

Fermi National Accelerator Laboratory

FERMILAB-Pub-87/127

Some New Ideas in Liquid Detectors*

David F. Anderson
Particle Detector Group
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

August 1987

*Presented at the London Conference on Position-Sensitive Detectors, University College London, London, England, September 7-11, 1987. To be submitted to Nucl. Instrum. Methods A.



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

FERMILAB-PUB-87/127

August 1987

Some New Ideas in Liquid Detectors

David F. Anderson
Particle Detector Group
Fermi National Accelerator Laboratory
Batavia, IL 60510 U.S.A.

Presented at the
London Conference on Position-Sensitive Detectors
University College London
September 7-11, 1987

To be submitted to
Nuclear Instruments and Methods in Physics Research A

Abstract

Three new techniques for the detection and imaging of the energy deposited in liquid detectors are discussed. These are: electrostatic imaging in liquid argon doped with methane, photon mediated charge amplification in liquid xenon containing photosensitive dopants, and electron extraction from liquid argon and 2,2,4,4-TMP with charge amplification in the gas phase.

1. Introduction

The use of liquids as the detection medium in instrumentation is not new. But, until this decade, the primary materials used were the liquefied noble gases. In particular, liquid argon (LAr) was the only liquid used as a serious experimental tool [1-4]. In a liquid ionization chamber the charge liberated by deposited energy is collected directly without amplification. The advantage of such a system is that the amount of charge collected per unit energy is very stable with time. The major disadvantage is that there is a relatively small amount of charge collected, and therefore, only large energy deposits can be measured. Thus it has primarily been a tool of high-energy and heavy ion physics.

There are three major "mainstream" directions in liquid detectors. The first is the traditional application of LAr for calorimetry. The second is in the application of such warm liquids as 2,2,4,4-TMP (henceforth referred to as TMP) and TMS in high-energy physics calorimetry. This work is represented by Engler and his colleagues [5-7], and the UA1 Collaboration represented by Rubbia [8]. The work of both investigators can be found elsewhere in this journal. The third direction is the use of large volumes of LAr for time projection chambers [9], discussed by Giorginis in this journal.

Here we will discuss some of the new, and less mainstream, applications of liquids. These applications in general lend themselves to smaller instruments than calorimetry. They are also techniques which are more directly applicable to the imaging of lower energy particles, such as x-rays and beta particles. The three subjects that will be discussed are: 1) electrostatic imaging in liquids, 2) charge amplification in liquid xenon, and 3) electron extraction from warm liquids. In all of these subjects, the charge is collected in unique ways from the process in a standard liquid ionization chamber.

2. Electrostatic Imaging

The primary goals of the work with electrostatic imaging in liquids are to obtain the projected image of the tracks of minimum ionizing particles for high-energy physics [10-12] and to image the beta-emitting lines on chromatographic gels. This technique may also find applications in other fields where the imaging of radioactive sources is of interest. The work discussed here is the first step in this research and consisted of the verification that charges liberated by ionizing radiation in LAr can be collected on a mylar sheet and imaged with presently available methods.

2.1. Experimental Procedure

A schematic of the experimental setup used is shown in fig.1 [13]. A radioactive source is separated from a 125 μm -thick mylar sheet by a 2 mm gap filled with a mixture of LAr and methane. The back side of the mylar sheet has a conductive layer of indium tin oxide (ITO) deposited on it. This conductive layer is in contact with the positive high-voltage electrode with the source held at ground potential.

The preliminary study was conducted with beta- and alpha-emitting sources. The image of the collected charges was developed with a liquid toner which is used in electrophotography. It is made of a dispersion of particles of a median size of 0.2 μm ,

which are positively charged and dispersed in an insulating liquid. In order to produce an image of the charge liberated in the LAr, the charge was collected on the mylar sheet for times that varied from a few minutes to several days, depending on the intensity of the source. With this toner, an image was observed when the surface potential reached about 25 V.

2.2. Results And Discussion

It was found that the quality of the image could be improved by the addition of a few per cent methane. This was due to a reduction in the diffusion of the electrons. We also found that the results were somewhat improved by an increase in the collection field, particularly with the LAr/methane mix. Most of the work was done with a field of 1250 V/mm.

One object of the effort was to image the beta-emitting lines on a chromatographic gel carrying proteins labeled with ^{35}S . After an exposure of 12 hours, the image in Fig. 2a was obtained. Figure 2b is an image produced by exposing the gel to a special autoradiography film for six hours. The distance between the three lines to the right of the two darkest lines is about 400 μm , with a line width of about 120 μm . The width of the lower strip of gel is about 6.6 mm. We obtained the correct pattern of lines, showing that our experimental procedure does not destroy the images, but the spatial resolution is clearly degraded.

The sensitivity of the toner was far below what is required for the imaging of minimum ionizing particles in LAr. However, these observations may prove to be of interest for applications where the acceptable level of sensitivity can be much lower. For instance, the spatial distribution of the beta-emitters is of primary importance in a field of research such as biology. A research effort has been invested in studying the possibility of replacing the photographic emulsions used for autoradiography, which suffer several defects: low sensitivity, lack of linearity, and small dynamic range.

The range of the emitted electrons is about three orders of magnitude smaller in LAr, which could be a great advantage if one could measure the collected charge with sufficient sensitivity and accuracy. At present, experiments ongoing at Ecole de Physique et Chimie in Paris, and at CERN, indicate that sensitivities at least ten times higher than the present toner can be obtained and that further substantial improvements in sensitivity can be reasonably expected [14].

3. Charge Amplification in Liquid Xenon

Liquid xenon (LXe) is the only liquid in which charge amplification can be reliably achieved [15-16]. Of all liquids suitable for use as a nuclear detection medium, it is the best medium for γ -ray detection because of its high density (3.06 g/cm^3) and high atomic number ($Z=54$). Therefore, there has been some effort in the development of a γ -ray camera using electron avalanche in the LXe [17]. With such a device, amplifications of 100 or more have been achieved with a spatial resolution limited only by the 2 mm wire spacing. The signal rise time observed was 150 ns when operated in the proportional

mode, demonstrating that counting rates of 10^5 s^{-1} per wire should be possible. An energy resolution of 11% FWHM was also achieved for Hg^{203} γ rays (279 keV).

The problem with such a system is that in order to achieve a substantial amplification, one must use very fine wires and high voltages. In the above work, it was shown that in order to achieve an amplification of only 10, voltages of about 2.5 kV and 4 kV are needed for anode wire diameters of 4 μm and 6 μm , respectively. This makes construction of an instrument of useful size very difficult, and has been one of the major cause that LXe detectors have not become a practical instrument.

3.1. Proportional Scintillation

The electrons in the strong electric field around a small anode wire in LXe produce light [18]. This light is proportional to the number of electrons present and is therefore referred to as "proportional scintillation." This is analogous to the proportional scintillation in gas scintillation proportional counters [19-20]. So far, proportional scintillation has only been reported in LXe.

It has been shown that proportional scintillation is much easier to achieve in LXe than charge amplification. The voltages required are 2 or 3 times lower than for charge amplification, with substantial light production even for anode wire 20 μm in diameter.

There are several problems with detecting the proportional scintillation as the readout for a γ -ray camera. It is difficult to build a cryogenic system with a large optical window. Also, because of relatively poor quantum efficiencies of photomultiplier tubes for LXe light, and because of geometric constraints, the light collection and conversion efficiencies are poor. This results in an instrument with very poor energy resolution. In addition, the relatively large size of photomultiplier tubes greatly limits the position resolution of such an instrument.

3.2. Photoionization in Liquid Xenon

It has been shown that the scintillation of LAr can be converted within the liquid itself by the addition of certain photosensitive dopants [21-23]. It was also suggested that the addition of trimethylamine (TMA) and triethylamine (TEA) to LXe could be used to convert the proportional scintillation to give electron amplification at substantially lower voltages than in pure LXe [22]. This would yield an interesting instrument for the imaging of γ rays in astronomy and nuclear medicine.

This "photon mediated avalanche" has been achieved by Suzuki et al. [24] with a small detector with 10 μm -diameter anode wires on a 2 mm spacing. Figure 3a-c shows the typical energy spectra for both ^{210}Po alpha particles and ^{207}Bi electrons and γ rays. Figure 3a shows the spectrum for pure LXe with an applied voltage of 2 kV. The peaks from left to right are due to alpha particles (5.3 MeV), gamma rays (0.57 MeV), electrons (0.98 MeV) overlapped with gamma rays (1.06 MeV), and a test signal. Figures 3b and 3c show the pulse height spectra for LXe doped with TEA (45 ppm) at voltages of 2 kV and 3.5 kV, respectively. The alpha peak has increased dramatically over its pulse height in the undoped LXe because of the high probability of recombination and therefore the

large amount of scintillation resulting in the photoionization of the TEA. For an applied voltage of 2 kV, the improvement in energy resolution is obvious.

Figure 4 shows the pulse height of the 1 MeV peak (^{207}Bi) as a function of applied voltage for pure LXe and for LXe doped with TEA (60 ppm) and TMA (40 ppm)*. At low electric fields, the charge collected in the doped LXe is about 30% higher than in the pure LXe. The sharp increase in collected charge at about 3 kV is not seen in pure LXe.

Figure 5 shows the pulse height for the ^{210}Po alpha particles as a function of applied voltage for pure LXe and LXe doped with TEA (10, 45, and 60 ppm) and with TMA (40 ppm). In this case, the collected charge at low voltages increased by more than a factor of 10 with the addition of the dopants. Again, a sharp increase in collected charge is seen at about 3 kV.

The best resolution for the alpha particles was 4% FWHM at a voltage of 2 kV, while the resolution in pure LXe was 15% FWHM, but the energy resolution became worse at about 3 kV. For the 1 MeV (electrons + γ rays) ^{207}Bi peak, the resolution improved with the addition of the dopants from 16% FWHM to 11% FWHM at 2 kV. At 3.5 kV the resolution had degraded to 26% FWHM.

Although the degradation in energy resolution with charge amplification is somewhat disappointing, these results are very encouraging. For the first try at such a new and nonconventional instrument, the results are remarkable and warrant further effort. This may well be an important instrument of the future.

4. Electron Extraction from Liquids

A growing interest has been expressed in the use of large volumes of liquid argon as the detecting medium of Time Projection Chambers [9]. The major applications are for proton decay experiments and neutrino physics.

Even though the energy loss for particle tracks in liquids is much larger than in gases, the absence of charge multiplication leads to the use of expensive low-noise amplifiers. There is also a limitation on the spatial accuracy due to limitations on cell segmentation and the electronic noise of such a high-capacitance system.

In order to improve the detection ability of liquids, two-phase systems have been studied where electrons are extracted from LAr [25] and liquid xenon LXe [26] into the gas phase above the liquid. Before these measurements, the possibility of extracting electrons from these materials was not obvious since their conduction band energy (V_0), which is the energy of the excess electrons measured with respect to the vacuum, is negative. Thus, a substantial fraction of an electron volt must be given to the electrons to free them from the liquid into the gas.

4.1. Experimental Results with LAr

The extraction from LAr of the electrons liberated by the 5.5 MeV alpha particles from the ^{241}Am proved to be very simple [27]. One advantage of LAr is the large amount of charge liberated. At a typical operating voltage for the experiment of 800 V/mm, there were about 2×10^4 electrons liberated. This produces a signal easy to detect.

A 4 mm ionization gap was first filled with LAr and a pulse height spectrum was taken. At a voltage of 3200 V (800 V/mm), a clean pulse-height spectrum was obtained with an energy resolution of about 25% FWHM. The LAr level was then lowered so that the liquid filled only half of the gap. At the same voltage the pulse height was reduced by 6%, but otherwise had the same shape and energy resolution.

The big disadvantage of LAr is that it is very difficult to maintain a constant pressure above the liquid in a small test system. Although it is easy to get charge amplification in the gas, the changing pressure made it impossible to maintain a stable gain. This proved not to be the case with TMP.

4.2. Experimental Results with TMP

The glass cell used in the work with TMP is shown in Fig. 6. It consisted of a test cell with two electrodes, and a reservoir for the excess liquid. The test cell and the reservoir were connected by a thin glass tube to allow the level of the TMP in the test cell to be adjusted. The electrodes were 15 mm in diameter and separated by a gap of 4 mm, with the lower electrode coated with an ^{241}Am alpha-particle source.

The major disadvantage of warm liquids for the study of a two-phase detector is the small amount of charge that is liberated. Since we worked with typical electric fields of only about 400 V/mm in the liquid, fewer than 10^3 electrons are liberated by the alpha particles [28]. Thus, the signal for the full-gap measurement was smaller than could be measured with the electronic system. Therefore, we were not able to study the shape of the alpha peak until the electrons were extracted and amplified in the gas.

The first tests were made with the cell filled with only TMP and its vapor. Because of TMP's low vapor pressure (about 14 torr and 40 torr at 20°C and 40°C, respectively [29]) amplification commenced at relatively low voltages. At room temperature, the estimated maximum charge gain was about 10^3 at a potential of 1400 V. The temperature of the system was raised in order to increase the vapor pressure of the TMP. At 40°C a gain of about 7×10^3 was achieved at a potential of 2300 V.

Figure 7 shows the charge liberated per alpha particle as a function of voltage across the gap for a second set of measurements. The charge collected in the gas per alpha particle at various temperatures is also shown. To improve the stability, 80 torr of argon was added to the cell for these measurements. It was estimated that 100% of the electrons escaped the liquid and were collected in the gas. In all cases, at a charge of a few times 10^6 electrons per alpha particle, the shape of the alpha peak became distorted, consistent with full amplification for a small part of the events and reduced amplification for the majority of events. This we believe to be due to the buildup of positive ions in the liquid, since with a charge collection of 3.5×10^6 e⁻/alpha, and a source intensity of 5700/s, the positive ion density in the liquid would be on the order of $10^7/\text{mm}^3$. Thus, areas with the greatest source intensity would have lower amplification because of electric field distortions.

4.3. Discussion

These results confirm that electrons can be conveniently extracted from LAr. In large time-projection chambers where the detection medium is LAr, one can envisage a proper mixture of argon and methane, allowing the amplification of electrons in a parallel grid structure with all the inherent advantages of large pulses and greater readout flexibility connected with pulses induced by gaseous amplification. These results also show that it is as easy to extract electrons from a warm liquid like TMP, widely considered for calorimetry in high-energy physics, with an easy and sizeable amplification of the extracted electrons in a parallel plate structure.

5. Conclusion

Three new and novel techniques of detecting energy deposited in liquids have been discussed. In the case of charge amplification in LXe containing photosensitive dopants, and in electron extraction, the charges measured can be 2 or 3 orders of magnitude higher than the initial ionization. This allows the energy of the primary ionization to be much smaller than could be detected before in liquids. This may open up the use of liquid detectors to many fields such as nuclear medicine, γ -ray astronomy, and triple beta decay experiments. In the case of electrostatic imaging, it allows weak signals such as from the beta-emitting lines on chromatographic gels, to be integrated over a long period of time, thus improving the sensitivity.

These techniques are far from fully developed. Only time and a considerable amount of effort will show their potential. They are good examples of what can be done in a field that appears to be very restrictive and well understood, when viewed in non-conventional ways.

Figure Captions

- Figure 1 Schematic of experimental setup for electrostatic imaging [13].
- Figure 2 a) Image produced on mylar film by beta-emitting lines on a chromatographic gel, and b) image produced with autoradiography film [13].
- Figure 3 Typical energy spectra for both ^{210}Po alpha particles and ^{207}Bi electrons and γ rays a) for pure LXe at 2 kV, b) for TEA doped LXe at 2 kV, and c) for TEA doped LXe at 3.5 kV [24].
- Figure 4 Collected charge for the 1 MeV peak (^{207}Bi) as a function of collection voltage for pure LXe and LXe doped with TEA and TMA [24].
- Figure 5 Collected charge for ^{210}Po alpha particles as a function of collection voltage for pure LXe and LXe doped with TEA and TMA [24].
- Figure 6 Schematic of glass cell for electron extraction [27].
- Figure 7 Charge collected per alpha particle as a function of voltage across the gap for a variety of temperatures. The amount of charge liberated in the TMP as a function of voltage is also shown [27].

References

- 1) G. Knies and D. Neuffer, Nucl. Instr. Meth. **120** (1974) 1.
- 2) J. Engler et al., Nucl. Instr. Meth. **120** (1974) 157.
- 3) W.H. Willis and V. Radeka, Nucl. Instr. Meth. **120** (1974) 221.
- 4) C.J. Fabjan et al. Nucl. Instr. Meth. **141** (1977) 61.
- 5) J. Engler and H. Keim, Nucl. Instr. Meth. **223** (1984) 47.
- 6) J. Engler, H. Keim and C. Müller, Nucl. Instr. Meth. **A254** (1987) 311.
- 7) J. Engler, H. Keim, and B. Wild, *Performance Test of a TMS Calorimeter*, KfK 4085, June 1986, Submitted to Nucl. Instr. Meth.
- 8) UA1 Collaboration, *A Proposal to Upgrade the UA1 Detector in Order to Extend Its Physics Programme*, CERN / SPSC/83-48, SPSC / P92 add.3, Aug. 1983.
- 9) ICARUS Collaboration, *The ICARUS Proposal*, INSN/AE-85/7, July 1985.
- 10) G. Charpak, R. Bouclier, A. Breskin, R. Chechik, Nucl. Instr. and Meth. **192** (1982) 235.
- 11) G. Charpak, H. Czyrkowski, A. Farilla, and S. Majewski, Nucl. Instr. and Meth. **196** (1982) 555.
- 12) R. M. Schaffer, *Electrophotography*, second ed., Focal Press, London, 1975.
- 13) G. Charpak, D.F. Anderson and B.J. Kross, *Electrostatic Imaging of Charges Liberated in Dielectric Liquids by Ionizing Radiation*, FERMILAB-PUB-87/79, submitted to Nucl. Instr. and Meth.A.
- 14) G. Charpak, private communication.
- 15) R.A. Muller et al., Phys. Rev. Lett. **27** (1971) 532.
- 16) J. Prunier et al., Nucl. Instr. Meth. **109** (1973) 257.
- 17) H. Zaklad et al, IEEE Trans. Nucl. Sci. **NS-19** (1972) 206.
- 18) K. Masuda et al., Nucl. Instr. Meth. **160** (1979) 247.
- 19) A.J.P.L. Policarpo, Space Sci. Instruments., **3** (1977) 77.
- 20) W.H.-M. Ku, C.J. Hailey and M.H.Vartanian, Nucl. Instr. Meth. **196** (1982) 63.
- 21) D.F. Anderson, Nucl. Instr. Meth. **A242** (1986) 254.
- 22) D.F. Anderson, Nucl. Instr. Meth. **A245** (1986) 361.
- 23) S. Suzuki et al., Nucl. Instr. Meth. **A245** (1986) 366.

- 24) S. Suzuki et al., Nucl. Instr. Meth. **A245** (1986) 78.
- 25) B.A. Dolgoshein et al., Sov. J. Particles Nucl. **4** (1973) 70.
- 26) H. Zaklad et al., "Liquid Xenon Multiwire Proportional Chambers for Nuclear Medicine Applications", submitted to the First World Congress of Nuclear Medicine, Tokyo, Japan, Sept. 30- Oct. 4, 1974, LBL-3000 ABST.
- 27) D.F. Anderson et. al., *Liquid Ionization Chambers with Electron Extraction and Multiplication in the gaseous Phase*, FERMILAB-PUB-87/81, submitted to Nucl. Instr. and Meth.A.
- 28) R.C. Muñoz, J.B. Cumming, and R.A. Holroyd, J. Chem. Phys. **85** (1986) 1104.
- 29) CRC Handbook of Chemistry and Physics, 67th ed, R.C. Weast ed. in chief, CRC Press Inc., Boca Raton, Fl. 1986.

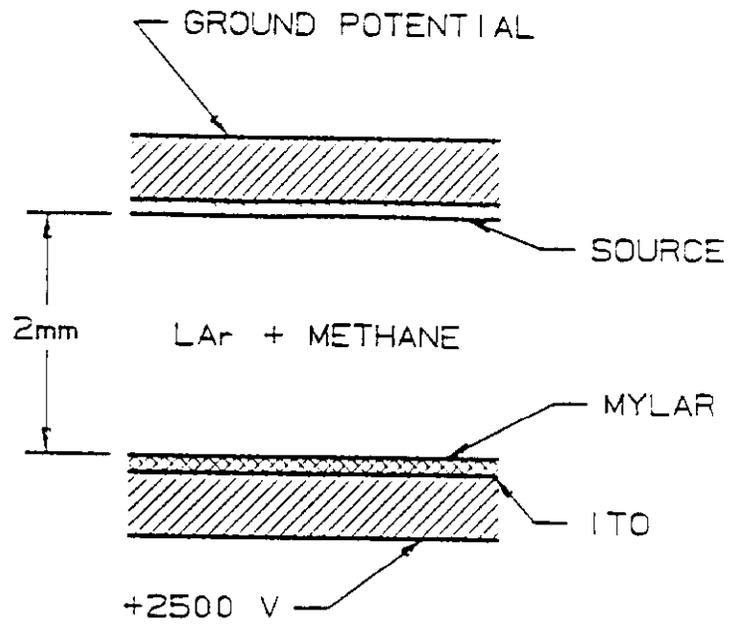


Figure 1

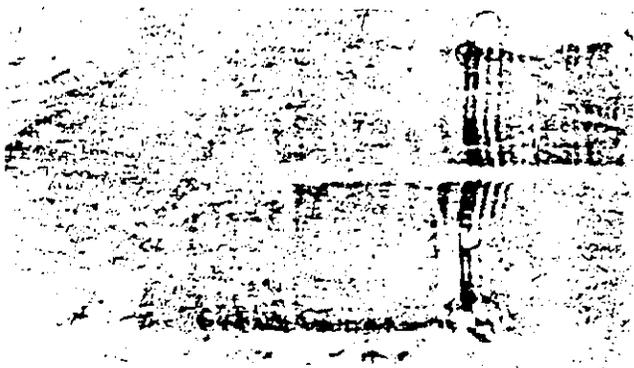


Figure 2a

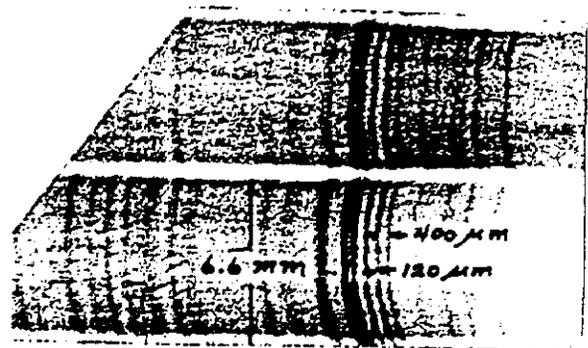


Figure 2b

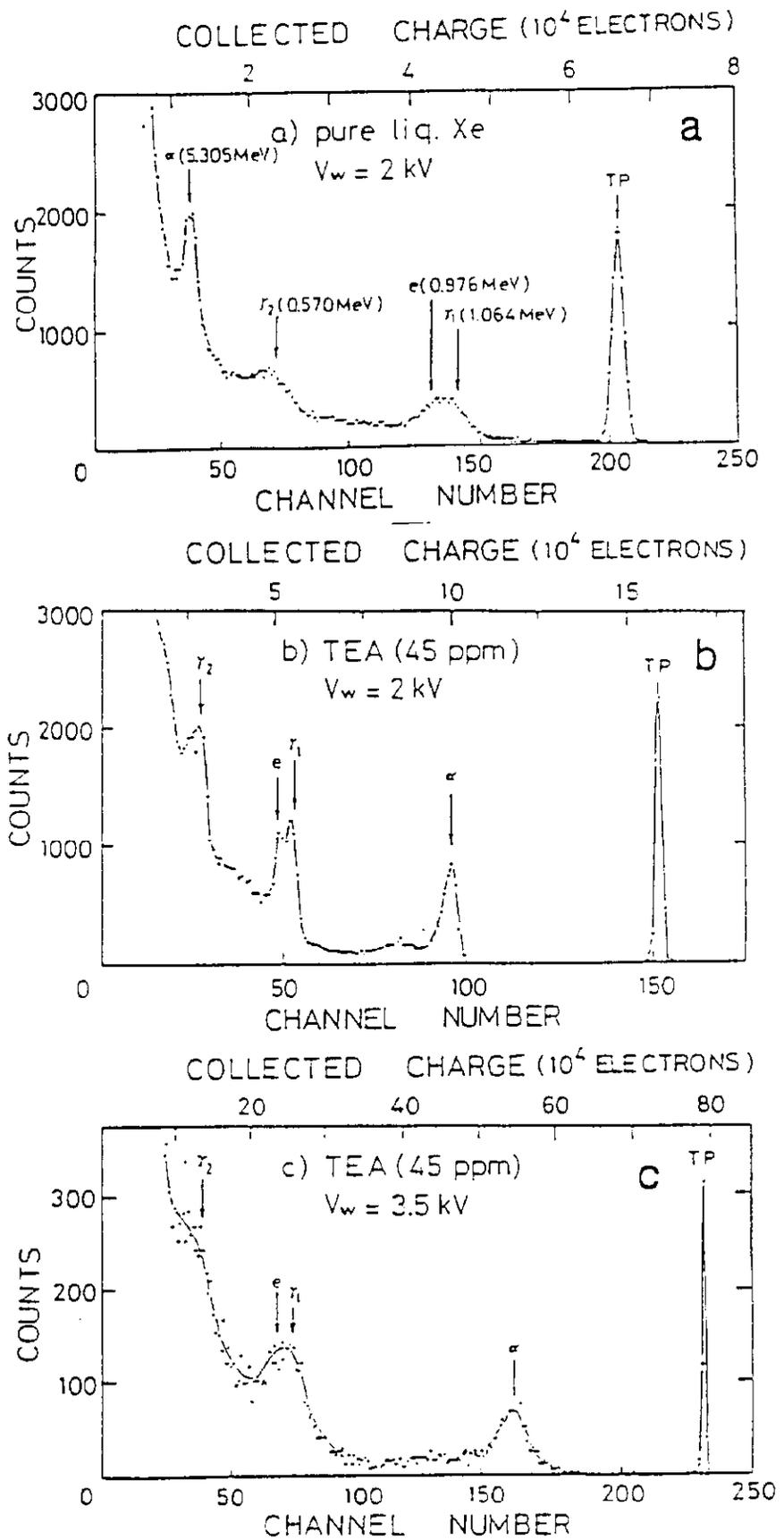


Figure 3

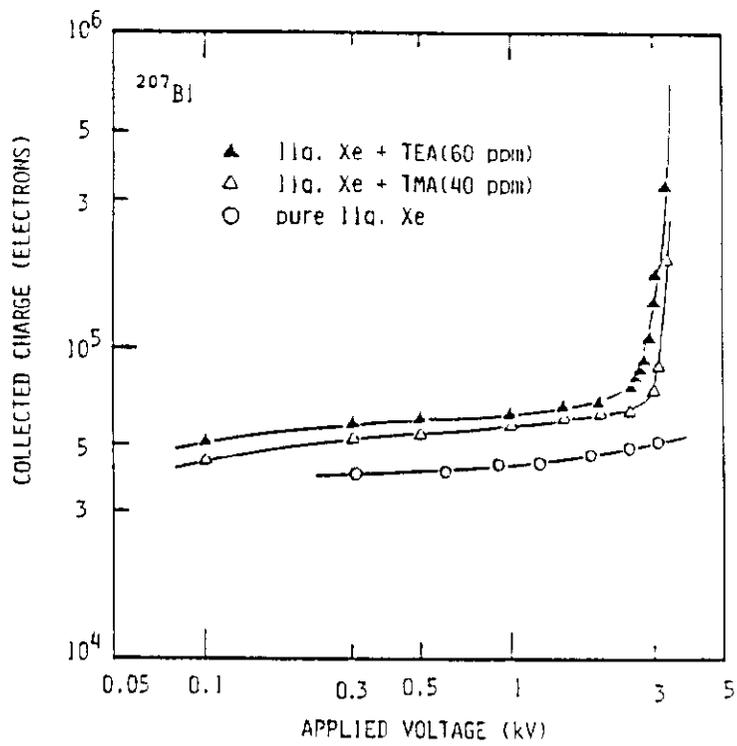


Figure 4

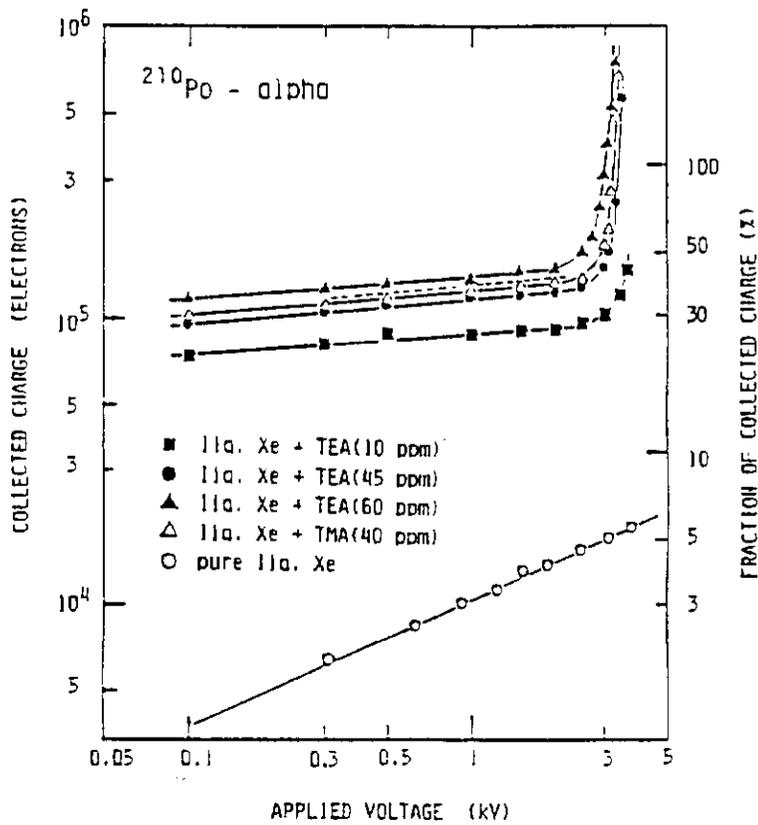


Figure 5

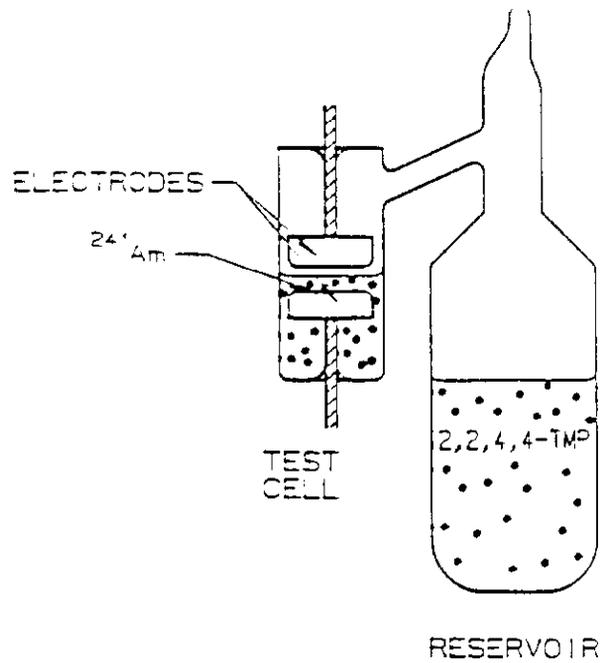


Figure 6

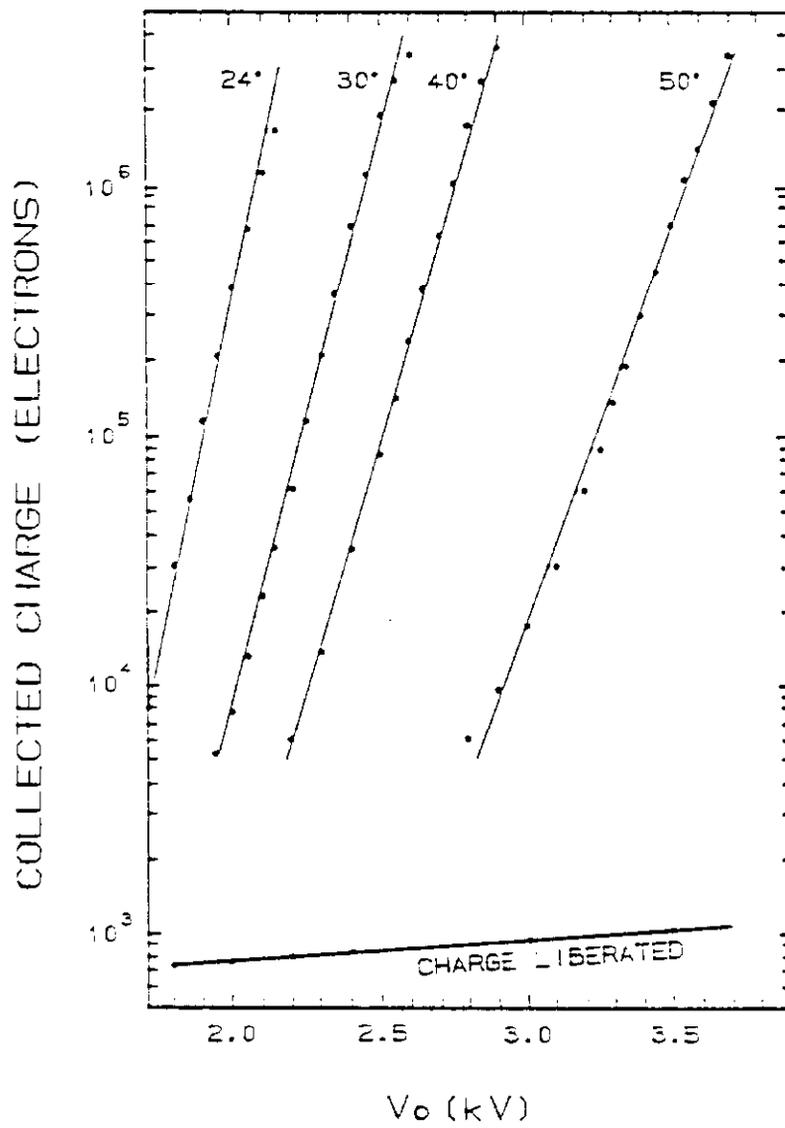


Figure 7