion chain. (See Fig. 3) However, it has been observed that only about half the number of predicted electron neutrinos from the sun are actually observed. This anomaly is known as the ‘solar neutrino problem’ and may lead to new physics beyond the Standard Model.

There are currently two main methods of detecting solar neutrinos. One method looks at the CC interaction ($n + \nu_e \rightarrow p + e^-$) in the nucleus of a heavy atom. Homestead, a solar neutrino detector in a
mine shaft in North Dakota, used a large mass of chlorine as the detection medium (other detectors use Gallium). An incident neutrino of energy $> 200\text{keV}$ occasionally turns a chlorine atom into an argon atom. After some finite time, the chlorine is removed and the number of argon atoms are counted. This method is able to determine the flux of neutrinos but unfortunately cannot determine the direction and initial energy of the neutrino.

Another method of neutrino detection utilizes Cerenkov radiation produced by particles traveling faster than the speed of light in a medium. When an electron neutrino elastically scatters with an electron in a large tank of water, the electron recoils with an energy proportional to the incident neutrino. If the electron recoils at a speed that is greater than the speed of light in water, then conical Cherenkov radiation is produced. The radiation is observed with photon multiplier tubes (PMTs) and used to determine the direction and initial energy of the neutrino. Unfortunately, to give the electron the required energetic kick, an incoming neutrino must have a minimum energy of 3 MeV to cause Cerenkov radiation. These water detectors, such as SNO in Canada and Super-Kamiokande in Japan, are able to measure the direction and energy of incoming neutrinos but they cannot detect low energy neutrinos. The next step in neutrino physics is to determine a method to observe, in real time, low energy neutrinos ($\approx 10\text{keV}$).

Figure 3: This figure shows the limits of current neutrino detectors superimposed on the theoretical flux of neutrinos produced by the p-p fusion chain in the sun’s core. Note the log-log scale shows that more than 90% of neutrinos produced by the sun cannot be detected in real time! Retrieved from [4]
1.3 eBubble Detector

A new ‘eBubble’ detection system is intended to detect neutrinos with energies < 1.4MeV, the threshold for the neutrino-nucleon interaction. To detect these low energy neutrinos the eBubble system utilizes electron-neutrino elastic scattering (ES). The cross section for this interaction is

\[
\sigma_{\nu_e e^- \rightarrow \nu_e e^-} = \frac{G_{\nu_e}^2}{\pi} \left( \frac{1}{2} + \xi \right)^2 + \frac{1}{3} \xi^2 \]

\[
\approx 9.5 \times 10^{-49} m^2 \left( \frac{E}{1\text{MeV}} \right)
\]

(1)

where E is the energy of the neutrino in MeV.\cite{5} Such a cross section would require a detection mass of five tons to achieve a reaction rate of 1000 events\text{year}^{-1}.

When a neutrino elastically scatters off an electron at rest in a medium, the electron recoils and ionizes the medium through which it passes. In the process of ionization the electron loses the kinetic energy given to it in the interaction and leaves a ‘track’ of electrons in its path. By measuring the distance the electron traveled, the length of this track, the initial energy can be calculated.

In many materials the electrons from the ionized atoms would recombine with or interact with neighboring atoms and thus the ‘track’ would diffuse. Liquid helium is chosen as the interaction medium in order to preserve the resolution of the tracks. The very low freezing and boiling temperatures of helium, 2.2 K and 4.2 K, ensure that the diffusion due to Brownian motion is minimal. The Einstein-Nernst equation for thermal diffusion of a charge in an electric field states that

\[
\sigma = \sqrt{\frac{2kTd}{eE}}
\]

where \(\sigma\) is the diffusion of the charge, E is the applied field, d is the distance traveled, and T is the absolute temperature of the medium.

The stable state of an electron in liquid helium is inside an ‘electron bubble’, or localized state, where recombination in the material is greatly reduced. This ‘bubble’ is a vacuum from which the helium atoms are excluded and is approximately 1 nm in radius. The ‘electron bubble’ forms because the helium atoms are repelled to the distance from the electron at which the electrostatic force between the electrons in the helium atom and the force exerted by the pressure of the material are at equilibrium. Only simple noble liquids, specifically helium, neon, and argon, form electron bubbles. If an electron is in a liquid which is not noble, it will be incorporated into one of the valence shells of the atoms in the medium rather than repelling

![Figure 4: A cartoon of an electron bubble forming in liquid helium (LHe).](image)
the atoms in the medium. If an electron is in a massive noble liquid, it will polarize the medium rather than repelling the atoms. This is because the greater number degrees of freedom in the atoms entails a greater electron mobility of the atomic electrons, allowing the electron orbitals to be shifted in the presence of a free electron. As the electrons form in ‘electron bubbles’, there is very little interaction with helium atoms and the electrons in the tracks created after an interaction diffuse very little and there is very little recombination. Helium is used for the eBubble experiment as its boiling point, at 4.2 K, is much lower than the boiling point of argon or xenon, at 85.4 K and 166 K respectively.

The energy and charge of the incoming neutrino can be determined from the length of the track of electrons. In the case that liquid helium is the detection medium, the path length is on the order of 1 mm. If, as is proposed, an aperture of \(25 m^3\) of helium is used there would need to be \(25 \times 10^9\) voxel (a three-dimensional pixel) elements in the medium. It is not viable to have a detection system such a great number of detection elements strung throughout the detection medium. To reduce the number of voxel elements, a downward electric field is applied to the medium which drifts the bubbles to a two-dimensional detection array.

At very low temperatures liquid helium acts as a superconductor. At a temperature of .274 K the electron mobility, a measure of the dependence of electron drift velocity on electric field strength, is 1350 cm\(^2\)V\(^{-1}\)sec\(^{-1}\) whereas at a temperature of 5.18 the electron mobility is 0.0157 cm\(^2\)V\(^{-1}\)sec\(^{-1}\). The low electron mobility arising from the ‘bubble’ structure, which gives the drifting electron a greater viscosity (similar to a balloon in water). For detection purposes it is advantages for the electron mobility to be low, thus in experiment the temperature is kept at approximently 4 K.

Before the track is detected it needs to be amplified. This is commonly accomplished via a ‘townsend avalanche’, in which a large electric field gradient gives a drifting electron sufficient momentum to ionize the material. The electrons resulting from this ionization repeat the process, creating a domino effect by which the signal can be amplified up to five orders of magnitude. This is often accomplished usually by a lattice of high voltage wires. As the drifting electron approaches the top of the detection medium, the avalanche can either take place in the liquid helium or in the layer of helium gas directly above the liquid. However, it has been oberved that the density of liquid helium is too great for electrons to achieve sufficient momentum to create an avalanche.

It is therefore desired to detect the signal in the helium gas. However, because the dielectric constants of liquid helium and helium gas differ, an electron below the surface of the liquid polarizes the gas and the interface receives a charge distribution which acts as if there is an ‘image charge’ in the helium gas that opposes the upward movement of the electron.
Suppose that an electron is in the following configuration:

![Diagram of an electron beneath the liquid-vapor helium interface](image)

Since the electric field from the electron, \[ \frac{1}{4\pi\epsilon_0} \frac{e}{(r^2 + (d+z)^2)^{\frac{3}{2}}} (r\hat{r} + (d + z)\hat{k}) \], polarizes the helium gas and since liquid helium does not polarize (thus the formation of localized states), the volume charge density inside the helium gas will be \( \rho = -\nabla \cdot \vec{P} \) and the surface charge density on the interface will be \( \sigma = \hat{n} \cdot \vec{P} \) where \( \vec{P} \) is the polarization in the helium gas and \( \hat{n} \) is the unit vector normal to the surface. If it is assumed that helium gas is a linear dielectric then \( \vec{P} = \epsilon_0 (\epsilon - 1) \vec{E} \), where \( \epsilon \) is the relative permittivity of helium gas.

\[ \vec{E} = \frac{1}{4\pi\epsilon_0} \frac{e}{(r^2 + (d+z)^2)^{\frac{3}{2}}} (r\hat{r} + (d + z)\hat{k}) + \sigma \hat{k}, \]

The contribution to the electric field is from the electron charge and the induced surface charge, respectively.

\[ \rho = 0, \quad \sigma = \frac{-e}{4\pi\epsilon_0 (r^2 + d^2)^{\frac{3}{2}}} \frac{e \times d}{r^2 + d^2}, \]

The electric field on the electron from induced charge on the interface is

\[ E = \frac{1}{4\pi\epsilon_0} \int \frac{\sigma dA}{r^2 + d^2} \cos(\theta) = \frac{e}{4\pi\epsilon_0} \left( \frac{e^{-1}}{r + 1} \right) \left( \frac{1}{2d} \right). \]

This happens to be the same electric field given by an ‘image’ charge \( \frac{e^{-1}}{4\pi\epsilon_0 (r + 1)} q \) at a distance \( d \) above the interface. When the electric drift field is applied the potential is then \( V = \frac{e^2}{4\pi\epsilon_0 (4\epsilon + 1)} \frac{1}{z} + eE_{\text{drift}} z \).

The potential minimum, where the electron comes to rest below the interface, occurs at \( \sqrt{\frac{e}{4\pi\epsilon_0} \frac{e^{-1}}{4\epsilon - 1} \frac{1}{E}} \).

### 1.4 Charge Ejection

Currently, a major objective in the experiment is to determine a method of ejecting the charge from the distance below the interface into the helium vapor. Three proposed methods are to eject the charge via a local field gradient, photoionization, and acoustic pulsing.

For the first method, the electron approaching the interface is given enough momentum to pass through the interface using an increased electric field at the top of the liquid helium. This is the most tried and true method, being used in the Xenon experiment at Nevis labs. If the amplification were attempted with lattice of high voltage wires, then the some of the gamma rays emmited by the accelerated electron would collide...
with the wires and by the photoelectric effect emit more electrons. In this way false signals would be
detected. Because of this a Gas Electron Multiplier (GEM) could be used to create the amplify the signal.
The GEM creates a large potential difference using two electrodes and has an array of holes through which
the accelerated electrons pass. Between these electrodes there is a layer of insulation, which absorbs the
gamma rays directed at the electrode. In research on GEM’s, gains of up to $10^5$ have been observed.

(a) Diagram of the cross section of a GEM  (b) The face of a GEM

In this method, the signal via the gamma rays that it emits by either an array of photo diodes or
a commercial camera. While this is a promising method, it is expensive, elaborate, and provides poor
spatial resolution of the direction of the track. For these reasons, charge emission by acoustic pulsing, and
photoionization have been suggested. These methods are elegant and provide very good spatial resolution.

The idea behind photoionization is that the electron in it’s vacuum bubble is much like a particle in a
box. In fact, Schoepe and Rayfield[6] have calculated the mean time that an electron is in a bubble before
it escapes. As the electron in an electron bubble is a confined quantum mechanical system, it has discrete
energy levels and if given a certain amount of energy it can break free of the potential barrier and into the
helium vapor. In photoionization, the electron would be energized by a stream of gamma rays.

The idea behind acoustic pulsing is that sending a sound pulse to the interface would create an in-
stability which would eject the electron into the vapor. Rayleigh-Taylor instabilities occur when a denser
fluid is being accelerated by a lighter fluid. In this instability a portion of the heavier fluid juts out so it is
surrounded by the lighter fluid, expands, and atomizes, or creates droplets. This process can be observed in
a lava lamp or some air humidifiers.

Directly above the electron bubble there will be a small bump on the surface of the liquid on the order
of 10-11 m. This bump arises as the surface tension force and gravitational force of the risen liquid balance
out the image force. If an acoustic wave has enough power to create atomization, it will create atomization
preferentially at the point of this bump. A main task investigated this summer is the power needed to create
atomization on the surface of a liquid using acoustic pulsing.
2 Experiment

Before a fullscale detector can be constructed, tests must be performed on a more manageable scale. Fig. 6 shows the prototype that is currently being tested at Brookhaven National Laboratory. A small chamber of $\approx 1.5L$ LHe is contained within.

Figure 6: (Left) schematic of eBubble chamber (Right) picture of eBubble chamber
The ejection of charge from the LHe- He interface is a crucial aspect of the detector and a smaller experiment was performed to investigate acoustic pulsing. An experiment was designed to investigate the atomization of water using acoustic pulses to better understand Taylor-Rayleigh instabilities. The method of doing so is to measure light scattered off of the surface of water. By disturbing the surface with acoustic pulse and observing the result scattering effects, important parameters can be found for atomization. Fig. 7 is a diagram of the experimental setup. Fig. 8 is a picture of the experimental setup.

Figure 7: schematic of the experimental setup

Figure 8: picture of the experimental setup
Acoustic pulses were generated from transducers purchased from OPTEL. The transducers can be used both as acoustic pulse emitters and receivers. They produce 10 MHz planar waves and software controls power of acoustic pulse.

Figure 9: picture of one of the transducers

The waveform produced by the transducers is an important aspect of this experiment. In order to understand how dependent the power of the wave is on the displacement from the transducer, we set two transducers facing one another with one transducer as an emitter and the other as a receiver. Then we measured the power of the wave as a function of displacement. (See Fig. 10)

Figure 10: experimental setup used to characterize wave profile produced by transducer (Left) top-view (Right) side-view
This experiment in general, being performed in water, required special considerations. A basic Brita filter system was constructed to minimize dust and particles in water. A tank cover was constructed to limit dust on the surface of the water. A consistent water level was maintained with a probe-resistance system. (See Fig. 11)

Figure 11: Set Probe A at desired water level. Submerge Probe B Slowly fill tank, turn water off when resistance between probes jumps to finite value

Background vibrations produced unwanted surface disturbances. A vibration table was made out of spare rubber hosing, steel plates, and lead bricks. Fig. 12 is a schematic of the vibration table.

Component alignment was a major consideration. The first step was to aim the laser at the point on the surface where the transducer was aimed. Problems with this were that there is a tedious ball and socket alignment of laser. Also the non-rigid transducer aim had insufficient precision. To combat this we built a new transducer holder that works better but is still not ideal. The second step was to align the photodiode to where the laser reflects. The problem with this is that the photodiode holder is dodgy and has poor

Figure 12: (Left) a cartoon of the table (Right) a picture of the table
precision. Another problem is that making any adjustments to these components disturbs the water, which must settle before measurements and realignment can be taken.

A mechanical wave generator was used to create periodic surface waves (for practice). We successfully observed periodic signal where both frequency and amplitude are dependent on frequency the wave generator. See Fig. 13.

Focusing the laser was another important consideration. The laser width at surface of water needed to be less than the wavelength of surface wave. For the small waves produced by the transducer, the laser needs to be focused on order 0.15 mm. Unfortunately proper optics equipment was not available and pinholes were used instead.

![Figure 13: a mechanical wave observed by looking at the signal from a photodiode collecting scattered light off the surface of the water.](image)

3 Results & Discussion

After measuring the wave profile we discovered that the wave form is highly collimated. Power decreases by an order of magnitude outside 5mm² area. (See Fig. 14)

![Figure 14: The waveform is highly collimated](image)
Surface disturbances created by background vibrations were successfully damped with the home-made vibration table. Fig. 15 is before and after damping.

![Figure 15: The](image)

After focusing laser and aligning components, no transducer effect was observed. There was no observable difference in the oscilloscope signal from when the transducer was turned on and off.

Potential causes of the problem were that we focused the laser on a region of the surface where the transducer was not directed. We were unable to focus the laser which resulted in averaging over multiple waves. We also had alignment difficulties hindered depth of investigation. For instance every time a component was adjusted the water was disturbed and thus we had to wait for the water to settle before realigning the components.

We would like to make some recommendations. First the experiment should be performed on an optics air table to prevent vibrations and allow for easy optics use. Second proper optics equipment would greatly facilitate this experiment. Third a smaller tank would be more convenient. Fourth we have designed a new experimental setup such that the components move independently of the tank that has new component holders that are capable of precise, multidimensional alignment.

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