Fermi National Accelerator Laboratory

FERMILAB-Conf-90/251

Prospects for Photosensitive Dopants in Liquid Argon *

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December 1990

* To appear in the proceedings of the International Conference in Calorimetry in High Energy Physics, Batavia. Illinois, October 29 - November 1, 1990.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

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Prospects for Photosensitive Dopants in Liquid Argon

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Abstract

Evidence is presented that the addition of a few ppm of a photosensitive dopant to a U/liquid argon or Pb/liquid argon calorimeter will make a substantial reduction in the e/π ratio. Previous results indicating high voltage problems and no change in the e/π ratio in tests of photosensitive dopants with the Fermilab D0 experiment's U/liquid argon test calorimeter are also explained.

1. Introduction

Saturation effects in liquid argon, LAr, can dominate when charge is collected from the interactions of heavily ionizing particles such as alpha particles or heavy ions. In such cases, most of the charge is lost through recombination. With increased recombination comes a proportional increase in the scintillation yield[1]. The saturation problem has been addressed in two ways: 1) the scintillation light is detected with a photomultiplier and the signal weighted and added to the direct charge signal[2], and 2) photosensitive dopants are added directly to the LAr so that the scintillation light is converted into detectable charge[3-8]. In the second technique the photons are converted on the average some distance from the region of high charge density and thus are less susceptible to recombination.

To date, photosensitive dopants have not been seriously considered for use in a large LAr calorimeter. Two things may have changed this recently. The first is that the HELIOS experiment at CERN added a small amount of methane to their U/LAr calorimeter to increase the electron drift velocity and saw a significant increase in the e/π ratio associated with increased saturation effects[9]. Figure 1 shows the e/π ratio for the HELIOS calorimeter as a function of energy for pure LAr. A logarithmic fit has been made to these data by this author to guide the eye. There is also a single measurement made with the addition of 0.35% methane at an energy of 100 GeV. The increase in the e/π ratio with the addition of the methane shows that there is a substantial amount of heavily ionizing

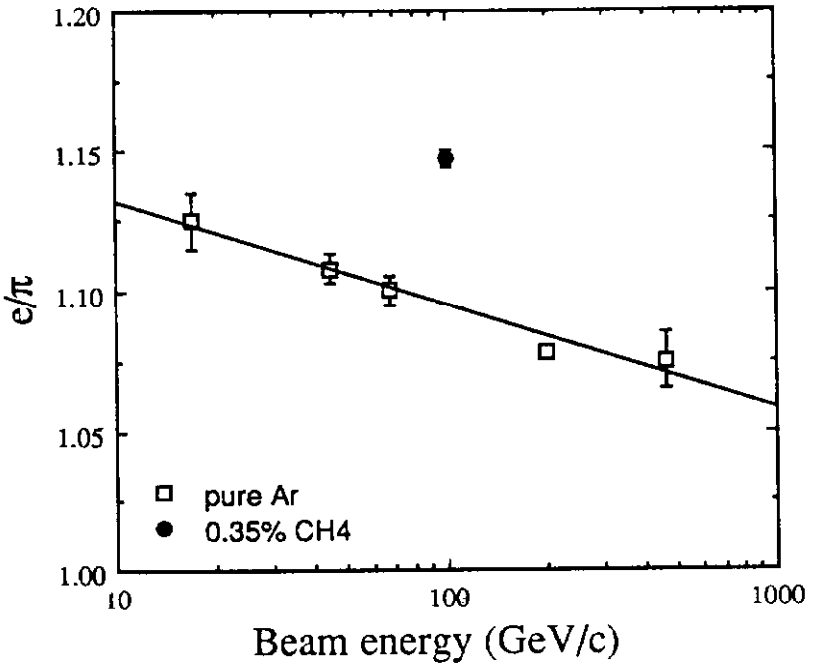

Fig. 1. HELIOS U/LA calorimeter's e/π ratio as a function of beam energy for pure LAr and for LAr + 0.35% methane.

interactions in the hadron shower whose signal is surpressed by the addition of the methane (see section 2.1).
The second is a simulation by J. Brau[10] of a U/LAr calorimeter where it is estimates that for a 5 GeV pion, 402 MeV is deposited in the LAr but due to saturation effects only 308 MeV is detected. Of the 94 MeV that is lost, 72 MeV is from neutron interactions. It is important to detect these neutrons since they are correlated with the nuclear binding energy losses. In the simulation, it was shown that if the saturation effects could be removed from the LAr the e/π ratio would decrease from 1.2 to 0.9. The calorimeter would then be over-compensating.

The above information argues for the addition of photosensitive dopants to LAr if it were not for a negative D0 beam test result. Photosensitive dopants (isobutylene and allene) were added to the already filled D0 U/LAr test calorimeter and very little time was given for mixing before high voltage was applied. In both cases there were problems with power supplies tripping and there was no change in the e/π ratio. This would argue against the addition of the dopants to a LAr calorimeter. Understanding the D0 results is the motivation behind the work presented here.

2. Dopants for LAr

There have been two type of dopants used in LAr: dopants such as methane to increase the drift velocity of the electrons, and photosensitive dopants to reduce the saturation effects. Both types change the saturation effects of the LAr. One way to parameterize the effect is to assume that the relationship between the signal and the dE/dx of the energy deposit obeys Birk's Law for scintillators (rewritten for collected charge)[11]:

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

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}). As kB increases in value the saturation effects increase.

2.1 *Methane*

Methane and ethane have been added in small amount (≤0.5%) to LAr to "cool" the excess electrons. This increases the electron mobility and decreases the diffusion. Improvements of greater than a factor of two in mobility have been achieved in this way[12].

It is sometimes mistakenly assumed that the the addition of methane will decrease the the e/π ratio of a LAr calorimeter by the addition of hydrogen to the readout. The methane increases the saturation effects by greatly reducing the thermalization length of the electrons thus increasing the probability of recombination. Because of this, the recoil protons contribute little to the signal. It has been shown[11] that above a concentration of about 5% methane, the only signal from an alpha particle is from the few delta rays escaping the region of high charge density. There is also a substantial loss in signal from minimum ionizing particles. Birk's constant as a function of methane concentration is shown for two electric fields in Fig. 2[11]. From this figure one can see that for a field of 2 kV/mm, kB increased from about 7.5×10^{-4} g MeV^{-1} cm^{-2} for pure LAr to about 1.2×10^{-3} g MeV^{-1} cm^{-2} with the addition of 0.35% methane. This is a 60% increase in kB.

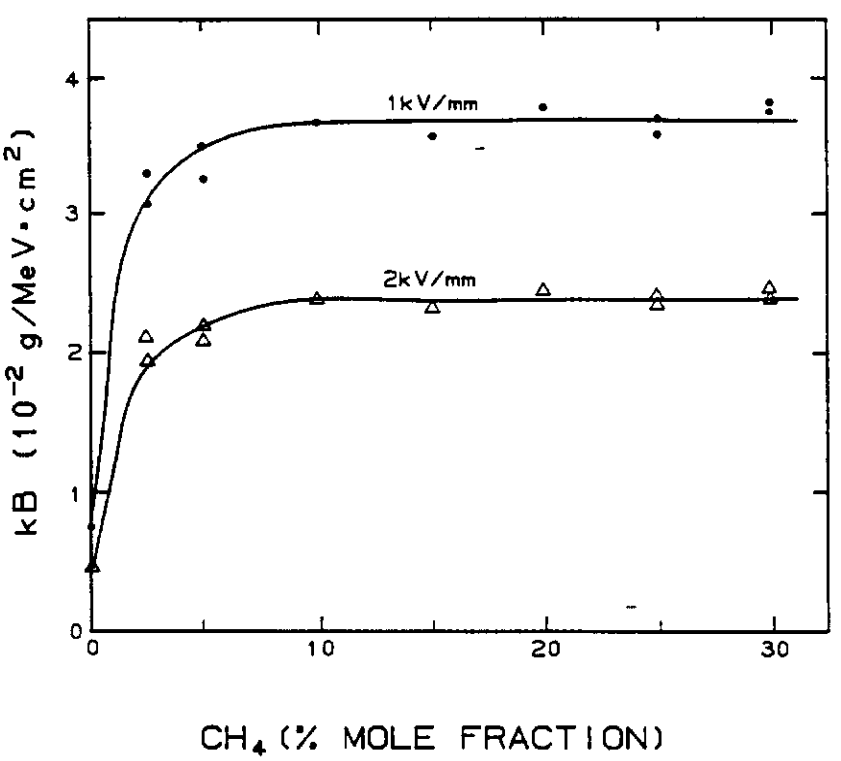

Fig. 2. Birk's constant as a function of methane concentration in LAr for electric field strengths of 1 kV/mm and 2 kV/mm.

2.2 *Photosensitive Dopants*

Photosensitive dopants decrease the saturation effects by converting the scintillation light from recombination into photoionization some distance away from the heavy ionization. As an example of the effects of photosensitive dopants, Figure 3[4] shows the

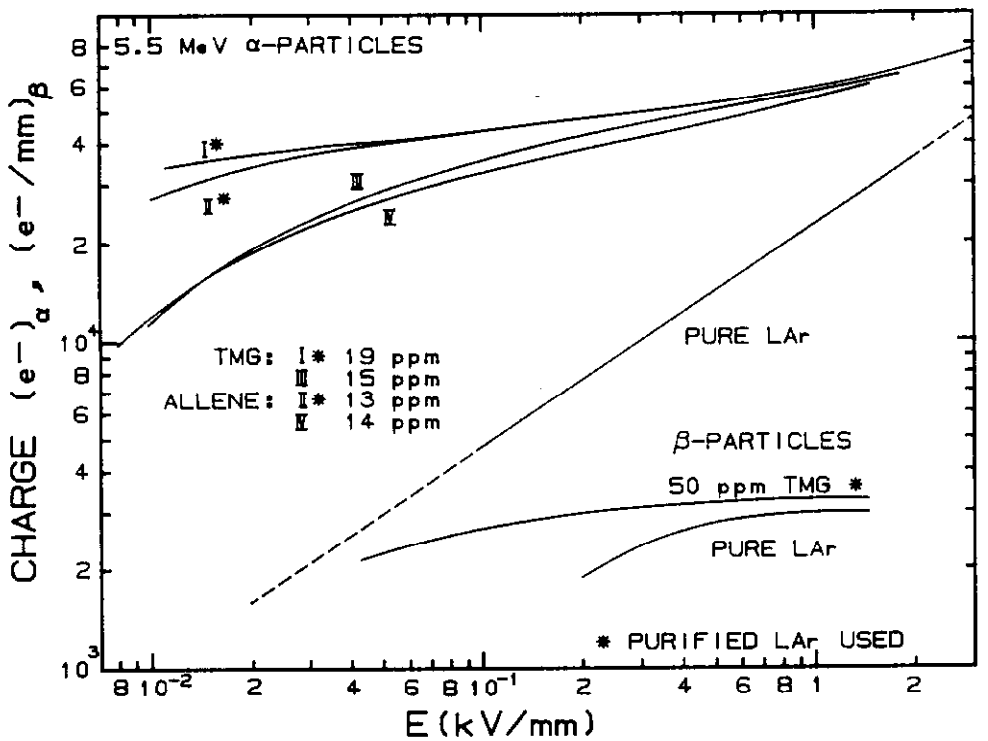

Fig.3. Charge collected for a 5.5 MeV alpha particles and for beta particles in pure LAr and in LAr doped with TMG and allene.

charge collected from alpha particles and beta particles as a function of electric field for LAr doped with allene and tetramethylgermanium (TMG). At low electric fields, the charge collected for alpha particles is increased by over an order of magnitude. At 2 kV/mm, the signal for alpha particles is increased by a factor of two while the signal from beta particles is only increased by about 13 %. This implies a substantial reduction in kB. For a field of 2 kV/mm, the addition of 15 ppm of allene (C_3H_4) decreases kB to about 2.5×10^{-4} g MeV^{-1} cm^{-2}. This is a 65% reduction over the value for pure LAr. This is probably an underestimation in the reduction in kB with a photosensitive dopant since the alpha particles deposited all their energy very close to the source and therefore half of the scintillation light was blocked by the source. It should also be noted that the signal for beta particles approaches its plateau at a much lower voltage with the addition of the dopants.

One might hope that a sufficient amount of photosensitive dopant could be added to the LAr so that there would be both the reduction in saturation and the hydrogen to thermalize the neutrons in the shower. Unfortunately, all known photosensitive dopants have solubilities in the 10's of ppm level or less. Another suggestion is that a mixture of methane and a photosensitive dopant be added; the methane to provide the hydrogen (H_2 is not soluble in LAr) and the photosensitive dopant to reduce kB. We have found that the addition of even a small amount of methane to LAr doped with a photosensitive dopant

negates all effects of the photosensitive dopant. This is believed to be due to the methane competing with the photosensitive dopant for the scintillation light. The methane is always added in much higher concentrations than the ppm levels of the photosensitive dopants.

3. New Results With Photosensitive Dopants

The fact that in the D0 calorimeter test the high voltage power supplies tripped due to high currents when the dopants were added would imply that the doped LAr would no longer sustain high voltage. That there was no change in the e/π ratio would imply that there really is not a substantial amount of signal lost to saturation in the LAr. The D0 results are considered below.

3.1 *Mixing Problem*

The largest problem with this study has been reproducibility of the data. The procedure for testing the various levels of dopant was to start at the highest concentration to be studied and then go to lower and lower concentrations by removing some of the doped LAr from the bottom of the dewar and refilling by condensing Ar gas at the top. It was finally realized that even with a heater to cause bubbling in the LAr, it takes hours for the doped and undoped liquids to mix thoroughly. This was improved by introducing the gas through a stainless steel filter placed at the bottom of the dewar so that the gas would vigorously agitate the liquid as it entered the dewar. For a system as large and as complicated as the D0 test calorimeter, mixing times would be on the order of days, not minutes. In practice, the dopants were never allowed to mix with the LAr in the D0 tests. In the NA34 test, the LAr and methane was mixed for several days[13].

3.2 *Investigation of High Voltage Problems*

It was first assumed that the negative results of D0 were because LAr doped with a photosensitive dopant would no longer hold high voltage. A test cell consisting of a series of 2 mm gaps totaling 720 cm^2 was installed to look for an increase in current when a dopant was added. No current increase was seen. High voltage stability problems were observed when an alpha source was utilized.

For high concentrations ($\geq$ 12 ppm) and high electric fields ($\geq$ 2 kV/mm) there was an instability in charge collection for some dopants. Under these conditions the (pulse-height) resolution would degrade. The signal would behave similarly to amplification in an under-quenched wire chamber. For this reason dopant levels should be kept below 8 ppm. Since the dopants were not well mixed in the D0 test, it can be assumed that there were regions of the calorimeter where the dopant levels were too high and with uranium as the converter, there is a constant charge source to cause high voltage problems.

4. Discussion

The Monte Carlo simulation of Brau has shown that there is a substantial loss in signal in a U/LAr calorimeter due to saturation effects in the LAr and that the calorimeter would be overcompensating if saturation effects could be removed. These conclusions seem to be supported by the NA34 test results which show that the addition of methane increased the e/π ratio. We have also reason to believe that the negative results with the D0 test calorimeter were caused by not allowing the dopant enough time to mix. Therefore, the existing evidence strongly suggests that the addition of a small amount of photosensitive dopant will make a substantial reduction in the e/π ratio of a U/LAr calorimeter. These dopants will certainly also have some beneficial effect on the e/π response of a Pb/LAr calorimeter.

There are still many things to be studied. Charge transport in a high electric field must be studied as a function of dopant and dopant level. At the moment, preliminary results indicate that allene at a concentration of 3-4 ppm is the optimum for combined stability and saturation reduction. With the addition of an organic molecule to the LAr, questions of long term stability and radiation damage must be addressed. These questions are presently under study.

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