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THE PROSPECT OF HIGH SPATIAL RESOLUTION FOR COUNTER EXPERIMENTS AT NAL: A NEW PARTICLE DETECTOR USING ELECTRON MULTIPLICATION IN LIQUID ARGON

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ABSTRACT

We have observed the multiplication of ionization electrons in liquid argon near the surface of a fine wire electrode. This effect shows promise of being used in a detector having high spatial resolution, since the density of liquid argon permits a thin gap and close wire spacing, and the pulse is large enough to permit convenient readout.

I. INTRODUCTION

As we probe the structure of matter at higher and higher energies, both at NAL and in cosmic-ray experiments, the need has arisen for a particle detector having the automatic readout of the wire spark chamber but a greatly improved spatial resolution. In the past we have depended heavily upon kinematical constraints for the identification of events. At higher energies it will be inordinately expensive and inconvenient to maintain the same degree of constraint either by increasing the size or strength of the spectrometer magnet or by increasing the lever arms between the wire spark chambers, (which would increase the size of nearly all the detectors in the experiment). Moreover, hyperon beam experiments at NAL and cosmic-ray experiments in balloons or satellites require short lever arms.

II. FACTORS WHICH LIMIT SPATIAL RESOLUTION IN GAS-FILLED WIRE CHAMBERS

To improve the gas-filled wire chamber by a significant factor, one must first understand its basic limitations:

1. In a typical wire chamber 8 mm thick and full of Ne gas at STP, only ~ 25 ion pairs are formed by the passage of a minimum ionizing particle. If the track is inclined only 15° from the normal, those 25 electrons are spread laterally over a distance of ~ 2 mm.

2. If the wire chamber is operated in the proportional mode,[1] the average electric field in the gap is ~ 1000 V/cm. During the 8 mm drift toward the anode, the electrons diffuse[2] laterally about 1 mm.

3. If operated in the spark mode, the electrons diffuse from 0.1 to 0.4 mm during the 0.1 to 1 μsec before the application of high voltage.[3] The spark itself is a plasma 0.5 to 1 mm wide.

4. When a delta ray is created in the chamber wall or gas, it deposits most of its ionization at the end of its track, and this can be several mm from the track which is to be measured.

It is therefore not surprising that however the primary electrons are detected, and however closely the wires in the array are spaced, it has not been possible to determine the center of a track in a gas-filled wire chamber with an rms error less than $\epsilon \approx 0.2 \tan\theta + 0.2$, where ϵ is in mm and θ is the angle the track makes with respect to the chamber normal.

III. ADVANTAGES OF LIQUIFIED NOBLE GAS AS A WIRE-CHAMBER MEDIUM

In November 1968, one of us suggested that these limitations could be reduced by two to three orders of magnitude, by using liquified noble gases.[4] Although useful electron multiplication had never been observed in any liquid, we were encouraged by the fact that electrons were free and had a high mobility in sufficiently pure liquid argon.[5-8] High electron mobility is essential for avalanche multiplication.

In liquid argon, a minimum ionizing particle produces 10 ion pairs per μm. In a average field of ~ 10^5 V/cm the electrons diffuse laterally at most 5 μm when traversing a 50 μm gap.[9] The fundamental resolution appears to be limited not by electron diffusion or delta rays but by the maximum attainable density of wires or by possible adverse coupling between neighboring wires.

There may exist some room-temperature liquid or solid that can amplify ionization electrons and give an accurate determination of their location, but our primary effort has been directed toward the use of liquid argon as a chamber medium. Liquid argon is inexpensive ($26 per 100 liters) and is one of the easiest cryogenic liquids to handle, since the chambers can be maintained at the proper temperature simply by immersing them in an open bath of liquid argon. Along the beam direction layers of He gas between sheets of aluminized mylar can be used to reduce the density without introducing a serious heat load.

Two Previous Attempts to Construct a Liquid-Filled Spark Chamber

K. Reibel and R. A. Schluter at ANL in 1963 attempted to make a high resolution optical spark chamber by using liquid helium between parallel plates 0.127 mm apart. A 32 kV pulse with a 15 to 25 nsec risetime was applied approximately 200 nsec after the passage of a cosmic ray. As these authors point out, there are at least four possible reasons why track sensitivity was not observed: (1) the ion pairs recombined

during the 200 nsec before the application of the hV pulse, (2) the primary electrons were swept out during the first 10 nsec of the pulse rise without producing secondary electrons, (3) field emission from the cathode was competing as a source of ions, and (4) the electron mobility in liquid helium may be too low at the fields used to permit avalanche multiplication.

The second attempt was motivated by the need for a "high mass" spark chamber for neutrino experiments. A. Riegler[11] at CERN in 1968 used liquid argon between parallel plates 2 mm apart and applied a 100-kV pulse with a 10-nsec risetime, approximately 400 nsec after the passage of a charged particle. A 2 kV clearing field prevented complete recombination while causing the electrons to drift only 0.5 mm before the high voltage was applied. In this case some track sensitivity was observed. When a well collimated beam was sent through a region in the upper half of the chamber, approximately 65% of the sparks occurred in that half. The other 35% of the sparks occurred in the lower half where there was no beam. The chamber was checked by sending the beam through a region in the lower half, and as expected the percentages reversed.

A fundamental problem in any liquid filled parallel plate spark chamber is field emission from the cathode. According to D. W. Swan,[12] even at field strengths where both secondary avalanche ionization and field emission both occur weakly, they can in combination produce a space charge distortion at the cathode which enhances their rates of ion production. This instability can lead to full spark breakdown.

IV. CHAMBER CONSTRUCTION AND USE AS AN IONIZATION CHAMBER

Learning this, we designed a chamber having a high field at the anode and a much smaller field at the cathode. Safe values for the cathode field would be below 10^5 V/cm while a calculation based on the assumption that liquid argon behaves like a dense gas indicated that fields of $\sim 5 \times 10^6$ V/cm would be required at the anode for avalanche multiplication. Accordingly, we built a chamber (see Fig. 1) with a very fine anode wire within a concentric cylindrical cathode. Not accidently, this electrode design is identical to that of gas-filled proportional and Geiger-Muller counters.

Our chamber was pumped to a pressure of 10^{-3} mm Hg with a Kinney mechanical pump, immersed in an open bath of liquid argon, and filled by condensing gas that had been purified by passing it over hot (280° C) calcium chips. Preparing the chamber by pumping to 2×10^{-5} mm Hg with a mercury diffusion pump has not significantly altered any of our observations.

By using a charge - sensitive amplifier, we were able to observe individual ionization pulses as 1-MeV γ rays from a Zn^{65} source produced Compton electrons in our chamber. A stopping 1-MeV electron produces 30,000 ion pairs

(5×10^{-3} picocoulombs) in liquid argon. The pulses above our noise level of 10^{-3} picocoulombs were counted and found to occur at a rate of ~ 200/sec.

V. DISCOVERY OF ELECTRON MULTIPLICATION IN LIQUID ARGON

In April, 1969, using a 4 μm diameter tungsten wire and a field of 1.5×10^{6} V/cm at its surface, we first saw large pulses of uniform height when the chamber was exposed to 1-MeV γ rays from the Zn^{65} source. Since then we have used more convenient 8 μm and 13 μm diameter wires. The electrical connections and a typical pulse are shown in Fig. 2. The risetime of 20 μsec is established by the mobility of Ar^{+} ions and the decay time of 100 μsec is determined by the load on the chamber.

Since the avalanches were undoubtedly occuring at the surface of the anode, we had what we wanted, an effect which could give us a large pulse from a cylindrical region of small diameter. All large pulses were nearly the same size, with a pulse height distribution having a fwhm of 30 to 50% at a particular operating voltage. The rate of the large pulses was ~ 6/sec, indicating a rather low efficiency for the Compton electrons. The pulse size could be varied from 1 to 50 picocoulombs by varying the operating voltage. Since our γ source gave us a uniform distribution of Compton electron energies, and since the large pulses were of uniform size, the counter was not giving us proportional amplification but acting like a Geiger-Muller counter, whose pulses are independent of the amount of initial ionization. Moreover, when the chamber was irradiated with 125-keV γ rays from a Co^{57} source, pulses of the same size and shape resulted. Pulses intermediate in size between the 10^{-3} picocoulomb ionization pulses and these larger pulses were looked for but not seen. Our pulse size is roughly the same as that produced by gas-filled pure argon Geiger-Muller counters, indicating that the space charge limiting mechanism may be the same in both cases.

When the pressure on the argon is dropped from 5 psig to 0 psig there is an increase in the pulse height by a factor of approximately two. We have been unable to take a repeatable set of measurements of this phenomena, and we suspect that there is an additional variable which we are not controlling. It is also conceivable that the discharge produces some cavitation (bubble formation) near the wire anode and that this process is enhanced by lowering the hydrostatic pressure.

VI. KNOWN AMPLIFICATION MECHANISMS IN GAS-FILLED DETECTORS AND THE ROLE THEY MIGHT PLAY IN A LIQUID ARGON WIRE CHAMBER

By assuming that liquid argon behaves somewhat like gaseous argon compressed to the same density (785 atm pressure at 273° K) we believe that we have been able to understand some of the processes going on inside our detector. There are many properties of argon gas which may be considered as functions of the variable E/d, where

E is the electric field and d is the density. Therefore by confining our calculations to those quantities that depend only on E/d, and by using, whenever possible, quantities measured in the gas at the appropriate values of E/d, we can get some idea of what to expect from a liquid argon chamber. In addition we have made use of the previous work[5-8, 12] on the movement of charged particles in liquid argon at low electric fields.

In Fig. 3 are shown mechanisms known to take place in gas-filled counters. Ion pairs (Ar^+ and e^-) are produced by ionizing radiation, and begin drifting in an electric field. In liquid argon, at fields below about 200 kV/cm, the Ar^+ ions drift toward the cathode with a velocity given by:[13]

$$v_+ = \mu_+ E, \tag{1}$$

where the positive ion mobility

$$\mu_+ = 2.8 \pm 0.3 \times 10^{-3} \text{ cm}^2/\text{V-sec} .$$

Before drifting apart an appreciable distance, some ion pairs recombine, and the fraction surviving recombination is $1/(1 + K/E)$ for minimum ionizing particles,[8] where $K = 1.1 \pm 0.2$ kV/cm.

Electrons will drift freely in liquid argon with a velocity[7] given by

$$v_- = 3160 \, E^{1/2} , \tag{2}$$

where v_- is in cm/sec and E is in v/cm. If the chamber has been pumped out with a mechanical pump, and filled with purified liquid argon, electrons will be captured in the liquid to form slow negative ions at the rate[8] of 5 to 10% per mm of drift, in fields of 10 kV/cm. Presumably dissolved oxygen which escapes the purification process is the leading agent for electron capture. Thin chambers such as we propose (~ 0.1 mm) should be relatively free from impurity capture, particularly when (in principle) only a few dozen electrons are actually needed near the anode to form a large pulse reliably. Those electrons which neither recombine nor are captured will drift toward the anode, inducing an emf on that electrode.

All these mechanisms had been known to occur in liquid argon for 15 to 20 years (note the dates of Refs. 5-8)--but our interest was to supply the free electrons with enough energy from the electric field to make inelastic collisions. If atoms are ionized by these collisions, new electrons are produced, which in turn make more collisions, and an exponential avalanche results. This process is called the first Townsend process. In a uniform electric field, the electron amplification factor is $e^{\alpha r}$

where r is the distance through which the avalanche has developed and α is a proportionality constant called the first Townsend coefficient.[14] In our case, the electric field is not uniform and the electron multiplication factor is given by

$$M = \exp\left[\int \alpha \, dr\right]. \tag{3}$$

For gas-filled proportional counters, this equation has been modified by Rose and Korff[15] to treat the fact that the electrons are not in equilibrium with the field (i.e. the field changes considerably over one mean free path). For a liquid filled chamber, however, this modification would not be necessary because of the short mean free path.

The possibility of excitation collisions changes this picture considerably. Starting with one electron, the first Townsend process results in M electrons. During the avalanche, a number of argon atoms N' will be left in an excited state. Each excited atom has a probability p of producing a secondary electron through one of two processes: (1) by emitting a UV quanta which produces a photoelectron at the cathode or from an impurity molecule, or (2) by ionizing an impurity molecule as a result of a collision with it. The second Townsend coefficient γ is defined as $N'p/M$ and is the average number of secondary electrons released for each of the M electrons in the previous avalanche. The result is the liberation of $M\gamma$ secondary electrons whose avalanche results in $M^2\gamma$ electrons. This process continues, and the grand total is given by

$$M + M^2\gamma + M^3\gamma^2 = \frac{M}{1 - M\gamma} \quad (M\gamma < 1). \tag{4}$$

If $M\gamma$ is less than 1, the series converges providing an amplification which is larger than the number M. On the other hand, if $M\gamma$ is greater than 1, the series diverges and the gain is infinite, the pulse size being limited by space charge. This space charge provides a quenching action because the positive ions move slowly and their presence lowers the field at the surface of the anode for a time longer than that required for both primary and secondary Townsend processes. At higher applied voltages, this condition is not met, and a continuous discharge or spark develops. In gas-filled Geiger-Muller counters, it is a good assumption that there is a critical field below which the Geiger discharge is effectively shut off. The amount of positive space charge necessary to reduce the field below this value is given by:

$$q = \frac{c}{2}(V - V_t),$$

where q is in picocoulombs, and C is the capacitance in a pf of the space charge-cathode system and V_t is the threshold voltage. C is given by

$$C = \frac{0.5564\ KL}{\ell n\ (r_c/r_s)} \ ,$$

where r_s is the space charge radius, r_c is the cathode radius, L is the active length of the anode in cm, and K is the dielectric constant of liquid argon, 1.53. Because of the slow logarithmic dependence on r_s and the short ionization mean free path, we can set r_s equal to the anode radius without introducing significant error.

D. W. Swan has measured the breakdown voltage of liquid argon for a parallel plate geometry. By noting a deviation from linearity in a plot of breakdown voltage vs plate spacing, he believes that he has detected the first Townsend process. Figure 4 shows the amplification factor calculated for a cylindrical liquid argon counter using Eqs.(3) and (4) and assuming Swan's values for α. His careful work is the closest approach to a measurement of the first Townsend coefficient in liquid argon ever reported. If his value is correct, and the second Townsend coefficient is small ($\leq 10^{-3}$), we surely would have seen intermediate size pulses due to proportional amplification. On the other hand, the apparent lack of a proportional region could be explained by a large value for γ. It is shown in Fig. 4 that if γ is 10^{-3}, the amplification increases from 10 to the space charge limit by an 18% increase in voltage. If γ is 0.5, the same range in amplification would be covered by a 2% increase in voltage. Since the field variations on the surface of the anode are much greater than 2%, the larger value of γ would explain the moderate efficiency for large pulse production as well as the negligible number of intermediate pulses for any voltage below the sparkdown voltage. It is important to note that at the Geiger threshold, this theory predicts at the mean free path for an ionization collision (the reciprocal of the first Townsend coefficient) is 0.2 to 0.3 μm. Even sub-micron irregularities on the surface of the anode could be an important influence on the development of the avalanche.

VII. QUANTITATIVE RESULTS IN CYLINDRICAL LIQUID ARGON CHAMBERS

Despite the fact that our liquid argon particle detector provided pulses of uniform height, our first observations indicated that its efficiency was quite low, never reliably above 3%. The count rate was a steep function of voltage (see Fig. 5) with a counting threshold at ~ 5200 V and a spark discharge threshold at ~ 6400 V. These sparks are not related to ionizing radiation in any obvious way: if all sources are removed the count rate for large pulses is < 1/min at 6200 V but when the voltage is raised to 6400 V a spark occurs in a few seconds.

Because of the low counting efficiency, we speculated that only portions of the anode wire had conditions suitable for the development of large pulses. A microscopic examination of the tungsten and stainless steel wires showed prominent surface irregularities which could be responsible for variations in field intensity as well as variations in the distance through which the avalanche develops. Our later investigations used Ni-Fe and stainless steel wire that had been drawn through 25 diamond dies in a special process by the California Fine Wire Co.* Our best results (see Fig. 6) were obtained using this wire, whose surface appears mirror-like (except for a few blemishes) when viewed through a 1000× oil-immersion microscope. Using this wire the efficiency for Compton electrons is reliably 20% and has been as high as 50% for some 5-minute periods of observation.

Contrary to our expectations, the use of "smooth" wire eliminated rather than enhanced the sharp rise in count rate at a specific voltage. In principle (although apparently not in practice) every point on a "smooth" wire should behave like every other point, so that below V_t the count rate (for large pulses) is zero and somewhat above V_t, the efficiency is ~ 100%. While we were using rough wire, pulses were first seen at 1.5×10^6 V/cm, and sparking occurred at 1.8×10^6 V/cm. Using the smooth wire, large pulses were seen at fields as low as 3×10^5 V/cm. (The field values given here are based on the assumption that the wire is a perfect cylinder and are not intended to represent the actual field experienced by the electrons as they avalanche.)

VIII. PRELIMINARY RESULTS WITH A THIN GAP MULTI-WIRE LIQUID ARGON CHAMBER

We are now testing a chamber which has a flat cathode, separated from an array of fine anode wires by 25 to 700 μm (adjustable) of liquid argon. The cathode has a "point" alpha source (Am^{241}, 5-MeV alphas) deposited on its surface and is movable in X and Y so that the source may be positioned opposite any section of wires and moved along the length of the wires. The range of a 5-MeV alpha is 50 μm in liquid argon and the source (diameter 25 μm) provides a cylinder of ion pairs ~ 125 μm in diameter.

We have observed α-ionization pulses with this chamber. They contain approximately 10^{-2} picocoulombs and are nearly uniform in size, having a pulse height distribution whose fwhm is about 20%. We have observed a moderate increase in pulse height with increasing voltage, but this is consistent with the reduction in columnar

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recombination expected at higher fields,[16] and not consistent with proportional amplification. We have determined the strength of our source with a calibrated gas-filled ionization chamber, and this calibration has enabled us to determine that the efficiency for 10^{-2} picocoulomb ionization pulses in our multi-wire liquid argon chamber is between 95 and 100%.

In a preliminary run using an α-source spot separated from 16 "smooth" stainless steel wires by 500 μm of liquid argon we were able to determine that using ionization pulses the spatial resolution for locating stopping 5-MeV alphas was better than 100 μm. The anode wire diameter was 13 μm.

Many large pulses have also been seen in this thin gap chamber but not for a long enough period of time to permit a systematic study as yet. With this chamber and a smaller α-source spot we should be able to determine our spatial resolution for large pulses, even if it is as small as 30 μm.

IX. HOPES AND PLANS FOR CONTINUED DEVELOPMENT

For the application of this effect in high spatial resolution detectors of large size, two questions are of paramount importance:

1. Is the efficiency close to 100% over some range of operating voltage?
2. Do closely spaced anodes trigger each other through some secondary mechanism?

We hope that we have given the impression that work is steadily progressing, and that it is merely a matter of time before we will have stable 100% efficiency and independent wire amplification. Why are we so confident?

1. We can add diatomic molecules such as carbon monoxide, nitrogen, or possibly even oxygen to act as a quenching agent. Unfortunately, few substances have any appreciable solubility in liquid argon. Quenching agents have been shown to provide the following beneficial effects in gas-filled proportional and Geiger-Muller counters:

(a) The UV quanta from excited argon atoms are not absorbed in pure argon, but are absorbed by and ionize or dissociate even a small amount of diatomic (or polyatomic) quencher. The Geiger discharge thus occurs entirely at the anode. The second Townsend process then takes place much more quickly and the discharge is less likely to go into the continuous mode.

(b) The UV quanta spread the discharge along the wire but not from wire to wire.

(c) Argon has metastable states, which can emit UV quanta and initiate another discharge ~ 100 μsec after the primary discharge. When a quencher is present, these states lose their energy through inelastic collisions rather than by UV emission.

(d) In pure argon, the Ar^+ ions from the discharge drift to the cathode and can

liberate secondary electrons there through field emission as they are neutralized. The Ar^+ ions transfer their charge to polyatomic quenching atoms quite readily, which then dissociate upon reaching the cathode. Unfortunately, diatomic quenchers are not very efficient in this regard.

2. We have found that 2 anode wires, 3 mm apart within an 8-mm cathode in liquid argon, act as independent counters. Since we are operating in a space charge limited region, the anode should emit UV quanta in all directions and in pure argon this would trigger the other wire. (Perhaps unavoidable trace impurities have acted to prevent UV quanta from traveling far from the anode, while proving the impurity ionization necessary for the Geiger-type discharge.)

3. It is possible to develop even smoother wire by providing California Fine Wire Co. with the necessary feedback in the form of electron micrographs of their product.

Manufacturing Fine Wire Anode Arrays

We have been investigating three approaches for manufacturing the fine wire anode arrays:

1. Winding wires onto a substrate covered by a type of glue which can be softened by the application of heat. Minimum anode wire diameter ~ 4 μm, minimum wire spacing ~ 20 μm.

2. Weaving wires into a cloth, using glass fibers or insulated wires for the cross weave. Minimum anode wire diameter ~ 4 μm, minimum wire spacing ~ 20 μm.

3. Using thin film techniques to provide us with lines which are, say 1 μm wide and 0.1 μm high, and then plating more metal onto them so that the result is an array of half-cylinders bonded to the surface. In our present state of knowledge, we prefer cylindrical conductors to ribbon-shaped conductors because the electric field at their surface is more uniform. Minimum anode diameter ~ 1 μm, minimum anode spacing ~ 5 μm.

The first two approaches appear easier, but the third holds the promise of smaller and more closely spaced conductors as well as lower cost, since tens of thousands of anodes can be manufactured simultaneously, rather than being wound or woven one at a time.

Time Resolution Attainable

Let us assume that we have an array of parallel anodes, 4 μm in diameter, separated from a flat cathode by 100 μm of liquid argon, and that the operating potential is 2000 V. The electron transit time from cathode to anode is 9 nsec. If through the addition of a quenching agent, the Geiger discharge occurs close to the anode,

then the sheath of positive argon ions will develop in a few nsec. The pulse seen on the anode is generated by these receeding ions, and rises very rapidly at first since ions in a high field have a high velocity. As shown in Fig. 7, the pulse rises to 10% of its height in the first 16 nsec and rises to 20% of its height in 55 nsec. Full pulse height occurs when the Ar^+ ions reach the cathode, 35 μsec later. A quantitative calculation has predicted the pulse shape shown in Fig. 2 quite well, and it remains to be seen (experimentally) whether the calculation is also correct for the close electrode spacings which we propose. If so, the liquid argon wire array can produce pulses which are both faster and larger than those from gas-filled proportional wire arrays. This is contrary to the rule of thumb that Geiger counters are "slow," and results from the fact that the detector proposed has both high fields and small spacings. In order to exploit the time resolution of this device, it is necessary to treat each anode or group of anodes as a separate data line. Many closely spaced anodes are necessary to achieve high speed, but it is not necessary to read them out separately. Practical considerations may dictate that the anodes be connected in groups in order to prevent the number of separate data lines from becoming overburdening.

X. SCANNED READOUT FOR HIGH SPATIAL RESOLUTION

For many applications (the most important of which is cosmic-ray research) it will be sufficient to periodically scan the anodes, and at the expense of time resolution reduce the readout to a single data line. In this way we can achieve the ultimate in spatial resolution since each line is interrogated separately during the scan. Scanning is possible because the decay time of the pulse is determined by the RC time constant of the load, and can be made long (many milliseconds) if R is sufficiently large. In Fig. 8 we show one idea for a scanned liquid argon wire array. We have considered many readout schemes, but this one seems superior in cost and feasibility. The success of this approach depends upon the availability of switches which have the following properties:

1. They must be inexpensive (< 20¢ each) and small enough to be assembled in a high density array so that anode wires spaced 20 μm apart can be bonded to them with a minimum of wire handling.

2. They must be non-conducting in darkness so that when the wire connected to a switch is charged to ~ 1 volt by a Geiger pulse less than 10^{-9} amps will flow through the switch.

3. Less than ~ 50 nsec after a switch is illuminated it becomes conducting, so that if the anode wire connected to it has been charged to ≥ 0.2 volts, then more than 10^{-3} amps will flow through the switch.

4. When a switch is illuminated it also develops a small photo-voltaic emf, which provides a fiducial pulse for every anode wire.

Fairchild Semiconductor Division is manufacturing such switches, 128 per integrated circuit chip, spaced 63 μm apart.[17] This spacing is dictated by existing wire bonding techniques. If only internal connections are required, they may be spaced 15 μm apart. These chips offer more externally accessible switching elements than any others that we have heard about. They are not difficult to manufacture and could be made by anyone in the integrated circuit business. Their cost (per chip) could, in our estimation, drop below $10, even assuming that the high-energy physics community were the only buyer. The operation of the readout scheme shown in Fig. 8 is described as follows.

When the laser beam starts its sweep, the scaler is zeroed. As it sweeps over the switches, small pulses are generated on the common line which increment the scaler. The scaler thus keeps track of the location of the laser beam each switch supplying what is effectively a fiducial pulse. Meanwhile, dc charge levels of about 10 picocoulombs are appearing on some of the anodes as charged particles traverse the chamber. Since the switch leakage is less than 10^{-9} amperes, less than 10% of the charge will leak from the anode during the ~1 msec sweep time. When the switch connected to a charged anode is closed by the light beam, a large pulse will be seen on the common line, which causes the contents of the scaler (i.e. the address of the struck wire) to be stored.

This scheme is capable of handling about 10^3 events/sec but this number can be increased to 10^5 events/sec by including information from a device having better time resolution but poorer spatial resolution. Such a device could be another liquid argon wire chamber, where the wires are connected in groups of, say 100, and each group treated as a separate data line. It would have negligible dead time and give fast, large pulses, suitable for prompt decision making and rough track localization. This appears to be a better candidate than the scintillation hodoscope (which is fast but costs ~ $200 per photomultiplier), the proportional wire chamber (which is slower and provides smaller pulses), or the wire spark chamber (which has ~ 1 msec dead time).

XI. COMPARISON WITH OTHER FILMLESS TRACK LOCATING DETECTORS

In Table I we outline the essential characteristics of the liquid argon wire chamber and compare it to presently available filmless detectors.

XII. PULSED OPERATION

By pulsing the high voltage, we can in principle obtain good time resolution even though our readout scheme is slow. Fast counters would be used to determine when

interesting tracks have passed through our chamber and a high voltage pulse would be applied promptly thereafter. This would be a useful mode of operation when looking for a rare event in a heavy background. There are two difficulties.

1. In liquid argon, ion recombination takes place in $< 10^{-11}$ sec. Clearing fields of about 10^3 V/cm are necessary to allow half of the ion pairs to escape recombination. If the chamber has 4 μm diam wires, separated from the cathode by 100 μm of liquid argon and if the cathode has a field of 1 kV/cm, the electron transit time from cathode to anode is ~ 65 nsec. This precludes anything but the simplest decision-making in determining when to pulse the chamber. The pulse must rise in ~ 5 nsec or faster in order to make the chamber sensitive before the electrons are swept out. Increasing the gap will increase the electron transit time at the sacrifice of spatial resolution.

2. The hV pulse will induce 10^4 picocoulombs or more on every anode and it will be desirable to have the track-induced discharge be comparable to this by going into the spark mode. We have found that sparks of this size damage the fine anode wires.

Nonetheless, we are now setting up in a parasite beam at the LRL Bevatron. By using a cylindrical chamber with an 8 mm cathode diameter and a 12 μm anode diameter, we have several microseconds in which to apply a hV pulse before the primary electrons are swept into the anode. We will use a clearing field, and we can deliver a 10 kV pulse less than 100 nsec after the passage of a charged particle.

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Table I. Filmless Track Locating Detectors[a]

	Gas-filled scanned spark chamber[b]	Gas-filled decision-making[c] wire spark chamber	Gas-filled wide-gap spark chamber (vidicon)[d]	Gas-filled proportional wire chamber (decision making[c])	Scintillator photomult. hodoscope	Liquid-argon scanned wire chamber[e]	Liquid-argon decision-making[c] wire chamber[e]
Spatial resolution (μm)	250	250	60	250	2000	10	250
Time resolution (sec)	2×10^{-7}	2×10^{-7}	5×10^{-7}	2×10^{-7}	2×10^{-9}	10^{-3}	5×10^{-8}
Digitization delay[f] (sec)	10^{-3}	10^{-7}	10^{-2}	2×10^{-7}	3×10^{-8}	10^{-3}	5×10^{-8}
Dead time of element (sec)	10^{-3}	10^{-3}	-	5×10^{-7}	5×10^{-9}	10^{-5}	10^{-5}
Dead time of array (sec)	10^{-3}	10^{-3}	10^{-3}	0	0	0	0
Max background rate (sec^{-1})	5×10^{6}	5×10^{6}	2×10^{6}	2×10^{6} per wire	2×10^{8} per element	10^{3}	10^{5} per wire
Max event rate (sec^{-1})	10^{3}	10^{3}	10^{2}	2×10^{6} per wire	2×10^{8} per element	10^{3}	10^{5} per wire
Cost per element[g]	$2	$2	-	$10	$200	$1	$2
Self triggering?	No	No	No	Yes	Yes	Yes	Yes
Problems in magnetic fields?	Yes	Yes	No	No	Yes	No	No

[a] all figures are order of magnitude estimates for purposes of rough comparison only.
[b] includes sonic, magnetostrictive, sparkostrictive, magnetic core memory, capacitor memory, and vidicon readout.
[c] a distinction has been made here between scanned readout which interrogates each element separately and decision-making readout, which reads all elements simultaneously and can perform fast logic decisions.
[d] requires scanning, say, a $10^4 \times 10^3$ raster in 10^{-2} sec.
[e] figures in these columns are predictions only.
[f] time delay between the passage of a particle and the first useful determination of its position.
[g] an attempt has been made here to include fabrication as well as components.

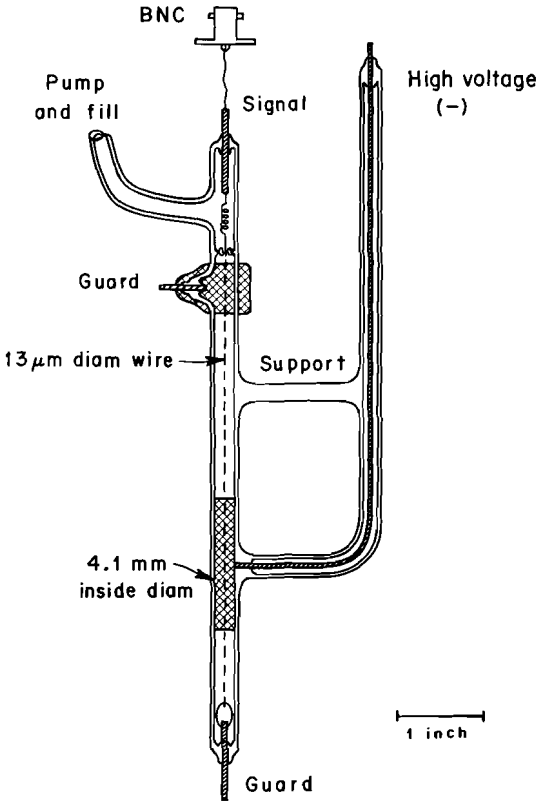


Fig. 1. Cylindrical liquid argon chamber. Shaded surfaces are conductive.

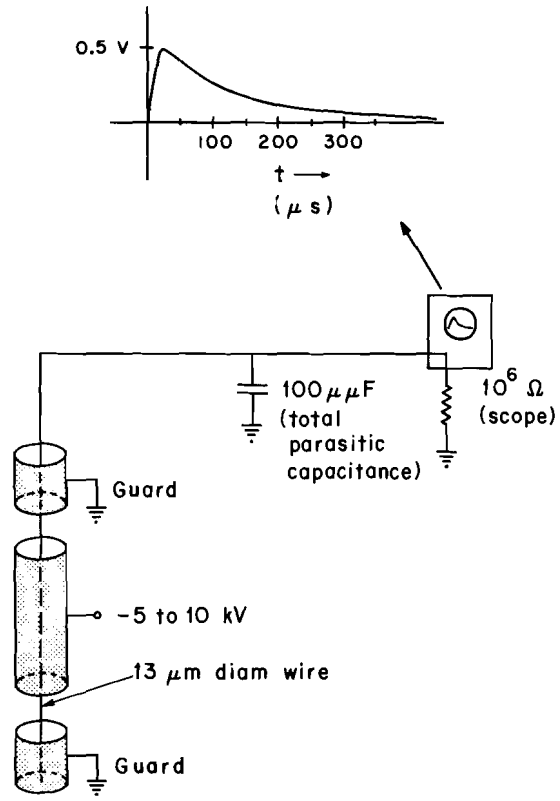


Fig. 2. Electrical connections to chamber and a typical 50 picocoulomb pulse.

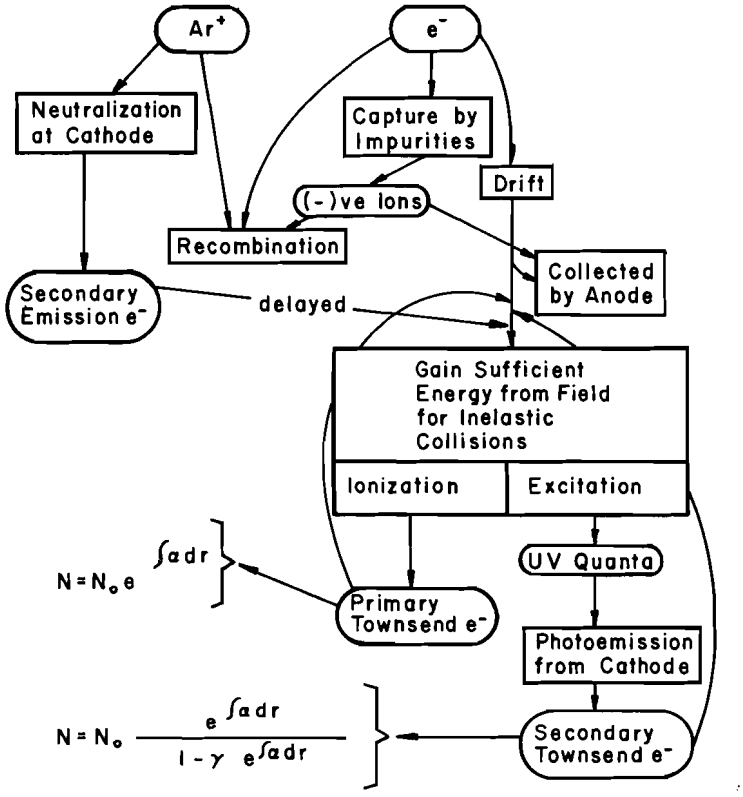


Fig. 3. Known amplification mechanisms in gas-filled detectors.

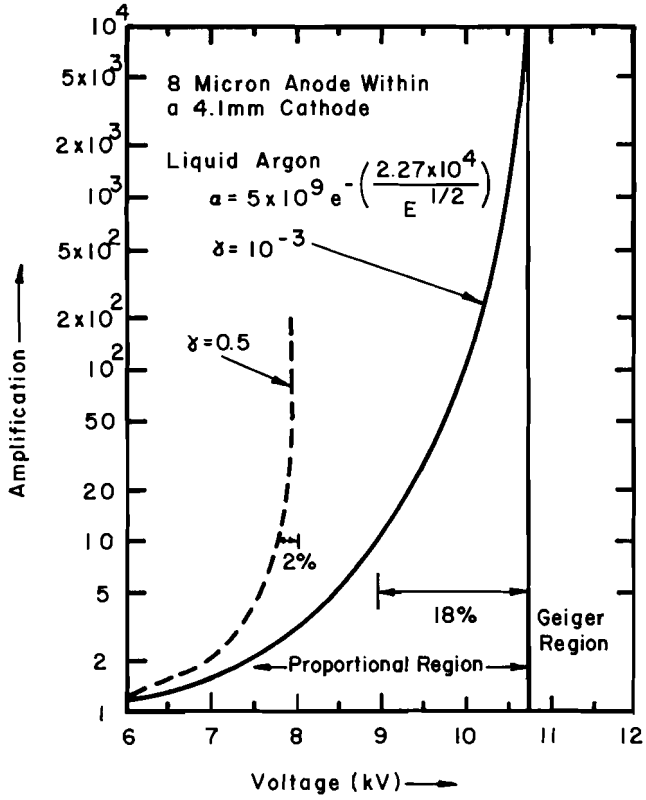


Fig. 4. Amplification as a function of voltage, predicted for liquid argon. (See text.)

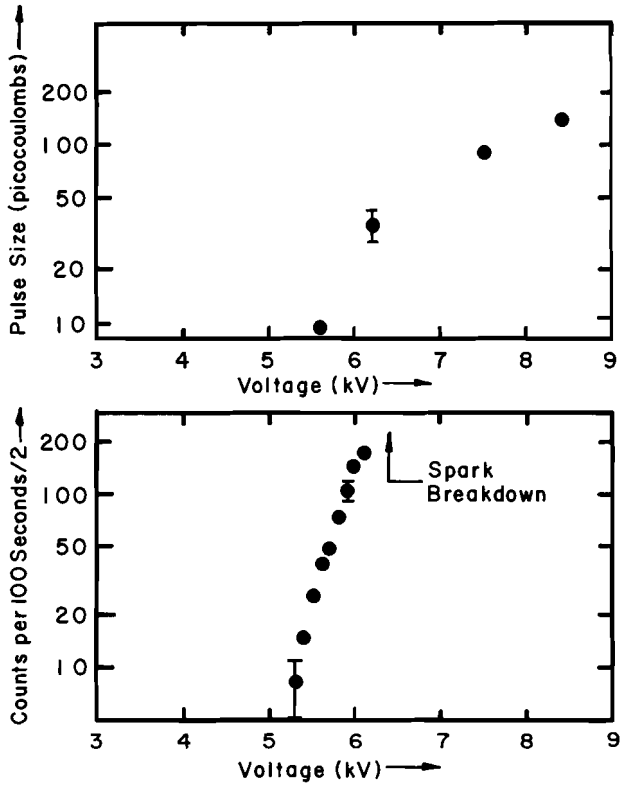


Fig. 5. Count rate and pulse size as a function of voltage for a rough tungsten anode, 13 μm in diameter.

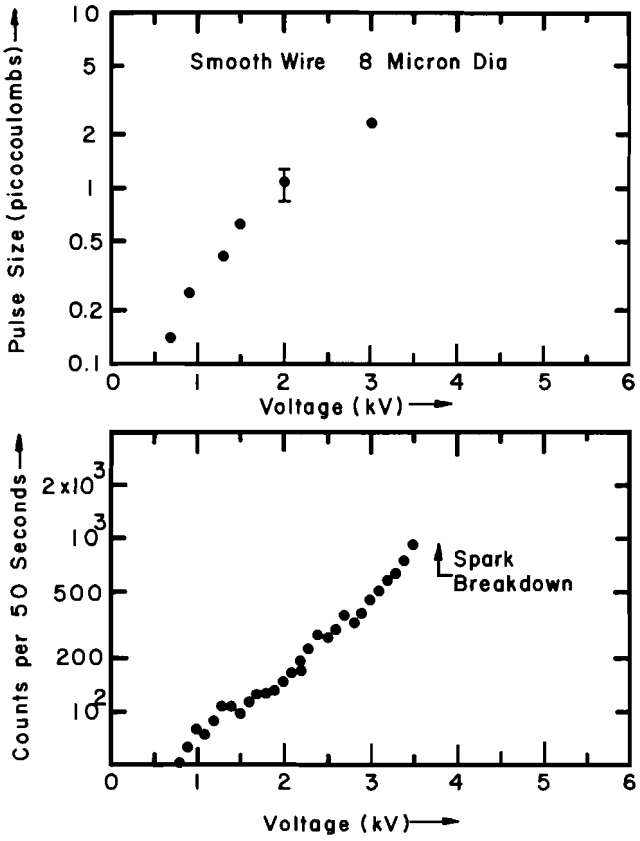


Fig. 6. Count rate and pulse size as a function of voltage for a smooth Ni-Fe anode wire 8 μm in diameter.

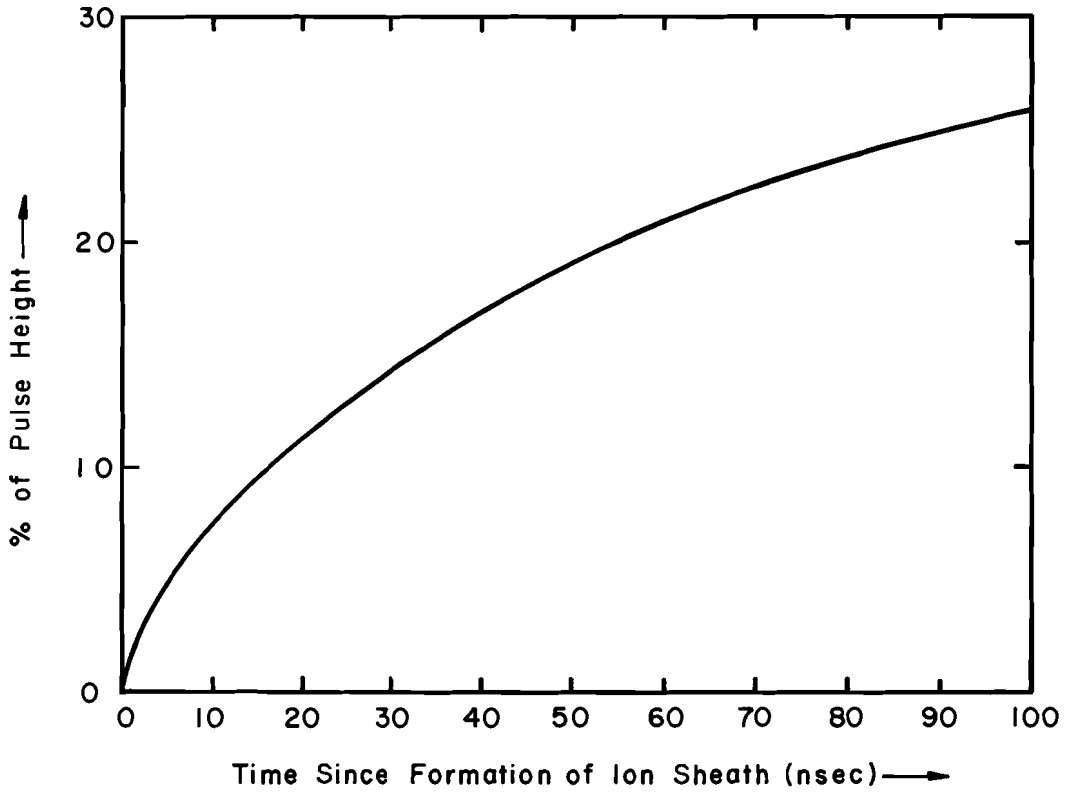


Fig. 7. Pulse height as a function of time, predicted for a 5 μm anode separated from a cathode by 100 μm of liquid argon. Operating potential 2000 V.

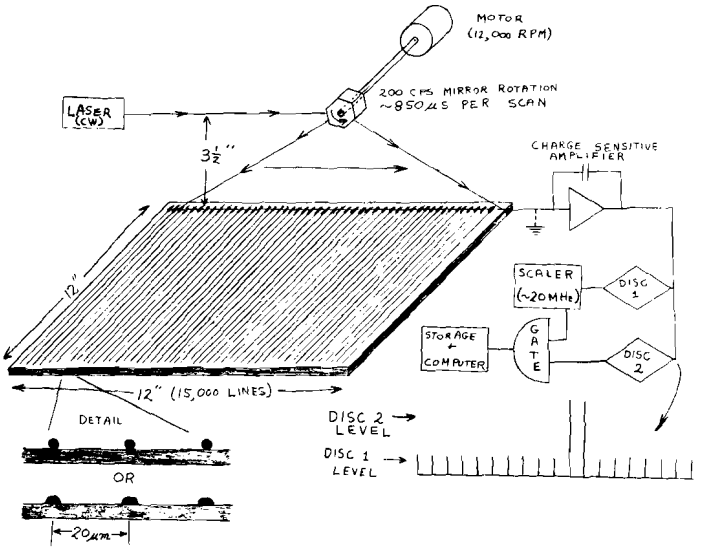
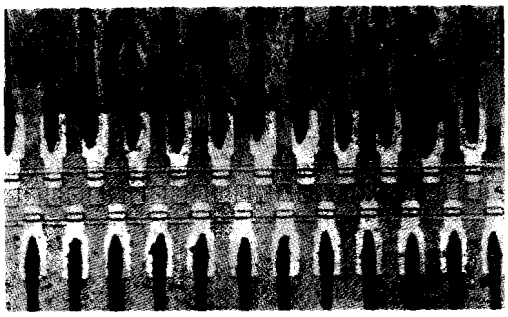


Fig. 8. Suggested readout scheme for a high resolution liquid argon wire chamber.



FAIRCHILD PHOTOTRANSISTOR ARRAY

DEVICES ARE SPACED 63 MICRONS APART

128 PER CHIP

LIGHT SENSITIVE AREA IS 43 X 43 MICRONS

WIRES SHOWN HERE ARE 25 MICRONS DIA

DARK CURRENT $<10^{-9}$ amperes AT 0°C

LIGHT CURRENT $>10^{-3}$ amperes AT 1 MICROWATT OF LIGHT POWER PER DEVICE } V_{CE} = -0.2 volts

PEAK SENSITIVITY AT 8000 Å

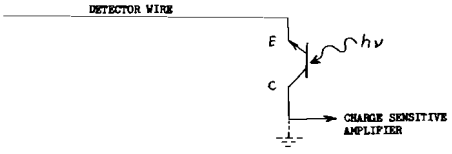


Fig. 9. Fairchild linear array of light-controlled switches. (Photo compliments of Fairchild Semiconductor Division of Fairchild Camera Co.)