A Report on the Research and Development of the e-Bubble Collaboration

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Abstract

The e-Bubble Group aims at building a low-energy neutrino detector with the particular goal of measuring an accurate, real-time flux of solar pp neutrinos. This document outlines the relevant developments made in recent years regarding neutrino physics. In addition the e-Bubble group has conducted many experiments using a small scale test chamber prototype. Multiple electron bubble characteristic were measured using the test chamber. Finally, many computer simulations were completed to model the electron bubble drifts in the test chamber. The simulations were used to analyze the data recorded in the experimental run as well as make predictions regarding future test chamber experiments.
1 Introduction

The story of the neutrino has endured many hardships since its theoretical postulation by Wolfgang Pauli in the year 1930, and it was not until recently (within the last five years) that significant progress has been made in the physical understanding of these elusive particles. As neutrinos were originally thought to be massless, they were incorporated into the Standard Model as so. However, data taken in collaboration of the Super-Kamiokande and the SNO experiments (H$_2$O and D$_2$O detector mediums, respectively) found a high-energy solar $\nu_e$ flux that was much less than expected, while SNO (sensitive also to $\nu_\mu$ and $\nu_\tau$) measured equal fluxes of all three neutrino types that, if analyzed under a lens of new neutrino physics, accounted for the predicted solar flux. This new physics postulated that neutrinos in fact are not massless and instead have very small masses (on the order of a few eV) that enable them to change flavor in a phenomenon known as quantum oscillation.

Due to oscillation, the probability that a $\nu_e$ will be detected as a $\nu_e$ a distance $L$ (in km) away from its origin is governed by the equation [19]

$$P_{ee} = 1 - \sin^2(2\theta) \sin^2\left(k\Delta m^2\frac{L}{E}\right)$$

(1)

Where $\theta$ is the mixing angle, $E$ is the neutrino energy and $k$ is valued at 1.27 when $\Delta m^2$ is measured in eV. This equation is derived by the assumption that the neutrino masses are a simple mixture of neutrino flavor eigenstates as described by the following relation.

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix}$$

The current mixing parameter values $\theta_{12}$, $\theta_{13}$ and $\Delta m^2$ have been experimentally measured via higher energy neutrino experiments (KamLAND), with $\Delta m^2_{12} = 7.9^{+0.6}_{-0.5} \times 10^{-5}$ eV$^2$ and $\tan^2 \theta_{12} = 0.40^{+0.10}_{-0.07}$ for the two-neutrino ($\nu_e \leftrightarrow \nu_\mu$) oscillation model [1]. The $\theta_{13}$ parameter has been measured, but with considerably less accuracy. In fact, much is known about the high-energy neutrinos ($> 5$ MeV) simply due to the fact that higher energy neutrinos interact with matter at greater cross-sections than lower energy ($< 3$ MeV) neutrinos and are thus easier to detect. But these higher energies can only tell us so much about the nature of neutrinos. More interesting physics lies at the low-energy scales that resist experimental detection. For example, oscillations that occur at high-energies are matter-dominated oscillations (by the MSW effect) that, at low energies, should change to vacuum-dominated oscillations [4]. A proper understanding of quantum neutrino oscillation cannot be obtained without accurate low-energy neutrino measurements.

Also, recall that neutrino detectors were initially constructed to investigate solar processes, not neutrino oscillations (oscillations were discovered by accident). In fact, the study of neutrino oscillations was initiated to explain experimental measurements of the solar neutrino flux that were $1/3$ of the value predicted by the Solar Standard Model (SSM). The theory of neutrino oscillations was formulated as a “bottom up” theory. Today, a comprehensive understanding of the Sun is still being pursued. Measurements of the high-energy solar neutrino fluxes have matched the SSM prediction of solar luminosity with great accuracy, but account for only $< 2\%$ of solar fusion reactions (see table 1) [3]. The total solar neutrino flux as given by the SSM is illustrated in figure 1. To date, there is no definitive measurement of the solar neutrino flux due to the small sample size of high-energy neutrinos and the difficulty of detecting low-energy neutrinos. An accurate measurement of the low-energy solar neutrino flux would have notable impacts on our understanding of neutrino physics (the low-energy neutrino vacuum oscillation behavior) and the energy mechanisms of the

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1The fact that neutrinos have mass also tells us that they have small magnetic moments, $\mu_\nu$. This has considerable influence on their interactions with matter, particularly in $\nu_e - e$ scattering (see section 2, equation 5)
The falsification of our SSM describing the solar energy mechanism of nuclear fusion by disagreeing photon and neutrino flux measurements would be groundbreaking.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$\nu_e$ Energy (MeV)</th>
<th>Percent Solar Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p + p \rightarrow ^2H + e^+ + \nu_e$</td>
<td>$\leq 0.4203$</td>
<td>85%</td>
</tr>
<tr>
<td>$p + e^- + p \rightarrow ^2H + \nu_e$</td>
<td>1.445</td>
<td></td>
</tr>
<tr>
<td>$^2\text{He} + p \rightarrow ^4\text{He} + e^+ + \nu_e$</td>
<td>$\leq 18.773$</td>
<td>$&lt; 2%$</td>
</tr>
<tr>
<td>$^7\text{Be} + e^- \rightarrow ^7\text{Li} + \nu_e$</td>
<td>0.862, 89.7%, 0.384, 10.3%</td>
<td>13%</td>
</tr>
<tr>
<td>$^8\text{B} \rightarrow ^8\text{Be} + e^+ + \nu_e$</td>
<td>$\leq 14$</td>
<td>$&lt; 2%$</td>
</tr>
<tr>
<td>$^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$</td>
<td>$\leq 1.199$</td>
<td>$&lt; 2%$</td>
</tr>
<tr>
<td>$^{15}\text{O} \rightarrow ^{15}\text{N} + e^+ + \nu_e$</td>
<td>$\leq 1.732$</td>
<td>$&lt; 2%$</td>
</tr>
<tr>
<td>$^{17}\text{F} \rightarrow ^{17}\text{O} + e^+ + \nu_e$</td>
<td>$\leq 1.740$</td>
<td>$&lt; 2%$</td>
</tr>
</tbody>
</table>

Table 1: Neutrino-producing Solar Reactions

1.1 Low-Energy Neutrino Detection

The e-Bubble neutrino detector is being designed with the priority of measuring the low-energy (particularly $pp$) solar neutrino flux. The detector will make accessible the measurements of low-energy neutrino oscillation parameters, the testing of the SSM by accurate low-energy neutrino flux measurements and possibly the measurement of the neutrino magnetic moment ($\nu_e$). The detector will be a tracking detector, i.e. one which reads the paths taken by charged particles produced in high-energy collisions in order to extract information about the collision and the particles involved. Due to the low-energy and low-interaction rate of the solar $\nu_{pp}$, the e-Bubble detector must be designed with specifications including precise energy resolution (effective down to sub $keV$ energies), precise spatial resolution ($< mm^3$), large detector volume (for a higher detection rate), low background noise and a low $\rho$ (density) detector medium to minimize multiple-scattering events (see section 3.1). The detector will include a drifting feature that will apply a strong electric-field to the tracks of ionized electrons and drift them to be detected on a 2-D surface. Both liquid helium (LHe) and liquid neon (LNe) exhibit features that make them strong candidates for detection mediums; specifically, their purity allows for long electron drifts (conducive to a large detector volume and low recombination) and their low-Z (low-$\rho$) and noble properties create an environment for unusual electron equilibrium states known as electron bubbles (that allow for very small drift diffusions and low drift velocities).

While in the Research & Development stage of its operation, the e-Bubble group is focusing primarily on researching the dynamics of electron bubble drifts in LHe and LNe. Proper real-time data analysis in the operational neutrino detector will require a broad understanding of electron bubble behavior in such environments.

2 Neutrinos

Interactions of neutrinos with matter are governed by the sizes of their interaction cross-sections. Each cross-section is expressed as an area, and can be derived by analyzing the respective differential cross-section, which is a function of incident particle energy. The differential cross-section can be derived by
considering the force(s) at work in the particle interaction. The differential cross-section for the neutrino weak-interaction is \[ \frac{d\sigma}{dT} = \sigma_0 \left[ g_L^2 + g_R^2 \left(1 - \frac{T}{E_{\nu}}\right)^2 - g_L g_R \left(\frac{T}{E_{\nu}}\right)\right] \] (2)

where the angular elements are contained in the values \( g_L \) and \( g_R \) (for \( \nu_e \)),

\[ g_L = \frac{1}{2} + \sin^2 \theta_W \quad \text{and} \quad g_R = \sin^2 \theta_W \] (3)

and

\[ \sigma_0 = \frac{2G^2 m_{\nu}^2}{\pi \hbar^2} = 88.083 \times 10^{-46} \text{cm}^2 \] (4)

where \( T \) is the kinetic energy of the recoil electron, \( E_{\nu} \) is the energy of the incident neutrino, and \( \theta_W \) is the scattering angle of the recoil electron. The weak interaction is very short-range, and involves the exchange of a \( W^+ \) or \( Z^0 \) boson between the neutrino and a particle in the atomic nuclei. Such an interaction is governed by \( d + \nu_e \rightarrow u + e^- \) (or \( n + \nu_e \rightarrow p + e^- \) for charged current \( W^+ \) exchange interactions) or \( \nu_e + d \rightarrow \nu_e + n \) (for neutral current \( Z^0 \) exchange interactions). Due to the neutrino magnetic moment \( \mu_{\nu} \), the neutrino can also interact with electrons directly via the electromagnetic force by the elastic interaction \( \nu_e + e \rightarrow \nu_e + e \). The differential cross-section due to this interaction is \[ \frac{d\sigma}{dT} = \mu_{\nu}^2 \frac{\pi \alpha^2 m_e}{m_{\nu}^2} \left( \frac{1}{T} - \frac{1}{E_{\nu}} \right) \] (5)
where $\mu_e$ is in units of $\mu_B$ (the Bohr magneton, $\mu_B = \frac{e}{2m_e} = 9.2741 \times 10^{-24}$ Am$^2$) and $\alpha$ is $1/\pi$. In order to calculate the effective cross-section, integration parameters must first be set. Setting $T_{min}$ and $T_{max}$ to be the minimum and maximum allowed energies of a recoil electron, respectively, the cross-section can be calculated to be [2]

$$\sigma(T_{min}) = \sigma_0 \left[ (g_L g_R^2)(T_{max} - T_{min} - \frac{g_L^2}{2E_{\nu}} + \frac{g_L g_R}{E_{\nu}})(T_{max}^2 - T_{min}^2) + \frac{g_R^2}{3E_{\nu}^2}(T_{max}^3 - T_{min}^3) \right].$$  \hspace{1cm} (6)

The differential cross-section can also be stated in terms of recoil electron scattering angle, $\mu$. The relationships between this angle and the neutrino and recoil electron energies

$$\mu^2 = \frac{T(1 + E_{\nu})^2}{(T + 2)E_{\nu}^2} \quad \text{and} \quad T = \frac{2E_{\nu}^2\mu^2}{(1 + E_{\nu})^2 - E_{\nu}^2\mu^2}$$  \hspace{1cm} (7)

lead to the equation for the angular distribution of a recoil electron from an incident neutrino$^2$ [2],

$$\frac{d\sigma}{d\mu} = \frac{4(1 + E_{\nu})^2E_{\nu}^2\mu}{[(1 + E_{\nu})^2 - \mu^2E_{\nu}^2]^2} \frac{d\sigma}{dT}(T(\mu));$$ \hspace{1cm} (8)

Bahcall has carried out these calculations in an integrated analysis of the differential cross-sections for the entire energy-spectrum of the solar $pp$ flux and extracted the results displayed in figures 2 and 3. A proper analysis of a $\nu - e$ interaction in the e-Bubble detection medium will require the consideration of these neutrino scattering parameters. Knowledge of the neutrino cross-sections is essential for the analysis of a neutrino induced electron-ionization track, which will provide the information referring to the initial conditions of the incident neutrino.

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\[2^2\]This relationship will be further considered when looking at the pointing ability of the detector (see section 3).

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**Figure 2:** Integrated energy distribution of $\nu_e$-$e$ scattering (solid line).

**Figure 3:** Integrated angular distribution of $\nu_e$-$e$ scattering (solid line).
3 The e-Bubble Detector

Determination of the most effective e-Bubble detector medium is currently at the forefront of the e-Bubble Group Research & Development. As previously mentioned, LNe and LHe are the two strongest candidates for such a medium, while LNe has been the focus of recent research due to the more extensive work that has been done on LHe. In particular, the behaviors of quasifree electron states (the electron bubble states) in LNe have been investigated.

3.1 The Functionality of LNe as a Detection Medium

LNe has been investigated in an effort to determine how well it satisfies the low-energy ($pp$) neutrino detection requirements mentioned in section 1. As a first approximation of the effectiveness of LNe, it is important to look at the $\nu_e - e$ event rate that a LNe detector would provide. The rate of the solar $pp$ reaction is $6.2 \times 10^{10}$ cm$^{-2}$s$^{-1}$ [5]. The number density of LNe is known to be $0.037$ A$^{-3}$. It follows by assumption that the number density of electrons in LNe is $0.37$ A$^{-3}$, or $3.7 \times 10^{-23}$ cm$^{-3}$. Equation 6 gives the $\nu_e - e$ cross-section to be $11.6 \times 10^{-46}$ cm$^2$ for low-energy $pp$ neutrinos. This information gives us the rate of $\nu_e - e$ scattering to be $2.66 \times 10^{-11}$ cm$^{-3}$s. The $\nu_e - e$ rate per metric ton LNe can then be calculated to be $674 \text{ year}^{-1}$ by using the atomic mass number of neon, 20.1797 amu.$^3$ This detection rate in LNe is suitable for maintaining a reasonable detector size to be mobile for transportation to detection sites far underground (for low background flux). Knowing the rate of neutrino detection in LNe gives a modest foundation for probing the characteristics of LNe even further.

In its functional state, the e-Bubble detector will be a tracking detector that works as follows. Assuming that a neutrino passes through the detector and interacts with the detection medium (LNe or LHe), that neutrino will scatter an electron (as governed by the $\nu_e - e$ cross-sections given in section 2) into the detection medium. The electron will then pass through the medium and lose energy through a series of ionizations that lead to some finite path length and ionization-density (radiative energy loss can be neglected due to the sub-MeV energy of the recoil electron). A track of electrons will result in the medium. The track will be characteristic of the neutrino energy and origin. A strong E-field will be applied in one dimension of the detector so that the ionized electrons (electron bubbles, see section 3.2) will drift to a 2-D surface where they can then be detected (see section 3.4). Complications that arise when immersing such detection apparatuses in very cold noble liquid environments require that the devices be located outside of the liquid. Thus, the electron bubble drifts must involve the passage through a liquid-vapor interface with discontinuous dielectric properties (see section 3.3). The characteristics of the equilibrium electron bubble state in LHe and LNe$^4$ are key for such a task.

3.1.1 Electron Ionization Tracks

The energy-loss of a charged particle traveling through a medium is primarily a result of the Coulombic forces acting on the incident particle. Due to nuclear interactions and Bremsstrahlung, radiative energy-loss may also occur. However, it can be neglected when considering electrons at low (sub-MeV) energies. $X_0$, the radiation length, is a material dependent quantity that expresses the mean path length over which an electron loses all but $e^{-1}$ of its energy. For LHe, $X_{0,LHe} = 7.6m$ and for LNe, $X_{0,LNe} = 24cm$. The

$^3$This $\nu_e$ flux does not take into account neutrino oscillation.

$^4$An advantage of LNe over LHe is that LNe is “self-shielding,” i.e. it is dense enough for its perimeter to serve as a shield to eliminate background events. Also, LNe has $10 \times$ the cross-sectional value of LHe, allowing for the same neutrino-dection flux in a much smaller volume. Both mediums are self-purifying and limit Brownian motion due their low temperatures.
ionization energy loss of an electron traveling through a medium is (neglecting the small density-effect correction) [17]

\[
\frac{dE}{dx} = A \frac{B}{\beta^2} \left[ B + 0.693 + 2 \ln \left( \frac{p}{m_0c} \right) + \ln W_{\text{max}} - 2\beta^2 \right]
\]

(9)

where \( \beta = v/c \) of the electron, \( m_0 \) is the rest mass of the electron, \( p \) is the momentum of the electron, \( W_{\text{max}} \) is the maximum energy transfer that can occur during an ionization event,

\[
A = \frac{2 \pi n e^4}{m_e c^2} \quad \text{and} \quad B = \ln \left[ m_e c^2 (10^6 \text{eV}) I^2 \right]
\]

(10)

where \( n \) is the electron density of the medium and \( I \) is the minimum energy required for ionization. For LNe, \( I = 137 \text{eV} \) [7] and \( W_{\text{max}} \) can be calculated by the relation

\[
W_{\text{max}} \simeq \frac{2 m_e v^2}{1 - \beta^2}
\]

(11)

for lower energy electrons. Note that the equation for ionization loss gives \( dE/dx \) in units of MeV cm\^2/g.

Taking into the account the mass density \( \rho_0 \) (g/cm\(^3\)) of specific materials, information regarding the stopping power (MeV/cm), track length (range) and ionization-density can be extracted. Figure 4 illustrates the stopping power of LNe \((\rho_0 = 1.24 \text{g/cm}^3)\) as a function of electron energy while figure 5 illustrates the number of electron ionization events per unit distance as a function of electron energy. Notice how the number of ionizations per unit distance increases as the electron energy decreases. This feature will play an important role in our “pointing” capability, or our ability to reconstruct the origin of the detected neutrino.

If the reciprocal of the equation for ionization density \((dE/dx)\) is integrated over energies from 0 → ∞,

\[
\int_0^\infty \left[ \frac{dx}{dE} \right] dE,
\]

(12)
a function for the range of the electron can be derived (see figure 6). Although this equation approximates continuous energy loss per unit distance, it provides an accurate result for electron track range in low
multiple-scattering mediums (such as LNe). Similar to the equation for stopping power (equation 9), equation 12 gives a result in units that are arbitrary of $\rho_0$ ($g/cm^2$)... so dividing this result by $\rho_0$ gives the range as a function of electron energy (see figure 7) [7].

![Figure 6: Electron range ($g/cm^2$) as a function of energy.](image)

![Figure 7: Electron range (mm) as a function of energy.](image)

In an effort to better understand the information that the electron ionization tracks contain about the incident neutrino, a Monte Carlo (MC) simulation was written specifically to simulate the ionization tracks of recoil electrons from $\nu_e$-$e$ events in a LNe detection medium. The simulation assumes that no multiple-electron scattering occurs and that the only interactions that take place among the tracked electron and the electrons bound to the LNe atoms are Coulombic in nature. Hence, each interaction in this simulation involves an ionization of $I$, the minimum required ionization energy for LNe (137 eV). Figure 8 shows ten tracks of incident electrons originating at the point (0,0,0) and projecting along the vector (1,1,1) with 250 keV initial energies, while figure 9 shows ten tracks of electrons with 100 keV initial energies. Track ranges that result from this MC method fall within 10% of the ranges predicted by equation 12. Also, this method is particularly useful in analyzing the inherent pointing capability of a recoil electron track. The $e^−-e^−$ (Møller Scattering) cross-section used for this simulation is given by [12]

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2(2E^2 - m_e^2)^2}{4E^2(E^2 - m_e^2)^2} \left[ \frac{4}{\sin^4 \theta} - \frac{3}{\sin^2 \theta} + \frac{(E^2 - m_e^2)^2}{(2E^2 - m_e^2)^2} \left( 1 + \frac{4}{\sin^2 \theta} \right) \right]$$

where $E$ is the incident electron energy and $m$ is the mass of the incident electron. Due to the singularity of $d\sigma/d\Omega$ at $\theta = 0$, this distribution was parameterized for the Monte Carlo simulation by fitting values at higher scattering angles with a gaussian function.\(^5\) By extracting the endpoints of each MC track in a higher-iteration statistical analysis, the average angular deviation from the initial electron path can be determined. This value is directly related to the pointing capability of the detector at various incident energies. Figure 10 shows this average angular deviation as a function of initial electron energy. In order to extract information regarding incident neutrinos, the $\nu - e$ recoil electron spectrum must be taken into account.

\(^5\)This singularity arises due to the classical nature of the differential cross-section and the infinite range of the classical Coulomb force. A formulation for the scattering distribution similar to the Debye screening formulation used in plasma physics seems useful here, except the assumption cannot be made that the charge carriers have, on average, kinetic energies much greater than their potential energies due to the extremely low temperature of LNe.
3.2 e-Bubbles

When the kinetic energy of a free electron in LHe or LNe goes to zero (i.e. approaches its equilibrium state), the electron reaches a strange quasifree state resembling a small (on the order of Å) bubble known as an electron bubble. The electron bubble state is a result of the free electrons repulsion of the atomic electrons due to the Coulomb forces and the obedience of the Pauli Exclusion Principle. Low-Z noble liquids are particularly conducive to the presence of electron bubbles due to their characteristic low densities, small surface tensions and atomic polarizability. The fact that electron bubbles occur in LHe and LNe are ultimately what make them candidates for low-energy neutrino detection mediums.

Formulations of electron bubble dynamics are hard-going. However, accurate approximations can be made using the Wigner-Seitz model in which atoms in a dense medium are replaced (conceptually) by hard spheres of radii on the order of the low-energy scattering length $l$ of the medium. In this model, the equivalent sphere radius is

$$r_s = \left(\frac{3}{4\pi n}\right)^\frac{1}{3}$$  \hspace{1cm} (14)

where $n$ is the number density of the medium. The condition for the wave number of a non-localized electron can be bound to the relationship

$$k_0r_s = \tan k_0(r_s - l)$$  \hspace{1cm} (15)

which leads to the Wigner-Seitz expression for the lowest energy state of the approximated electron bubble,

$$E_0 = \frac{\hbar^2k_0^2}{2m}$$  \hspace{1cm} (16)

Figure 11 shows the temperature dependence of $E_0$ at scattering lengths of $l = 0.39a_0$ and $l = 0.24a_0$, where $a_0 = 0.529\text{ Å}$ is the Bohr radius. These values arise from the experimentation of Miyakawa, T. and D.L. Dexter [14].
Figure 10: The mean angular deviation of the scattered electron (degrees) from its initial direction of propagation. An exponential fit is represented by the dashed-line.

Figure 11: Barrier height $E_0$ as a function of temperature $T$ (°K) in LNe where curves 1 and 2 use Wigner-Seitz method of approximation with $l = 0.39a_0$ and $l = 0.24a_0$, respectively. [14].
Figure 12: The temperature dependent mobilities of electron bubbles in LNe using experimentally determined (Bruschi et al) values of η(T). [9]

Having an understanding of the ground-state energies of electron bubbles is essential for understanding their more complicated behaviors. For example, the radius of the electron bubble (not \( r_s \)) is known to be related to the surface tension of the medium it is immersed in by \( E_0 \propto \sigma \). Experimental results [15] have shown that the electron bubble radius \( R \propto \sigma^{1/4} \). We can then see that \( E_0 \propto R^2 \).

3.2.1 e-Bubble Mobility and Drift Behavior

In order for the e-Bubble detector to have a reasonable time slot to read out track data in real-time, the drift velocities of the electron bubbles must be slow in the noble liquid. A common unit of measurement to express the motion of charged particles in a liquid is their mobility \( (cm^2/Vs) \). Low mobilities at equilibrium states lead to very small diffusions during the drift lifetime of the electron bubbles (for good for spatial resolution) and low drift velocities. Theoretical expressions for the calculation of mobilities become very complicated, and to some level still have to rely on experimental determination. However, a simple and effective approximation for the mobility of an electron bubble of radius \( R \) is given by [9]

\[
\mu = \frac{e}{4\pi R \eta}
\]

(17)

where \( \eta \) is the viscosity of the liquid. Figure 12 shows the temperature dependence of the electron bubble mobility in LNe, using experimentally determined values of \( \eta \). The e-Bubble group has studied the behaviors of electron bubbles in LNe in various E-Fields and matched results for electron mobility (see section 4.2). The drift velocities of electron bubbles are directly proportional to their mobilities by the relationship

\[
V_d = \mu E.
\]

(18)

Using this ideal theoretical model for LNe, in a 1000 \( V/cm \) field, \( V_d \approx 1.6 \, cm/s \), in a 5000 \( V/cm \) field, \( V_d \approx 8 \, cm/s \), and in a 10,000 \( V/cm \) field, \( V_d \approx 16 \, cm/s \). These drift velocities, along with the density of
LNe, ensure that no ionization avalanching occurs in the medium. Also, the drift velocities of electron bubbles are intimately related to the ability of the detector to read-out the charges as a signal beyond the liquid-vapor interface of the detection medium. The read-out scheme (see section 3.4) will have to involve a configuration so that the ratio of electron bubble arrival times at the liquid surface to the frequency of charge read-out is conducive to high-spatial resolution (i.e. the electron bubble charges are released from the liquid surface frequently during their arrival distribution).

Since the electron bubbles are in thermal equilibrium with their surrounding medium, they obey the Einstein-Nernst equation for thermal diffusion. This equation predicts the expected transverse diffusion of an charged particle in a applied electric field to be

$$\sigma = \sqrt{\frac{2kTd}{eE}}$$

where \(k\) is Boltzmann’s constant, \(E\) is the electric field value and \(d\) is the distance of the drift. Figure 13 shows diffusions for various electric field values in LNe at \(T = 27^\circ K\). These results imply the lack of pointing capability that the e-Bubble detector (with drifts \(\geq 1\) m) will have for low-energy neutrinos leaving recoil electron tracks of lengths on the order of \(\sigma\).

### 3.3 The Trapping of e-Bubbles at the Liquid-Vapor Interface

Due to the difference in dielectric behavior between the liquid and gaseous states of LHe and LNe, the behavior of electron bubbles (and all charged particles, for that matter) at the liquid-vapor interface involves a trapping phenomenon. The Poisson equation

\[\nabla \cdot \mathbf{E} = 4\pi \rho\]

where \(\mathbf{E}\) is the electric field and \(\rho\) is the charge density. If a localized charge in some medium has an electric field applied to it, avalanching occurs when the energy loss by ionization is less than the kinetic energy gain between ionizations due to the acceleration by the field. Such a phenomenon in the detection medium would greatly distort the track during drifting.
\[-\nabla \cdot [D(r) \nabla \phi(r)] = \frac{\rho(r)}{\epsilon_0}\]  

(20)

predicts that a charge near a dielectric discontinuity will induce a repulsive charge in a space dependent on the shape of the discontinuity. In the case of the liquid-vapor interface, the discontinuity is sharp (literally discontinuous) so that the charge in the vapor mirrors the charge of the electron bubble in the liquid. Thus, the electron bubble encounters a potential well near the liquid vapor interface (where the dielectric constant of the liquid \(\epsilon_l > \epsilon_v\) of the vapor) where the trapping phenomenon occurs. When there is a homogeneous electric field applied normal to the liquid-vapor interface, the shape of the potential becomes a function of the field strength,

\[\Phi(x) = \frac{A}{x} + eEx\]  

(21)

where

\[A = \frac{e^2(\epsilon_l - \epsilon_v)}{4\epsilon_l(\epsilon_l + \epsilon_v)}\]  

(22)

is in units of \(K\)\(Å\) and \(x\) is the normal distance from the liquid-vapor interface. The temperature dependence of \(A\) for LNe is shown in figure 14. For LNe, \(\epsilon_l\) has been determined to be a quantity weakly dependent on temperature, so that at 25 \(K\), \(\epsilon_l = 1.19\) and at the critical point \(\epsilon_l = 1.07\) (\(\epsilon_v\) for LNe is effectively 1). In figure 15, equation 21 has been used to represent the shapes of the potential wells at varying electric fields for LNe. Notice that as the strength of the applied electric field increases, the well deepens yet rises closer to the liquid surface; also, the function always has a minimum at \(x_{min} = (A/eE)^{1/2}\). This is the most likely trapping position of an electron bubble. If the potential value at \(x_{min}\) is \(\Phi_{min}\), then the total potential barrier seen by the electron bubble due to its ground state energy \(E_0\) is \(\Delta E = \Phi_{min} - E_0\).

![Figure 14: The temperature dependence of the constant A used in the potential well and trapping time formulations. [9]](image1)

![Figure 15: The shapes of the potential wells at the liquid-vapor interface as plotted in reference [9] at electric fields of 1000 \(V/cm\) and 250 \(V/cm\).](image2)

Due to its quantum characteristics, the electron bubble (instead of being classically trapped in the potential well) has some probability of tunneling through the potential barrier, \(P = \tau^{-1}\) where \(\tau\) is the
trapping time of the electron bubble at the surface. $\tau$ is best described as a function of either electric field or temperature. Schoepe, W. and G.L. Rayfield have developed an elaborate theoretical model for the trapping times of electron bubbles in LHe, and have made accurate experimental measurements of these trapping times [15]; however, such modeling of the trapping phenomenon in LNe requires a modified formulation.

The material specific quantity $\alpha$ plays a key role in predicting the trapping time $\tau$. Where $n$ is the number density of the medium and $l$ is the scattering length,

$$\alpha^2 = 4\pi nl. \quad (23)$$

For LHe, $\alpha$ has been determined to be $0.431 \text{Å}^{-1}$ while for LNe, $l = 0.365 a_0 \text{Å}$ and $n = 0.037 \text{Å}^{-1}$ give $\alpha$ to be $0.299 \text{Å}^{-1}$. Also, for LHe at $T \simeq 1.5 \text{K}$, $A = 1099 K\text{Å}$ and for LNe at $T \simeq 27 \text{K}$, $A = 3044 K\text{Å}$. The probability for electron bubble tunneling in LHe, $P = \tau^{-1}$ is predicted by [15]

$$P(\alpha, R, E, T) \simeq \frac{1}{2} \nu e^{2\alpha R} G(E, T) \times e^{2(\alpha eE)^{1/2}/T} e^{-(8\alpha A/T)}, \quad (24)$$

where

$$G(E, T) = \left(2\tilde{\alpha} \alpha^{7/4} \frac{A^{1/2}}{16(\alpha eE)^{1/2}} \left(1 + \frac{3T}{16(\alpha eE)^{1/2}} \right) \exp \left[ \frac{eE}{\alpha T} \left( \frac{\alpha A}{2T} \right)^{1/2} + \left( \frac{2T}{\alpha A} \right) \right] \right)^{-1} \quad (25)$$

and

$$\nu \simeq \frac{(2E_0/m_e)^{1/2}}{2R} \quad (26)$$

is the semiclassical frequency at which the electron hits the walls of the bubble. Schoepe, W. and G.W. Rayfield’s results were reproduced for LHe by analyzing this equation using the ROOT data analysis software [21] as shown in figure 16. When attempting to analyze the trapping phenomenon of electron bubbles in LNe, problems arose when using this algorithm with direct substitution of the values specific to LNe. In particular, equation 24 exhibits very strong temperature dependence that fails to make the expected predictions at higher (LNe) temperatures. This implies that the formulation of a proper equation for tunneling probability or trapping time should take more medium specific parameters into account.

In recognition of this LHe specific prediction, L. Bruschi et al [10] have taken a more general approach to the problem. They begin with a simpler form of the Smoluchowski equation

$$\tau = \frac{2\pi e}{\mu(\Phi_m' \Phi_0'')}^{1/2} e^{\Delta \Phi/kT} \quad (27)$$

that describes the simple model of tunneling through a potential barrier where $\mu$ is the electron bubble mobility and $\Phi_m'$ and $\Phi_0''$ describe the curvature of the potential $\Phi(x)$ at the minimum and maximum, respectively. Note that neither can be formulated by a direct relationship to $\Delta E$, the height of the potential barrier. They then go on give their equation for the trapping time, formulated using equation 27, value-fitted using experimental results to be

\[\text{This is assuming that we expect some effective trapping time in LNe. Using the } A, \alpha \text{ and } T \text{ values for LNe in equation 24 predict trapping times on the order of } 10^{-20} \text{ seconds in fields strong enough to maintain low diffusion.}\]
\[ \tau = \beta \left[ \exp \left( -\frac{215A^{1/2}E^{1/2}}{T} \right) \right] \]

where the information regarding the charge distribution in at the potential is contained in the term

\[ \beta = \frac{46A^{1/4} \exp (\Phi_0/T)}{\mu(\Phi_0')^{1/2}}. \]

They conclude that a better understanding of the behaviors of the electron bubble charges at the surface, contained in the elements \( \Phi''_m \) and \( \Phi''_0 \), is required to have a more definite prediction of \( \tau \), and that more experimentation is necessary to clarify the behaviors of the electron bubbles at the liquid-vapor interface.\(^8\) By assuming \( \Phi_0'' \) to be constant (not temperature or field dependent) and setting \( \Phi''_m \) to experimental fit values, equation 28 predicts the field dependence of \( \tau \) for LNe at 27 K as shown in figure 17. Clearly, such trapping times are measureable, and certainly seem more realistic(and useful) than those predicted for LNe by equation 24.

\[ \Phi''_0 \text{ constant} \]

Figure 16: Experimental results for the trapping time of electron bubbles in LHe at varying electric fields as a function of temperature. This data was fit using equation 24.

Figure 17: Electric Field dependence of electron bubble trapping times using equation 28 and experimental fit values obtained from reference [10].

### 3.4 Methods of 2-D Detection

If the drift velocities of the electron bubbles in the detection medium are too great or their trapping times at the liquid-vapor interface are too small, the spatial resolution of the detector is lost due to the limitations of the 2-D detection methods. An ideal detection medium would either have a large trapping time so that the charges could be released from the surface by some read-out method (photo-induced or otherwise) or have a very predictable trapping time so that the charge tunneling through the surface would accurately represent their depth in the dimension of the electric field. At the surface of the detection medium, methods are being considered for such read-out schemes. Also, methods for the actual charge detection (charge-amplification and photo-multiplication) are being considered.

---

\(^8\)Current experimentation by the e-Bubble group aims towards such clarification.
Methods of charge-ejection from the liquid surface include acoustic pulsing, photo-ionization and the application of a strong local field at the surface. Previous research by the e-Bubble group has shown the utilities of each, but have been inconclusive to date. Acoustic pulsing would utilize the phenomenon of Raleigh-Taylor instabilities present in the detection environment, and eject the charges by exploiting the instabilities inherent between the electron bubble and the noble liquid by disturbing them with an acoustic pulse. Photo-ionization would utilize the fact that electron bubble states are physically large and hence are very susceptible to excitations by external sources. Incident gamma-rays at the liquid surface would provide enough energy to the electron bubbles to release them from the potential well. Finally, configuring a strong field at the liquid-vapor interface would lower the electron bubble trapping times (due to their field dependence) to be effectively zero. Physical problems with this method include the interaction of the electron bubbles with the field anodes that would distort the resolution of the track.

Whatever method is used to release the charges from the liquid, some amplification process must be applied on order to turn the small amounts of charge into measurable quantities. Gas Electron Multipliers (GEMs) have been considered for such a task. The GEM, which would be placed just above and parallel to the liquid surface, are silicon wafers with thin conductive sheets on either side of them. Because the silicon is in insulator, when a potential difference (400 V) is applied across the GEM (25µm width) dense field lines are produced through the holes in the GEM (40 µm) as illustrated in figure 18. When a negative charge carrier passes through this GEM, self-interactions produce excesses of photons and negative charges... the GEMs have been shown to produce electrical gains up to 1000× in noble gases. Also, the light produced by GEMs can be utilized as a low temperature method of detection by using high-resolution photo-capture. The GEMs have resolution down to $10^7\, m^{-2}$, thus a mechanism to detect the amplification from GEMs would have to match this resolution. The most likely proposition to date for such a detector is the use of commercial CCD cameras at 1 MPixel each to observe the light emitted by the GEM amplifications in real-time. These cameras could sit a lower temperatures and read-out the GEMs from a workable distance.

![Figure 18: The field lines of a GEM foil. Region 1 represents the homogeneous drift field and region 2 represents the location of the avalanche process. [16]](image1)

![Figure 19: This is a Garfield [20] simulation of an avalanche event occurring in a GEM foil. [8]](image2)
4 Research and Results

4.1 Test Chamber

Purpose
A small scale prototype of the proposed e-Bubble chamber has been the greatest tool during the Research and Development stage. This prototype, the test chamber, was designed to provide a "proof of principle" for the large scale e-Bubble detector. The test chamber enables the study of electron drifts through many media including LNe and LHe. Measurements of many electron bubble drift properties including velocity, mobility, drift time, and signal shape were extracted from such drifts. The test chamber will continue to be used to test the experimental and theoretical e-Bubble detector design.

Design
During operation the test chamber is enclosed in a cryostat. The chamber is cooled using liquid helium and liquid nitrogen. The complex cooling method is monitored by over a dozen temperature sensors. The chamber pressure is also monitored. There are 3 optical windows, 2 along the side and one on the bottom, of the chamber. In total the test chamber is about 7" in diameter and 8" tall.

Certainly the neutrino interaction rate is insufficient to study electron bubble drifts inside the test chamber. As an alternative several sources have been proposed to either inject or ionize electrons within the test chamber in order to study the ensuing drifts. These alternatives include a photo-cathode, radioactive alpha source, and a high-voltage or field emitting tip.

4.2 Experimental Run

The e-Bubble group conducted an experimental run between the dates of June 20, 2005 and June 24, 2005. The run was conducted using a LNe drift medium. The primary goal of the run was to determine which electron source was most effective for studying electron bubble drifts in the test chamber. Measurements of electron bubble drift velocity, mobility, and liquid-gas interface trapping time were also attempted. Figure 20 displays a basic schematic of the test chamber used during the late June, 2005 run.

4.2.1 Photo Cathode

A photo-cathode was the first electron source which was tested in the test chamber. The photo-cathode was unsuccessful in LNe.

As diagramed in the lower section of Fig 20, the photo-cathode made use of the optical window on the bottom of the test chamber. A gold plate (80 angstroms wide) was located inside the chamber that emitted electrons via the photo-electric effect when the photo-cathode was in operation.

The photo-cathode had proven to successfully emit electrons within gNe at 3 atm and 30 K. Signal amplitudes were measured to range between 20 and 120 mV as the applied potential ranged from 500 to 1200 V accordingly.

The neon was liquefied very slowly. When the liquid rose above the anode the high voltage on the photo-cathode was maximized (-9.6 kV). No signal was observed.
4.2.2 High Voltage Tip

A high voltage tip (HVT) proved to be the most effective electron source tested during the run in late June, 2005. The HVT, as shown in the upper section of figure 20, consisted of three regions; emission, drift, and collection. The tungsten tips, (photos included in Appendix B), were located within the 3.5 mm emission region which was formed by a copper cathode on the lower bound and a wire mesh on the upper bound. As shown in figure 20, the tip was configured horizontally 1.5 mm below the mesh. The drift region was 5 mm and the collection region was 1 mm. The tip was approximately 1 micron in diameter at the point.

Measurements were taken with a large vapor pressure on the liquid-gas interface in order to suppress gas bubble formation. The tip was pulsed with a high voltage and electron bubbles were drifted through the drift region and collected at the anode. Measurements of drift time, velocity, mobility, tip charge emission, and mesh transparency were made. Specific data is located in the Appendix.

Experimental Drift Time

Figure 21 displays the dependance of drift time on the electric field in the drift region. The data is located in A. The plot is fitted using,

\[ t_d = \frac{1}{\mu} \left( \frac{d_d}{E_d} + C \right) + t_0 \]  

where \( t_d \) is the measured drift time (ms), \( d_d = 0.5 \) is the drift distance (cm), and \( E_d \) is the electric field in the drift region (V/cm). The fit parameters are \( \mu \), the mobility (cm²/V s), \( C \), the overestimate of drift time due to the drift in the tip and anode regions, and \( t_0 \), a parameter that could represent any systematic shift in the measured times due to pulse broadening or other shifts resulting from the electronics (ms).

Despite the large \( \chi^2 \) value the drift time data is encouraging. Many approximations were used for the theoretical prediction. Most notably, the theory approximates the entire drift by only using the drift region (therefore neglecting the emission and collection regions). Secondly, the data points for low fields (0 to 4
Figure 21: Measured drift time as a function of drift field for all drift time measurements. The length of the high voltage pulse (V_{pulse} = -1.5 kV) was 2 ms. Note: \( t_0 = C = 0 \).

\( kV/cm \) have a slightly different voltage setting than those for high fields (4 to 8 \( kV/cm \)). When analyzed independently, considering nontrivial combinations for \( t_0 \) and \( C \), the \( \chi^2 \) values are reduced to approximately 11 for low fields and 0.5 for high fields. Also the derived mobility varies slightly (See Appendix A). (Note that a more precise drift time prediction is located in 4.3, 4.3.2,'Drift Time'.)

**Experimental Mobility**
The fit used for figure 21 yields an electron bubble mobility of \( 1.6 \times 10^{-3} \text{ cm}^2/\text{V s} \). This derived mobility is in excellent agreement with results from Storchak, Brewer, and Morris [18]. However, this mobility calculation makes many approximations, as explained in 'Drift Time'. (A mobility of \( 1.9 \times 10^{-3} \text{ cm}^2/\text{V s} \), which also agrees with Storchak, Brewer, and Morris, is calculated by a more precise method in 4.3.2).

**Experimental Drift Velocity**
The electron bubble drift velocity was calculated to be 6.64 cm/s. This velocity is directly related to the mobility and electric field according to equation 31.

\[
V = \mu E
\]

(31)

Where \( \mu \) is the mobility in \( \text{cm}^2/\text{V s} \) and \( E \) is the electric field in \( \text{V/cm} \). For this calculation \( \mu \) was \( 1.66 \times 10^{-3} \text{ cm}^2/\text{V s} \) and the drift electric field was 4000 V/cm.

**Experimental Tip Charge Emission**
The charge emitted from the tip is dependant on the tip voltage and the pulse width applied to the tip. Figures 22 and 23 display the dependence.

The charge magnitude was calculated using equation 32,

\[
Q = q \frac{A \Delta T}{a \Delta t}
\]

(32)
where $32Q$ is the total charge (MeV) and $q$ is the charge injected by the pulse (MeV). $A$ is the measured amplitude (mV) and $a$ is the amplitude of the calibrated pulse voltage (mV). $\Delta T$ and $\Delta t$ are the measured signal and calibration pulse full width at half maxima (FWHM) respectively (ms). Figures 22 and 23 use calibration values: $q=10$; $a=14.6$; and $\Delta t=.222$.

**Experimental Mesh Transmission**
The electron bubble transmission through the mesh varied according to the ratio of the field in the drift region and the field in the anode (collection) region. Figure 24 displays the transmission.

**Experimental Trapping Time Measurement**
After measuring the drift times (while the anode was submerged in LNe) the liquid neon level was lowered below the frisch grid (see figure 20) to a location in the drift region. Overpressure was maintained in order to suppress gas bubbles. The overpressure also liquefied the neon gas, gradually raising the liquid level. With the liquid level well below the frisch grid no correlated signal was seen. The liquid level rose and suddenly a correlated signal appeared. The liquid level appeared to reach the bottom of the anode. This procedure was repeated and the liquid level was monitored more closely. Again, no signal existed when the liquid level was significantly below the frisch grid. However, a correlated, anti-symmetric signal was
observed as the liquid level approached the frisch grid support. Although the liquid level appeared to be below the frisch grid it was suggested that the meniscus could have possibly created a contact.

The few data points which were recorded are presented in Table 2.

<table>
<thead>
<tr>
<th>$V_{\text{frisch}}$ (kV)</th>
<th>$V_{\text{cathode}}$ (kV)</th>
<th>$V_{\text{mesh}}$ (kV)</th>
<th>$V_{\text{tip,DC}}$ (kV)</th>
<th>LNe Drift Time (ms)</th>
<th>Peak Time (ms)</th>
<th>FWHM (ms)</th>
<th>$\tau_{\text{rise}}$ (ms)</th>
<th>$\tau_{\text{fall}}$ (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.8</td>
<td>-4.0</td>
<td>-3.3</td>
<td>-6.0</td>
<td>55.3</td>
<td>89.5</td>
<td>52.7</td>
<td>27.3</td>
<td>120.0</td>
</tr>
<tr>
<td>-0.8</td>
<td>-4.0</td>
<td>-3.3</td>
<td>-5.1</td>
<td>55.3</td>
<td>78.4</td>
<td>33.8</td>
<td>25.5</td>
<td>51.6</td>
</tr>
<tr>
<td>-0.8</td>
<td>-4.5</td>
<td>-3.8</td>
<td>-5.8</td>
<td>46.1</td>
<td>65.5</td>
<td>33.6</td>
<td>26.4</td>
<td>37.3</td>
</tr>
<tr>
<td>-0.8</td>
<td>-3.5</td>
<td>-2.8</td>
<td>-5.1</td>
<td>69.1</td>
<td>81.5</td>
<td>43</td>
<td>28</td>
<td>40</td>
</tr>
</tbody>
</table>

Table 2: First trapping time measurements in LNe. The anode was at ground and the tip was pulsed at $V=-1.7$ kV for 1 ms. The LNe drift time column is the predicted drift time should the anode be entirely submerged in LNe, according to the average mobility ($1.65 \times 10^{-3}$ cm$^2$/Vs) extracted from the fits to our mobility drift time measurements. This prediction ignores the emission and collection regions.

**Experimental Electron Ejection Dynamics**

The signal shape was wider and displayed a more significant tail than expected. The e-Bubble group hypothesized that the tip was emitting electrons with some initial kinetic energy. As a result the electrons emitted in a downward direction would travel against the electric field for some time before beginning to drift toward the anode. The signal would be wider and contain a significant tail. This situation prompted the e-Bubble group to erect the high voltage tips vertically in sequential runs (late July, 2005) in order to distribute ejected electrons more uniformly.

In addition, this odd behavior motivated the group to begin photographing the tips (using an electron...
microscope) to assess the deformities that the tips obtained during operation. These photos are available in Appendix B.

Finally, the electron ‘ejection’ is approximated using specific circular patterns for electron drift starting points in simulations displayed in Appendix B.

4.2.3 Radioactive Alpha Source

A radioactive alpha source was also proposed as a source of drift electrons. Alpha particles emitted from the source ionize electrons in the drift medium which would consequently form electron bubbles enabling drift measurements. The alpha source has not yet been tested. However, the alpha source may be capable of providing a direct current (DC) to the anode. With a consistent and well understood alpha source the e-Bubble group would be able to take advantage of a DC to study the liquid-gas interface trapping time of electron bubbles in various media. Trapping time can be determined by measuring the exponential decay of the current when the alpha source is “turned off” (“turning off” the alpha source would be accomplished by configuring electric fields in such a manner to block electron bubble drifts within the liquid medium.)

4.2.4 Experiment Conclusions

The experimental run in late June, 2005 succeeded to determine an effective electron source for the test chamber. The high voltage tip was successful. The photo-cathode, as expected, was not successful. In addition, the group’s understanding of electron bubble mobility and velocity were confirmed. The group also extracted information about the charge emitted from a tip and mesh transmission. However, the group was presented with several new obstacles. Most notably the group struggled to eliminate gas bubble formation in the test chamber. Overpressure was an immediate solution but a more static solution is desirable. Secondly, the trapping time measurements were not definitive. The group will continue to study the neon liquid-vapor interface via trapping time measurements.

4.3 Simulations

Many simulations of the experimental run were created using Garfield. Example source code located in Appendix C.

4.3.1 Garfield Overview

Garfield is a program which facilitates the simulation of drifting electrons or ions in the presence of electric and magnetic fields. Garfield is designed for gaseous drifting media. There are 9 “sections” of Garfield, however only the 5 relevant sections will be outlined here. In addition there are many “call” commands which will execute a specific task; such as drifting an electron from a certain starting location using Monte Carlo integration. An example of a Garfield program is located in Appendix C.

Garfield Cell

Cell section enables the user to specify the cell geometry. Garfield cells used for e-Bubble studies were all in 2-D. The user defines dimensions and voltages on the components of the cell.

Garfield Gas

The Gas section of Garfield allows the entry of a gas definition into the previously defined cell geometry. The gas entered will be the drift media. This section usually invokes the Magboltz and Heed programs to
calculate electron or ion drift properties.

**Garfield Field**
Field displays plots of the defined cell. Examples of plots that can be created using Field include electric field vector plots, electric field contour plots, and surface plots.

**Garfield Drift**
Electrons and ions can be drifted using the Drift section. There are several different ways to drift particles. The options include flexible starting points, integration methods (Monte-Carlo or Runge-Kutta-Fehlberg), and determining which physical characteristics (such as mean free path) to include in the drift calculations.

**Garfield Signal**
The Signal section produces simulated signals which would result from the drifting of electrons or ions. The user must specify the anodes to be considered and a time window. The time window sets a duration over which the signal is summed. The program will then compute the direct and induced current for selected anodes.

### 4.3.2 Garfield Results
The e-Bubble group was able to create a basic Garfield cell (figure 25) which very closely mimicked the actual test chamber (in 2-D). Several simulations were conducted using variations of the cell geometry in figure 25, accompanied by voltage definitions, and extended Garfield functions.

![Vector plot of EX, EY, EZ](image)

**Figure 25:** General cell geometry used for the majority of Garfield simulations.
Simulated Drift Time

Figures 26 displays the mean drift time for the simulation; 76.85 ms. The recorded drift time is 76 ms. A drift time prediction results in a drift time of 78.5 ms (this prediction uses a 0.5 cm drift region distance, 0.1 cm emission distance, and a .1 cm collection distance under fields of 8600 kV/cm, 4000 kV/cm, and 8000 kV/cm respectively). The drift times used in figure 26 are extracted from drift lines such as those in figure 28. The prediction geometry is identical to the simulated geometry. The equation used for the predicted drift time is located in Appendix D.

Figures 26 and 28 use electron bubble drifts that all begin at a common emission point. In the simulation electron bubble mobility is set to $1.9 \times 10^{-3} \text{ cm}^2/\text{V} \cdot \text{s}$ and the electric fields ($V/cm$) are: emission field= 8600; drift field= 4000; anode field= 8000. Longitudinal diffusion is set to 0 by default and the transverse diffusion is set to $.01 \text{ cm/cm drift}$. 

Simulated Mobility

Figures 26 and 27 display the effect of varying mobility in the Garfield simulation on the total drift time. The recorded drift time measurement at 4 $kV/cm$ is 76 (ms) which gives evidence of an electron bubble mobility equal to $1.9 \times 10^{-3}$. Both plots also match the theoretical drift time predictions closely as displayed in Table 3. Predicted drift time calculations include the emission and anode regions. The predicted drift time equation is included in the Appendix D.

Simulated Diffusion

Signal widening and reduced amplitude are effects of increased electron bubble diffusion (in simulation and in reality). In simulation, longitudinal and transverse diffusion affect the result of electron bubbles drifts. Specifically, when the diffusion is large the probability of reaching the anode decreases. However, the drift time and signal width are relatively uneffected when the diffusion (longitudinal or transverse) remain under a certain threshold. If this threshold is crossed then many of the electron bubbles do not reach the anode and, as a result, the time histogram is drastically altered. This effect is notable in figures 29 and 30. It should be noted that an observer, in reality, is blind to the end-point of electron bubble drifts that do not hit the anode. As a result the signal observed would not be altered as drastically.

Specific histograms and drift plots for several diffusion combinations are included in Appendix D. The data for figures 29 and 30 are also included in Appendix D.

Simulated Signal Analysis

Figure 31 displays the signal which was compiled from simulating the drifts of 80 electron bubbles. The relevant portion of the garfield code is located at the end of Appendix C. The signal displays a interesting double peak shape.

The signal (and signal code) is the first step to enabling e-Bubble to study the effects of various parameters (such as mobility,electric field, etc) on the signal shape via the Garfield program.
Table 3: Mobility dependence of theoretical and simulated drift times

<table>
<thead>
<tr>
<th>Mobility $cm^2/Vs$</th>
<th>Theoretical Drift Time (ms)</th>
<th>Simulated Drift Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.6 \times 10^{-3}$</td>
<td>93.2</td>
<td>91.29</td>
</tr>
<tr>
<td>$1.9 \times 10^{-3}$</td>
<td>78.5</td>
<td>76.85</td>
</tr>
</tbody>
</table>
5 Conclusion

Much progress has been made in the Research and Development of the e-Bubble Detector. The possibilities of using LNe as a detection medium are now much better understood due to theoretical investigations and experimentation. Our experimental run provided many answers, but opened the door for twice as many new questions. The results include the discovery that the photo-cathode did not operate in LNe, confirmation that electron bubble mobility in LNe is between $1.6 \times 10^{-3}$ and $1.9 \times 10^{-3}$ cm$^2$/Vs, a derivation of an electron drift velocity of 6.64 cm/s, high voltage tip charge emission properties and mesh transmission as a function of relevant ratio of fields. Questions were raised regarding the liquid-vapor interface trapping time in LNe, gas bubble suppression, high voltage tip durability and electron ejection dynamics (specifically
initial kinetic energy).

The Garfield simulation proved to be a useful tool for the e-Bubble analysis. Electron bubble drifts were successfully simulated with user defined mobilities. The simulated drift data closely matched the data taken from experimental drifts. Additionally, information regarding electron bubble diffusion in LNe was extracted. Simulated signals may also become very useful in the near future.

The Research and Development of the e-Bubble group will continue with the decision of a detection medium to use in the final detector. In the mean time, further measurements in LNe must be made, including an accurate trapping time measurement. Then the implementation of a 1 m\(^2\) protocol will provide further simulation and proof of principle as the larger scale functions are investigated.

6 Acknowledgments

We would like to recognize the generosity of our advisors Dr. Jeremy Dodd and Dr. Raphael Galea, and thank them for their enormous influence and help. Also, we would like to thank the project coordinator Dr. William Willis, the cryogenics expert Dr. Yonglin Ju and the other collaborators Dr. Valeri Tcherniatine and Dr. Pavel Rehak. Finally, for the honor of participation in the Columbia University REU at Nevis Labs, we owe our thanks to Dr. John Parsons and the National Science Foundation.
### A Experimental Data

<table>
<thead>
<tr>
<th>Drift Region Electric Field (kV/cm)</th>
<th>Drift Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>199.3</td>
</tr>
<tr>
<td>2.4</td>
<td>131.5</td>
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<td>7.2</td>
<td>44.8</td>
</tr>
<tr>
<td>8.0</td>
<td>41.5</td>
</tr>
</tbody>
</table>

Table 4: Experimental Drift Time Data (Note that voltage settings varied slightly for low fields and high fields, variation begins between the 4.4 kv/cm data points.

![Figure 32: Drifttimeplot1](image-url)
Figure 33: Drifttimeplot2

Figure 34: Drifttimeplot3
B  Electron Starting Points

Figure 35: Circle drift starting pattern.

Figure 36: Track drift starting pattern.

Figure 37: GoodTip.

Figure 38: BadTip.
C Garfield Program

// Creates a cell containing a series of planar anodes similar to those used for
// eBubble runs in late June, sets ion mobility,
// drifts negative ions, computes signals, sums signals and writes drift data to histograms.

!add meta type PostScript file-name "plots/lastcell_senseplanar_transplotsdiff1.ps"
!open meta
!act meta

// Determines what files are used
Global cell_file ‘cell_files/NEONCELLSENSEPLANARFINAL.DEFAULT’
Global gas_file ‘gas_files/NEON_SAT.DAT’
Global iter = 12 //set the number of times settings are changed & program re-run
for q from 1 to {iter} do
Global plotnum = {q}

**********************************************************************************
//Define cell
&cell

Call inquire_file(cell_file,exists)
If exists Then
get {cell_file}
Say "Cell definition taken from {cell_file}." Else
//User sets fields (V/cm)
Global Fieldbot = 4000
Global Fieldtop = 8000

//User Set distances
Global yCath = 1
Global Cathtomesh = .35
Global meshtoAn = .6

//Program Calculates voltages
Global An = 0
Global mesh1 = {An} - {Fieldtop}*{meshtoAn}
Global Cath = {mesh1} - {Fieldbot}*{Cathtomesh}
Say "Vmeshbot={mesh1},VCathode={Cath},VAnode={An}."

//Establish cell geometry
plane y {yCath} V={Cath}
rows
p 112 .005 -2.8+i*0.05 {yCath}+{Cathtomesh} {mesh1}
s 110 0.0050 -2.8+i*.0525 1.95 {An}
p 110 0.0075 -2.8+i*.0525+0.00875 1.95 {An}-320
p 110 0.0075 -2.8+i*.0525-0.00875 1.95 {An}-320
p 110 0.01 -2.8+i*.0525+0.02 1.95 {An}-400
p 110 0.01 -2.8+i*.0525-0.02 1.95 {An}-400

opt wire-markers
write {cell_file}
Say "cell data written too {cell_file}.
Endif

******************************************************************************
//plots vector and contour field
&field
area -3 1 3 2.5
plot vector
//plot contour
//area -.5 1.5 .5 2.0
//plot vector
area -.05 1.8 .05 2.0
plot vector

******************************************************************************
// Add gas
&gas
Call inquire_file(gas_file,exist)
If exist Then
get {gas_file}
//Defines the mobility
Global mob=1.6 //units V/cm and cm2/V*sec (truncated)
Vector E_NE mu_NE
0  {mob}
385  {mob}
770  {mob}
115  {mob}
1540  {mob}
1920  {mob}
230  {mob}
2690  {mob}
3070  {mob}
3460  {mob}
3840  {mob}
4225  {mob}
4609  {mob}

// conversion to cm^2/V* microseconds
Global mu_NE = mu_NE*1e-9

// Add the electron mobility to gas file
add ion-mobility mu_NE vs E_NE

// Set the various longitudinal diffusions
Global longdiff1 = .00001
Global longdiff2 = .00005
Global longdiff3 = .0001
Global longdiff4 = .0005
Global longdiff5 = .001
Global longdiff6 = .005
Global longdiff7 = .01
Global longdiff8 = .05
Global longdiff9 = .1
Global longdiff10 = .5
Global longdiff11 = 1.0
Global longdiff12 = 5.0

// Set ion transverse diffusion
Global longdiff = .001 // cm of diff per cm
Global trandiff = longdiff{q} // cm of diff per cm
parameters LONG-ION-DIFFUSION {longdiff}
parameters TRANSVERSE-ION-DIFFUSION {trandiff} // cm of diffusion over 1 cm drift
Say "longdiff = {longdiff} and trandiff = {trandiff}"

// Write gas file
// write gas_file/NEON_SATMOB2.DAT
Say "Gas definition taken from {gas_file}."
Else
     temperature 30 K
     pressure 3 atmosphere
     magboltz neon 100 electric-field-range 1 1000 mobility
     heed neon 100
     write neonmob.dat
     Say "Gas definition file saved as neonmob.dat."
     &main
     write {gas_file}
     Say "Gas definition saved to {gas_file}."
Endif

//make plots of gas properties
options gas-plot gas-print
plot-options drift-velocity

*******************************************************************************
// calculate drift
&drift
area -3 1 3 2.5 // x-min y-min x-max y-max
int-par mc-dist-int .001 //sets the distance between interactions(cm) (10 micron default)
call plot_drift_area

//Creates histograms
call book_histogram(timehist,100,50000,90000)
call book_histogram(timehist2,150,0,150000)
call book_histogram(xposhist,100,-2.5,2.5)
call book_histogram(yposhist,100,0,2.2)
call book_histogram(pathlength,200,0.6,1.)
call book_histogram(stat,18,1,19)
call book_histogram(steps_hist,100,500,900)

//User defined inputs for the drift and signal analysis
Global strttime = 60000 // signal computation start time (microseconds)
Global numoftimes = 1000 //number of time steps in signal computation
Global timeint = 15 //size of time steps (microseconds) in signal comp.
Global numdrift = 1 // number of different ion drift starting points
Global numions = 1 // number of ions drifted at each starting point

//book matrices for signal analysis
Call book_matrix(direct,1000)
Call book_matrix(direct_sum,1000)
Call book_matrix(times,1000)
//for t from 1 to {numdrift} do
//call book_matrix(direct{t},1000)
//endo

//Drift ions, plot drift lines, fill histograms
//double for loop iterates the ion's starting position
for u from 1 to 500 do // # of different starting points
  for i from 1 to 1 do // # of ions drifted from each point
    &drift
    //Convert polar coordinates to create a circular ring to begin drifts
    CALL POLAR_TO_CARTESIAN(.00,u*11,x,y) // (radius, angle, x, y)
    call drift_mc_negative_ion(x,1.25+y,0,status,time) // (x-start, y-start, z-start, status, time)
    call plot_drift_line
    Say "time is {time}.")
    //Selects data from drifts which finished
    //If 'status='Calculations abandoned'' Then
    //Say "Time omitted."
    //Else
    call fill_histogram(timehist,{time})
    call fill_histogram(timehist2,{time})
    //endif
    call drift_information('x-end',x)
    Say "x-pos is {x}.")
    call fill_histogram(xposhist,{x})
    call drift_information('y-end',y)
    Say "Y-End is {y}.")
    call fill_histogram(yposhist,{y})
    call drift_information('path-length',pl)
    Say "path length is {pl}.")
    call fill_histogram(pathlength,{pl})
    call drift_information('steps',steps)
    Say "Step # is {steps}.")
    call fill_histogram(steps_hist,{steps})
    //Create histogram values for status (individual wires must be specified)
    Say "status is {status}.")
    If 'status='Left the drift area'' Then
      Call fill_histogram(stat,1)
    Elseif 'status='Too many steps'' Then
      Call fill_histogram(stat,2)

Elseif 'status='Calculations abandoned'' Then
    Call fill_histogram(stat,3)
Elseif 'status='Hit a plane'' Then
    Call fill_histogram(stat,4)
Elseif 'status='Left drift medium'' Then
    Call fill_histogram(stat,5)
Elseif 'status='Left the mesh'' Then
    Call fill_histogram(stat,6)
Elseif 'status='Hit the minimum x plane'' Then
    Call fill_histogram(stat,7)
Elseif 'status='Hit the maximum x plane'' Then
    Call fill_histogram(stat,8)
Elseif 'status='Hit the minimum y plane'' Then
    Call fill_histogram(stat,9)
Elseif 'status='Hit the maximum y plane'' Then
    Call fill_histogram(stat,10)
Elseif 'status='Hit p wire N'' Then
    Call fill_histogram(stat,11)
Elseif 'status='Hit a replica of p wire N'' Then
    Call fill_histogram(stat,12)
        ElseIf 'status='Hit S wire 163'' Then
            Call fill_histogram(stat,13)
        ElseIf 'status='Hit S wire 164'' Then
            Call fill_histogram(stat,13)
        ElseIf 'status='Hit S wire 165'' Then
            Call fill_histogram(stat,14)
        ElseIf 'status='Hit S wire 166'' Then
            Call fill_histogram(stat,15)
        ElseIf 'status='Hit S wire 167'' Then
            Call fill_histogram(stat,16)
        ElseIf 'status='Hit S wire 168'' Then
            Call fill_histogram(stat,17)
        ElseIf 'status='Hit S wire 169'' Then
            Call fill_histogram(stat,18)
Else
    Call fill_histogram(stat,19)
    Say "Shit!!!!!!!"
Endif

//Signal Analysis
//&Signal
//aval fixed 1 //Amplification factor for avalanche
//window {strttime} {timeint} {numoftimes} //time window (start, steps, #ofsteps)
//sel (s) //wires to be analyzed
//call add_signals //Constructs signal from drift
//call get_signal(1,times,direct,cross) //gets signal data and puts in 1-D matrices
// Global direct{u} = direct
// Write-signals dataset "signal_{u}.list"
// Say "signal written to 'signal_{u}.list'"
// Plot-signals wire all // plots a single drift signal
call plot_comment('up-right', 'longdiff={longdiff},transdiff={trandiff}')
// Say "drift # {u} of {numdrift}.
// Call plot_end
enddo

// Global direct_sum = direct1 // Essentially initializes "direct_sum"
// for v from 2 to {numdrift} do // Loop sums the signals from all drifts
// Global direct_sum = direct_sum + direct{v}
// enddo
// Call plot_graph(times, direct_sum) // plot on X-Y graph
// Call plot_end

// Plots all histograms and writes histograms to ".rz" files
call plot_histogram(timehist, 'time t [microsec]', 'time')
call plot_comment('up-left', 'longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left', 'mobility=(mob)E-3cm/V*s')
// Call write_histogram_rz(timehist, 'plots/hist/difftimehist(plotnum).rz', 'Time Histogram')

call plot_histogram(timehist2, 'time t [microsec]', 'time')
call plot_comment('up-left', 'longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left', 'mobility=(mob)E-3cm/V*s')
// Call write_histogram_rz(timehist2, 'plots/hist/difftimehist2(plotnum).rz', 'Time Histogram')

call plot_histogram(yposhist, 'y-end [cm]', 'y-end')
call plot_comment('up-left', 'longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left', 'mobility=(mob)E-3cm/V*s')
// Call write_histogram_rz(yposhist, 'plots/hist/diffyposhist(plotnum).rz', 'Y Position Hist')

call plot_histogram(xposhist, 'x-end [cm]', 'x-end')
call plot_comment('up-left', 'longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left', 'mobility=(mob)E-3cm/V*s')
// Call write_histogram_rz(xposhist, 'plots/hist/diffxposhist(plotnum).rz', 'X Position Hist')

call plot_histogram(pathlength, 'path length [cm]', 'pl')
call plot_comment('up-left', 'longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left', 'mobility=(mob)E-3cm/V*s')
// Call write_histogram_rz(pathlength, 'plots/hist/diffpathlength(plotnum).rz', 'Path Length')

call plot_histogram(steps_hist, '# of steps', 'steps')
call plot_comment('up-left', 'longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left', 'mobility=(mob)E-3cm/V*s')
//Call write_histogram_rz(steps_hist,'plots/hist/diffstepshist{plotnum}.rz','Number of Step Events')

call plot_histogram(stat,'# w/ Status','Status')
call plot_comment('up-left','longdiff={longdiff},transdiff={trandiff}')
call plot_comment('down-left','mobility={mob}E-3cm/V*s')

//Call write_histogram_rz(stat,'plots/hist/diffstatushist{plotnum}.rz','Status of drifts')

enddo

!deact meta
!close meta
!del meta
D  Garfield Data and Calculations

\[ t_{total} = \left( \frac{1}{\mu} \left( \frac{d_e}{E_e} \right) \right) + \left( \frac{1}{\mu} \left( \frac{d_d}{E_d} \right) \right) + \left( \frac{1}{\mu} \left( \frac{d_a}{E_a} \right) \right) \] (33)

In equation 33, \( t_{total} \) gives total drift time where \( E_e \) is the emission field, \( E_d \) is the drift field, and \( E_a \) is the anode field. Similarly, \( d_e \) is the emission distance, \( d_d \) is the drift distance, and \( d_a \) is the anode distance. \( \mu \) is 1.9\(^{-3}\) in \( \frac{cm^2}{Vs} \).

Figure 39: Time histogram for various diffusion. (diffusion in \( \frac{cm}{cm_{drift}} \))

<table>
<thead>
<tr>
<th>LongDiff ( \frac{cm}{cm_{drift}} )</th>
<th>TransDiff ( \frac{cm}{cm_{drift}} )</th>
<th>Mean Drift Time (ms)</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>ruleOpt3ex 1. ( \times 10^{-5} )</td>
<td>.001</td>
<td>68827</td>
<td>1945.77</td>
</tr>
<tr>
<td>.00005</td>
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<td>68729</td>
<td>1986</td>
</tr>
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<td>.001</td>
<td>68926</td>
<td>2002.56</td>
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<td>68915</td>
<td>2117.93</td>
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<td>.001</td>
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<td>28078.6</td>
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<tr>
<td>.5</td>
<td>.001</td>
<td>32302.4</td>
<td>32146</td>
</tr>
<tr>
<td>1</td>
<td>.001</td>
<td>17139.7</td>
<td>22586</td>
</tr>
<tr>
<td>5</td>
<td>.001</td>
<td>3698</td>
<td>11839.4</td>
</tr>
</tbody>
</table>

Table 5: Data used for figure 29
Figure 40: Time histogram for various diffusion. (diffusion in $cm$/$cm_{drift}$)

<table>
<thead>
<tr>
<th>LongDiff ($cm$/$cm_{drift}$)</th>
<th>TransDiff ($cm$/$cm_{drift}$)</th>
<th>Mean Drift Time (ms)</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>.001</td>
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<td>75860</td>
<td>5535</td>
</tr>
<tr>
<td>.001</td>
<td>.001</td>
<td>71641</td>
<td>2226.7</td>
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<tr>
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<td>.001</td>
<td>68788</td>
<td>1791.2</td>
</tr>
<tr>
<td>.001</td>
<td>.005</td>
<td>68142</td>
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<tr>
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<td>.01</td>
<td>68623</td>
<td>2106</td>
</tr>
<tr>
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<td>.05</td>
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</tr>
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</table>

Table 6: Data used for figure 30
References


