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ENERGY RESOLUTION CONSIDERATIONS IN LIQUID IONIZATION CHAMBERS†

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The calculated Fano factors limit the energy resolution of liquid argon and liquid xenon ionization chambers to 4 keV FWHM and 2 keV FWHM respectively at 1 MeV. This paper discusses the problems encountered when trying to achieve these limits. First experimental results of our liquid argon detector are presented.

I. INTRODUCTION

Liquid argon (LAR) and liquid xenon (LXe) have drawn considerable interest as ionization chamber mediums.^{1,2,3,4} This interest is attributable to their density, low Fano factor, and low cost in large volumes. The Fano factor in particular has been calculated to be low enough to permit these liquids (especially LXe) to attain nearly the resolution of a germanium crystal.⁵ If these resolutions can be realized, one could have relatively high-resolution detectors of volumes difficult to achieve with solid-state detectors.

However, no one has come close to achieving the predicted energy resolution. The purpose of this study is to understand the limitations in achieving the predicted high resolution.

II. THEORY

In spite of the good properties of LAR and LXe, there are several bad properties which account for some of the problems in achieving high energy resolution. First, the cost per ion pair, w , is high (23.6 eV/pair for LAR and 15.8 eV/pair for LXe). This means that the signals will be small compared to solid-state detectors where $w \approx 3$ eV/pair. Second, the positive ions are essentially immobile, so only one charge carrier is observed. Third, the mobility of the electrons is only a few times 10^5 cm/sec.⁶ This means that these detectors will be relatively slow, and extremely vulnerable to trapping of electrons by impurities.

For LAR the drift velocity is about 4×10^5 cm/sec in a 10-kV/cm electric field. Thus, even at moderately high fields, a detector with a 1-cm gap will have a charge collection time of about 2 μ s. The mean lifetime before trapping of the electrons by electronegative impurities is short (2 μ s at 10 kV/cm and 1 ppm)⁶ so one is driven to use high electric fields not only for timing, but also for charge collection. Fields of 10 kV/cm are necessary and fields of 100 kV/cm appear desirable. Even with such fields, trapping by oxygen is so severe that it must be kept to ppb levels. If one assumes that charge loss due to trapping follows Poisson statistics, then 12% charge loss contributes as much to the variance in charge as does the Fano factor. But worse, the signal will be down by $\sim 12\%$ and the resolution will increase from 4 keV FWHM to 5.8 - 6.4 keV (assuming no other noise sources).⁷ Our calculations show that the oxygen level must be less than 100 ppb for the trapping effects to be comparable to the Fano contribution.

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The fact that the positive ions are immobile necessitates a grid. Otherwise a variance is added which is roughly equal to the mean stopping distance of the radiation divided by the chamber size.⁸ Thus, short-ranged particles, such as several-MeV α particles show little dependence on this effect. However, with these particles, recombination is so severe that 90% or more of the charge is lost. Our data shows that geminate recombination is a strong contribution to charge loss.⁹ The grid itself is a potential place for charge loss. The grid geometry and operating voltage must be chosen carefully to obtain maximum shielding and maximum transmission.¹⁰

The high w simply demands that one use the lowest noise preamplifier available. Room-temperature FET preamplifiers will not suffice. One can usually obtain 300 electrons FWHM with a room-temperature FET and there are some preamplifiers capable of 200 electrons FWHM.¹¹ But even 200 electrons FWHM contributes 4.7 keV to the resolution (i.e. more than the Fano factor) for a total of 6.2 keV FWHM if there is no charge loss. Detector capacitance must be kept low not only for the sake of the preamplifier, but also to prevent coupling of noise from the power supply to the preamplifier via the grid. If the grid to collector capacitance is 10 pf and one wishes the noise contributions of the power supply to be less than the Fano contribution, then the noise on the grid must be less than 1 μ V(rms). Maintaining the grid at 20 kV $\pm$ 1 μ V ripple is not easy (0.05 ppb). Not only must the power supply be well filtered, but also one must be careful of shot noise if a single power supply is used with the grid receiving its voltage via a voltage divider.

III. EXPERIMENTAL

We have constructed an ionization chamber consisting of two parallel stainless steel plates and a grid. The chamber is 6.4 cm in diameter with 0.6 cm between the cathode and grid, and 0.5 cm from grid to collector. A ^{207}Bi source is deposited on the cathode to provide the conversion electrons used for our resolution measurements. The grid is a mesh of etched nickel film, 25 μ m thick, yielding 12 μ m wide wires on 127 μ m spacing.¹² The grid and spacing were chosen to provide optimum resolution for the 976-keV conversion electron of ^{207}Bi . This choice was based on the electron mean range, the grid shielding inefficiency, and the oxygen level at which we operate.

The cell is contained in a 5.5-l stainless steel dewar which we fill to about 3 l with argon. The argon is purified with a gettering furnace and oxygen levels are monitored with a fuel-cell oxygen monitor.^{13,14} One pass through the furnace at a flow of 3-4 l/min reduces the tank gas from 1-10 ppm to < 100 ppb. The dewar system is unique in the sense that the liquid is continuously vaporized, passed through the purifier, and recondensed.¹⁵ This cycle is concurrent with its use as a detector. After a day, the system stabilizes to about 10 ppb oxygen. The system has operated continuously at 10 ppb oxygen and one filling of argon

for three weeks with no problems. We consume about 25 l of liquid nitrogen per day as the refrigerant.

High voltage is provided by a Spellman KHSR 25 PN 60 supply.¹⁶ A capacitive filter network and a resistive divider network feed the cathode and grid from this one supply.

The detector capacitance is 0.5 pf with another 10 pf in the leads to the outside. This raises our 300-electron FWHM electronic noise to 450 electrons. This is with a dc-coupled, room-temperature preamplifier. A cooled preamplifier is being prepared for future use. After heavy filtering we still get a noise increase to 600 electrons FWHM when the voltage is set at 25 kV total. A little corona anywhere in the filter or divider quickly turns this into 1000.

In the absence of corona, we feel the high voltage noise contribution is primarily shot noise in the divider network of giga-ohm resistors. We are purchasing a second high voltage power supply so that the divider will be unnecessary.

Figure 1 shows the ^{207}Bi spectrum obtained with our detector. The K and L conversion lines are resolved for the 569.7-keV and 1063.6-keV transitions. The efficiency for the photo events is too low to see a peak, but the Compton edges are relatively distinct. The energy resolution at 976 keV is 34 keV FWHM and 26 keV FWHM at 480 keV. With 600 electrons electronic noise, we would predict 15-keV and 14.4-keV resolution for these peaks. At this time we do not understand the difference between the predicted and measured resolutions. However, note that our resolution is the best reported with LAr.

IV. CONCLUSION

If the calculated Fano factors are correct, then one sees that the resolution of a LAr or LXe detector is limited by electronics and geometry, and not necessarily by the physics of the liquids. While this presents some challenging experimental difficulties, it is our opinion that it is much better for the limitations to be as they are since one would hope them to be solvable.

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Fig. 1. The spectrum of ^{207}Bi as detected with our
LAR ionization chamber.