# Recombination in Liquid Argon

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## Introduction

The primary goal of the eBubble working group this summer has been to obtain a Townsend avalanche of electrons, or charge multiplication, at the anode of an electrode structure in a liquid argon cryostat. Our cathode is a Polonium plated pin, which emits alpha particles that ionize the argon atoms. The electrons produced by this ionization are then propelled to the anode by the electric field. In order to obtain an avalanche, we want to ensure that the greatest number of electrons reach the anode as possible. Recombination-- the capture of free electrons by positive ions--is an effect that reduces the probability of an avalanche. Therefore, it is imperative that we study the effects of recombination in our liquid argon cryostat.

## Recombination Theory

Recombination rates of a given particle are determined both by the particle's ionization density and by the external electric field. The more densely ionizing a particle is, the more susceptible it is to recombination. On the other hand, the rate of recombination will decrease as the external electric field increases.

Furthermore, we are concerned with two different forms of recombination: initial and columnar. *Initial* recombination is the recombination of a charged particle with its parent ion, whereas *columnar* recombination involves all of the ions created by one ionizing particle.[1]

A thorough and accurate theory of recombination was difficult to locate. Jaffe computed the effects of columnar recombination in 1913, and Onsager purported the first theory of initial recombination in 1938. Onsager's theory is based upon two primary assumptions. One is that the ion and electron are spatially separated, and the second is that an infinite range Coulomb force is the mode by which ions and electrons interact. In 1987, Thomas and Imel outlined a more accurate model of recombination. In their paper they show that, though Onsager's theory is good for low fields, their model is a better fit to current data. Specifically, they assert that Onsager's second assumption is not valid because he neglects the effects a high coefficient of polarization has on the effective charge of an ion. This effect plays an important role in argon because of its high coeffecient of polarization. The conclusion of their complex recombination calculations is Equation 1, which describes the fraction of charge collected.

$$Q/Q_0 = (1/\xi) \ln (1 + \xi), \quad \xi = (N_0\alpha)/(4a^2u_E)$$

Equation 1. The fraction of charge collected.[2]

For recombination along an electron track in liquid argon, $\xi E = .84$ kV/cm. $\xi E$ must be much greater for an alpha particle in liquid argon, however, because of the particle's high ionization density. Specifically, $\xi E = 470$ kV/cm for an alpha particle track.[2]

Figures 1 and 2 depict the total charge collected as a function of electric field for an alpha particle and for an electron, respectively.

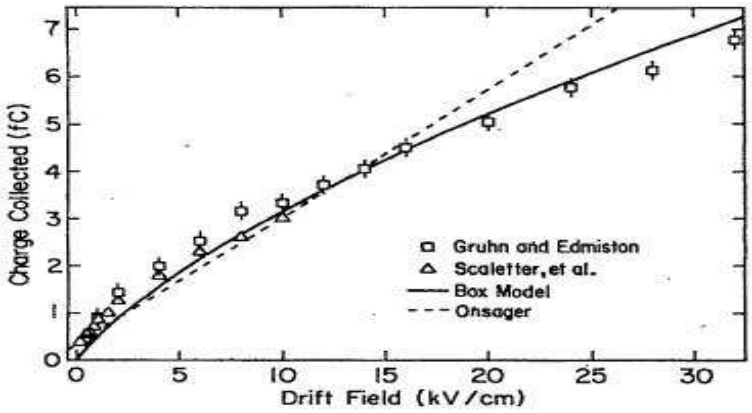


Figure 1: Charge collected versus drift field for alpha particles in liquid argon.[2]

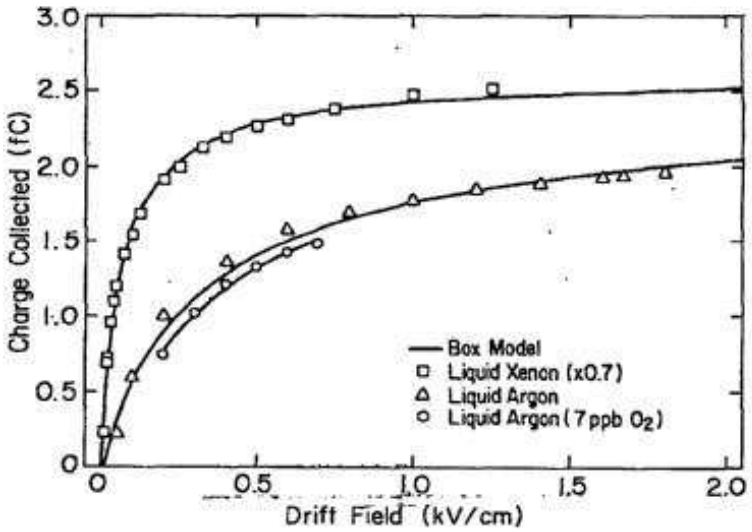


Figure 2: Charge collected versus drift field for electrons in both liquid argon and liquid xenon.[2]

## Calculations

The first step in analyzing recombination effects was to investigate recombination along the track length of an alpha particle. In order to do this, we had to know the range of alpha particles in liquid argon.

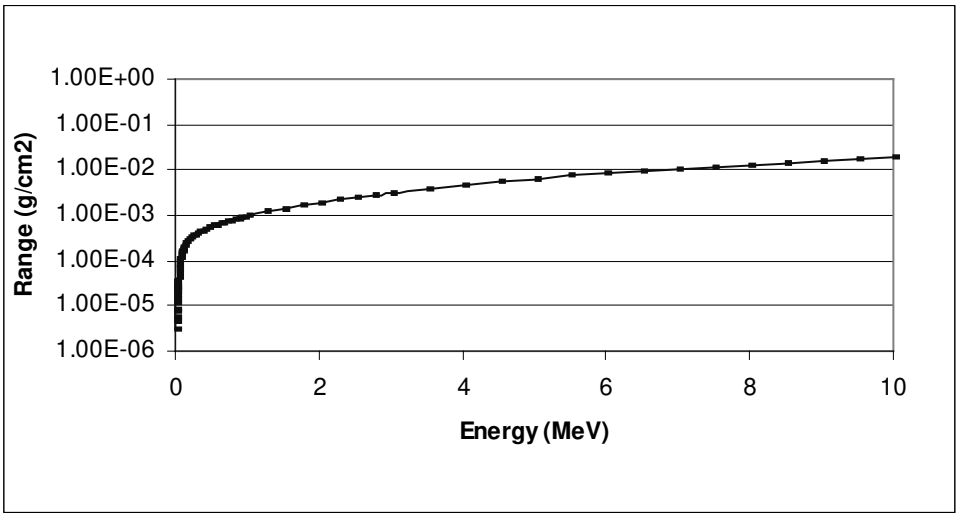

Figure 3: Range vs. Energy for alpha particles in liquid argon.[3]

Figure 3 depicts the relationship between the energy of an alpha particle and its range in liquid argon. The energy of alpha particles emitted by the radioactive source on our pin is 5.3 MeV, which corresponds to a range of $6.96 \times 10^{-3}$ g/cm$^2$. Since the density of liquid argon is 1.4 g/cm$^3$, we see that the average alpha particle in liquid argon will travel a distance of 50 μm.

Our next step was to investigate the change in the field 50 μm from the tip of the cathode. We chose two of the most favored electrode geometries for our calculations and discovered that the electric field does not vary greatly from the tip of the cathode to a distance of 50 μm. This fact allowed us to take the average of the fields along the 50 μm range and use this average for our recombination calculations. The geometries and the precise data follow.

**Geometry A:** Cathode and cathode guard ring at 0 V. Cathode flush with guard ring. Anode guard ring at 200 V; anode at 1000 V. Anode recessed .4 mm from anode guard ring. Anode and cathode separated by 2.4 mm.

| μm | kV/cm |
|---|---|
| 0 | 1.755 |
| 10 | 1.705 |
| 20 | 1.617 |
| 30 | 1.537 |
| 40 | 1.464 |
| 50 | 1.401 |

Average Field: 1.58 kV/cm

Table 1: Field corresponding to distance from cathode for Geometry A.

**Geometry B:** Cathode and cathode guard ring at 0 V. Cathode recessed .4 mm. Anode guard ring at 200 V; anode at 1000 V. Anode recessed .4 mm from anode guard ring. Anode and cathode separated by 2.8 mm.

| μm | kV/cm |
|---|---|
| 0 | .945 |
| 10 | .919 |
| 20 | .874 |
| 30 | .832 |
| 40 | .796 |
| 50 | .765 |

Average Field: .855 kV/cm

Table 2: Field corresponding to distance from cathode for Geometry B.

Since the average field around the cathode will vary linearly with an increase in the anode voltage, we determined how the charge collection will be affected by an increase in potential difference between the cathode and the anode. Figures 4 and 5, below, depict the relationship between charge collection and anode voltage for Geometry A and for Geometry B, respectively.

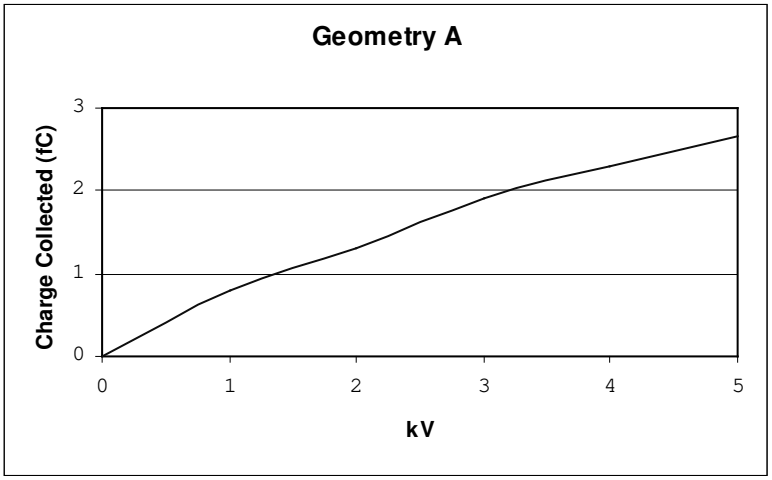


Figure 4: Charge collected versus anode voltage for Geometry A.

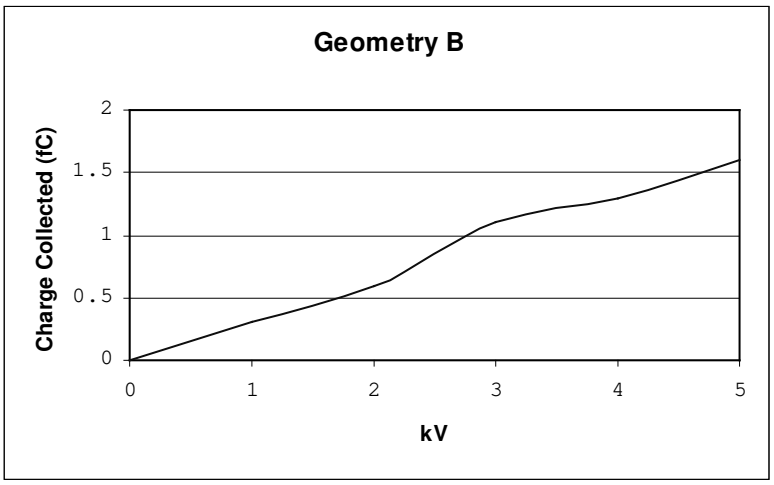


Figure 5: Charge collected versus anode voltage for Geometry B.

These graphs show that in order to reduce the recombination rate, we must increase the anode voltage. Furthermore, Geometry A is preferable in terms of charge collection on the anode. (Geometry B, however, may prove to be more ideal when considering other factors such as landing position of the electrons and the electrons' time of flight.)

**Further Considerations**

Now that we have determined the recombination effect for 5.3 MeV alpha particles, the next step is to consider the recombination along the electron tracks. The calculations for recombination along the electron tracks are more complex to calculate than that of the alpha particles because of the differences in the particles' ionization densities. The ionization density of alpha particles does not vary greatly along the particles' 50 μm range, whereas the ionization density of an electron varies greatly along its path length. Because of the electron's varying ionization density, one must integrate over the entire track length of the electron to be able to utilize the information in Figure 2. Unfortunately, we did not have a chance to complete these calculations this summer. To fully understand the effects of recombination in liquid argon, the recombination along the electron track length must be investigated further.

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[1] Onsager, L. *Initial Recombination of Ions*. Phys. Rev. 54, pp. 554-557, 1938.
[2] Thomas, J. and Imel, D.A., *Recombination of electron-ion pairs in liquid argon and liquid xenon.* Phys. Rev. A, 36, pp. 614-616, 1987.
[3] National Institute of Standards and Technology, http://physics.nist.gov/PhysRefData/Star/Text/ASTAR.html