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The Effects of Photosensitive Dopants on Electron Mobility in Liquid Argon

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Abstract

The effects of photosensitive dopants on the electron drift velocity in liquid argon is presented. Collection times can be shortened by as much as 24% with the addition of 40 ppm of allene. There is no lengthening of the signal seen due to the slow scintillation component of argon.

1. Introduction

There is now experimental and Monte Carlo evidence that a hadronic shower in a liquid argon, LAr, calorimeter deposits a substantial amount of its energy by particles with high energy loss, dE/dx. The NA34 experiment at CERN showed that the addition of 0.35% methane to their U/LAr calorimeter increased their e/π ratio from about 1.09 at 100 GeV to about 1.15 [1]. This change is due to the methane increasing the saturation losses in the LAr [2]. Saturation losses at high dE/dx means that the charge collected ceases to grow linearly with dE/dx. In a simulation of a U/LAr calorimeter, Brau and Furuno [3] estimate that the e/π ratio would decrease from 1.2 to 0.9 if the saturation effects in the LAr could be removed. This simulation shows that the e/π response of a LAr calorimeter is very sensitive to the amount of signal lost for high dE/dx particles due to saturation.

One way to parameterize saturation effects is to assume that the relationship between the signal and the dE/dx of the energy deposited obeys Birk's Law for scintillators (rewritten for collected charge) [2]:

$$\frac{dQ}{dx} = \frac{c\ dE/dx}{1 + kB\ dE/dx} . \tag{1}$$

Here Q is the amount of charge collected, c is a proportionality constant and kB is Birk's constant (in units of g MeV^{-1} cm^{-2}). The larger the value of kB the greater the saturation effects.

The only effective way to passively decrease the saturation effects in LAr is to add photosensitive dopants [4-9]. These dopants, added on the ppm level, convert the scintillation photons from ion recombinations and from excited atoms to detectable charge some distance from the volume of high dE/dx. It has been shown that the addition of a few ppm of allene (C_3H_4) or tetramethylgermanium ($Ge(CH_3)_4$), TMG, decreases kB by more than a factor of 4 [10]. For comparison, the addition of 0.35% methane increases kB by a similar factor [10]. Thus the addition of a small amount of photosensitive dopant should make a substantial improvement in the e/π ratio of a LAr calorimeter.

There has been some concern expressed that the long scintillation decay time (≈1500 ns) of LAr will require a long electronic integration time in order to achieve the desired improvement of the e/π ratio. Table 1 lists the decay times and the fraction of the light in the fast component of LAr for electrons and for alpha particles. It can be seen from this table that for heavily ionizing interactions somewhere between 57% and 77% of the scintillation occurs in about 7 ns or less. Thus, a significant fraction of the scintillation will be collected within short integration times.

It has also been reported that the addition of 60 ppm of allene to LAr yields a substantial increase in the electron mobility [13]. Since these measurements were made with alpha particles, which experience a substantial increase in charge due to converted photons. This in itself would indicate that the slow scintillation component does not make a significant contribution to the signal.

The concern that the long scintillation decay constant of LAr would require a long electronic shaping time to improve the e/π ratio, and the interesting report of a photosensitive dopant improving the electron mobility are the motivation for this work. We report here on the mobility as a function of allene and TMG concentration and as a function of electric field strength.

1. Experimental Procedure

The measurements were made with a simple, 2 mm gap ionization chamber and an alpha source. Since the current due to the electrons produced by an alpha particle is a constant, the integrated charge rises linearly with time until the electrons reach the anode [14]. This is not entirely true when photosensitive dopants are added since some of the charge in then distributed across the gap. An example of the shape of the signals measured is shown in Fig. 1. In the figure, the LAr is doped with 10 ppm of TMG and the electric field strength is 1.5 kV/mm.

The measurements of the electron collection time were taken directly off of the oscilloscope. The position of the signal and vertical amplification of the oscilloscope were adjusted so that the envelope of signals at the baseline and at the peak signal height were centered on two horizontal marks on the screen. A straight edge was then placed on the screen to coincide with the average slope of the signals. The time was determined between where the straight edge crossed the two horizontal marks. There were four independent measurements made and averaged for each data point, with the indicated uncertainties reflecting the spread in the four determinations of collection time. The reproducibility of the measurements was good but we cannot estimate the value of systematic errors. These measurements are intended to expose the physics of electron drift in LAr with photosensitive dopants. The values given are of relative value and not to be taken as absolute values.

Although, typically 50% of the signal in these measurements with doped LAr was due to photoelectrons, it should be noted that this technique is not very sensitive to the slow scintillation component if it does not make a significant contribution to the signal. No evidence was seen for a slow component contribution to the oscilloscope traces.

2. Experimental Results

Fig. 2 show the electron drift velocity, for three electric field strengths, as a function of allene concentration. The curves drawn through the points are exponential fits. The most striking feature of these data is that the increase in drift velocity saturates at a fairly low concentration and the concentration needed to reach the maximum drift velocity increases with increasing electric field. The maximum increase in drift velocity is approximately 12, 18, and 24% for electric fields of 1.0, 1.5, and 2 kV/mm, respectively.

Fig. 3 show the drift velocity, for three electric field strengths, as a function of TMG concentration. Because of TMG's lower solubility [10] the maximum concentration tested was only 30 ppm. The horizontal scale of fig. 3 is the same as for fig. 2 to facilitate comparison of the data. A saturation in the drift velocity at higher TMG concentration is also evident from these curves. Unlike for allene, the maximum drift velocity increase for TMG remains constant at about 13% for all three electric fields. Allene at a concentration of 30 ppm had increases in drift velocity of 10, 17, and 21% for electric fields of 1.0, 1.5, and 2 kV/mm, respectively.

The electron drift velocity for allene doped LAr as a function of electric field is shown in fig. 4. The data for concentrations between 40 and 80 ppm are grouped together and the data for pure LAr is shown separately. One can see that the drift velocity for pure LAr is starting to saturate at these field strengths as is seen in the literature [15], while the drift velocity for the doped LAr is still increasing approximately linearly with electric field. A representation similar to fig.4 of the data for TMG is not presented because TMG is not soluble enough to reach saturation in electron mobility with concentration.

3. Discussion

Although the reproducibility of the measurements was good, we are not able to evaluate the systematic errors. The values for the electron drift velocity in pure LAr agrees fairly well with the literature [15]. This study shows the relative decrease in the electron collection time with the addition of photosensitive dopants. It also shows that the slow scintillation component of the argon scintillation does not make a significant contribution to the signal. Photosensitive dopants not only offer the potential to improve the e/π response of a hadron calorimeter, they also shorten the electron collection time by as much as 24%.

Table 1: Decay times for the fast, τ_f, and the slow, τ_s, components of LAr scintillation and the fraction of the scintillation in the fast component, I_f, for electrons and alpha particles.

Particle	τ_f (ns)	τ_s (ns)	I_f (%)	**Reference**
Electron	4.6	1540	21	[12]
	6 ± 2	1590 ± 100	23	[13]
Alpha	4.4	1100	77	[12]
	7.1 ± 1.0	1660 ± 100	57	[13]

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Figure Captions

Figure 1: Oscilloscope trace of typical signals. (10 ppm TMG, 1.5 kV/mm)

Figure 2 : Electron drift velocity as a function of allene concentration for electric field strengths of 1.0, 1.5, and 2.0 kV/mm.

Figure 3 : Electron drift velocity as a function of TMG concentration for electric field strengths of 1.0, 1.5, and 2.0 kV/mm.

Figure 4 : Electron drift velocity as a function of electric field strengths various levels of allene concentration and for pure LAr.

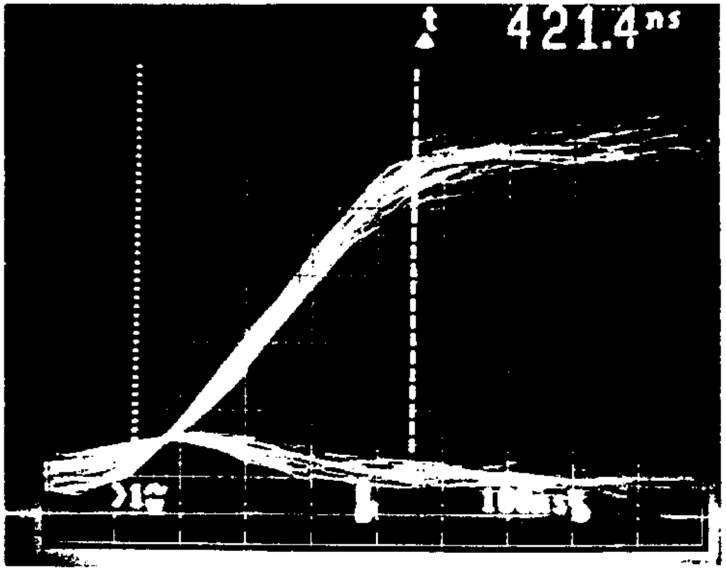

Figure 1

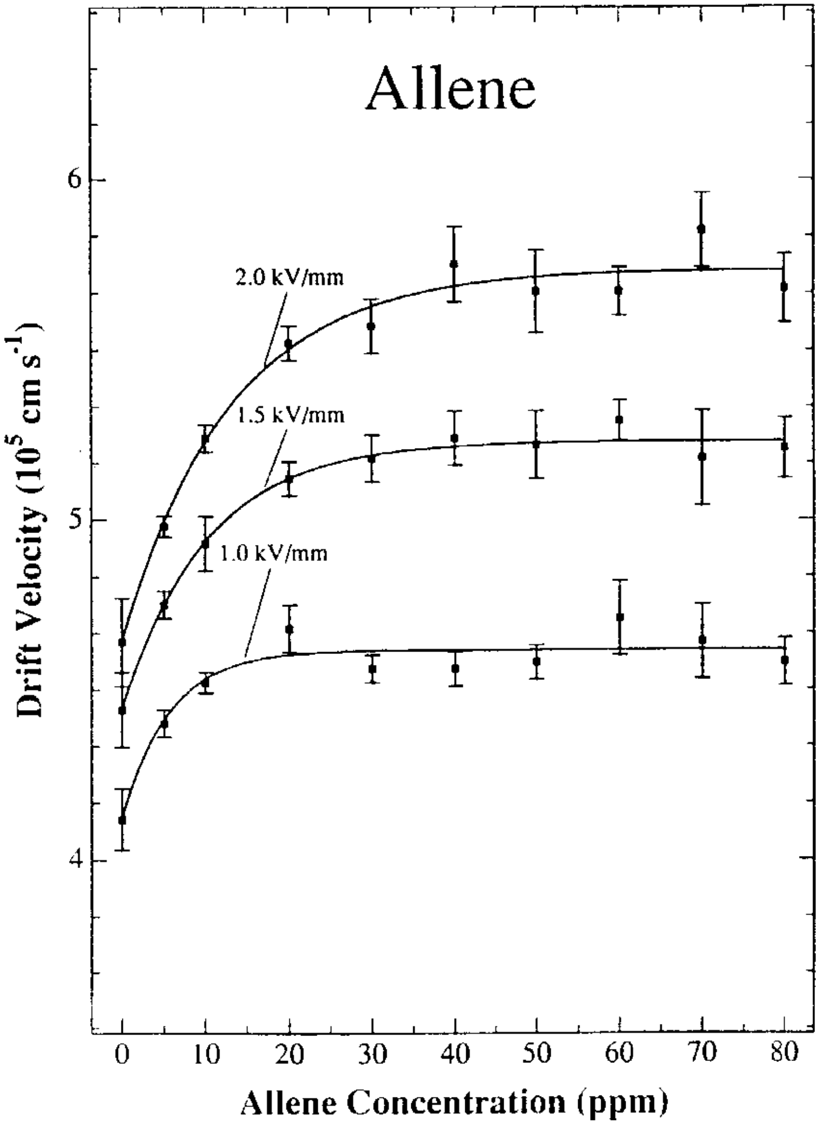

Figure 2

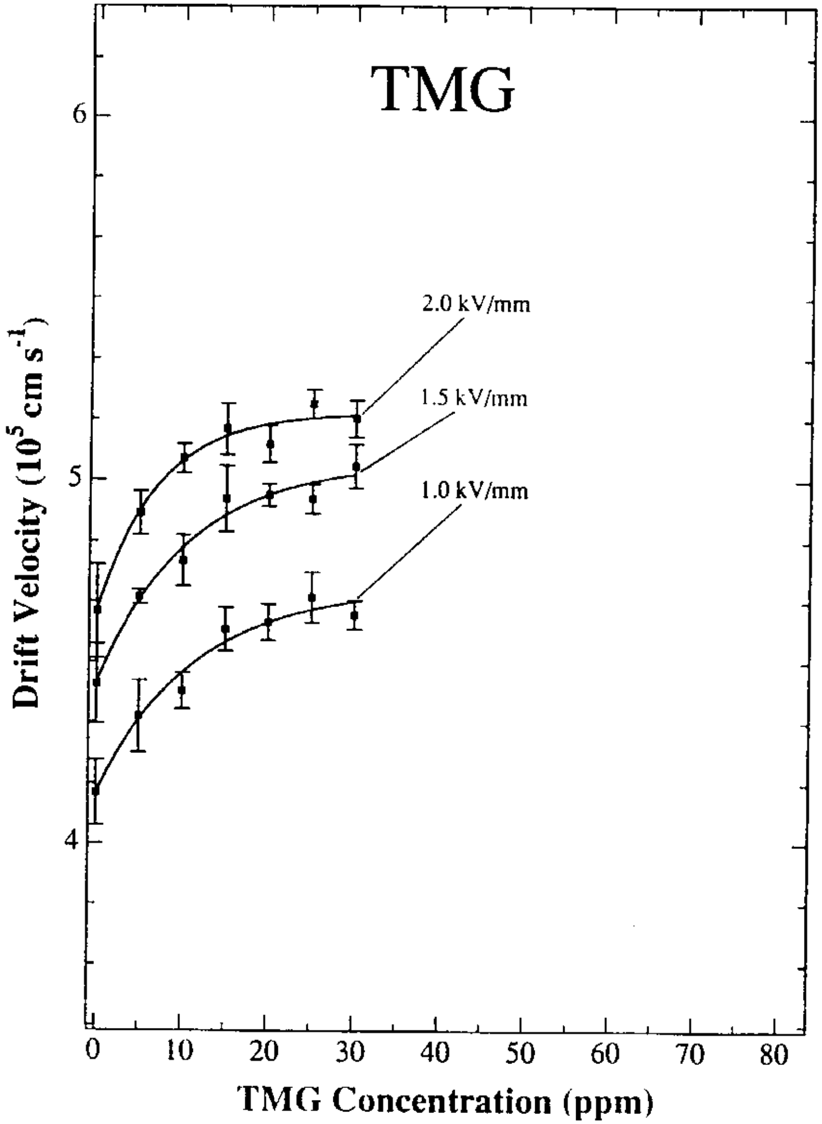

Figure 3

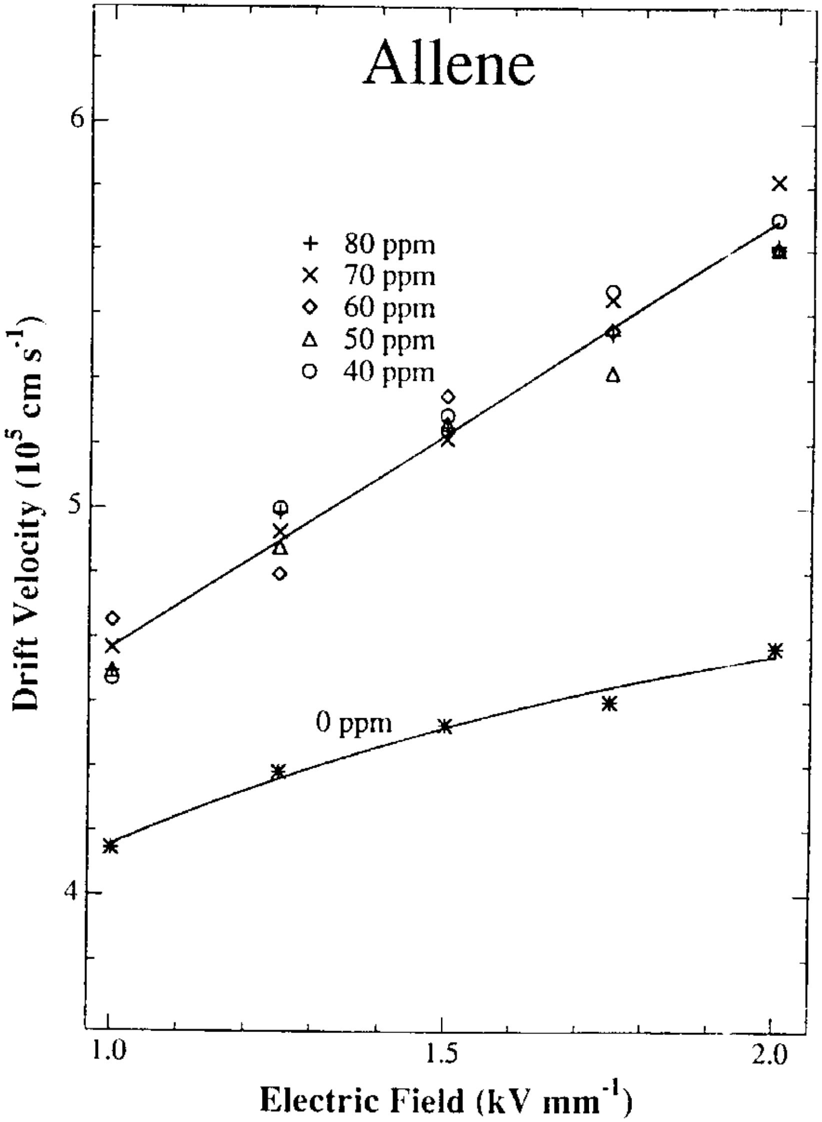

Figure 4