Electronic method of detecting particles in two-phase liquid–gas systems

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The principle of operation and characteristics of two-phase electron detectors of ionizing radiation are described. The detectors are filled with liquid argon. Particles are detected in various types of detectors of this kind, described in the paper, on the basis of the electrostatic emission of the electron image of the particle track from the liquid to the gas phase. It is shown that the tracks of ionizing particles in the liquid argon can be detected without film by means of a system of wire electrodes at a 100% particle-detection efficiency.

INTRODUCTION

In our opinion, there is promise for developing electron methods of detecting particles in liquids in the following directions:

1) fast electronic detection of neutral radiation (neutrons, γ rays, and especially neutrinos);[1-3]

2) the achievement of a high spatial resolution (down to 10^{-3} cm, which is made possible by the low diffusion of the electrons, their high density in the particle tracks, and the short mean free path of δ electrons in a liquid);[4-8]

3) the use of liquid electron detectors as total absorption spectrometers.[9]

In addition, we should mention an electronic detector of tracks in liquid hydrogen; the promise of such a detector does not require further comment. However, at the present time the only liquid available in large quantities in which there exist free electrons is a liquified noble gas. Noble gases being chemically inert, it is relatively easy to extract electronegative impurities from them. Therefore, virtually all studies on liquid electron detectors have been made with a liquified noble gas (argon and, less frequently, xenon).

Previous investigations of electronic processes in noble gases and in liquids (see, for example, ref 1) undertaken with a view to creating liquid electronic detectors of particles similar to the well-known gas-discharge detectors (Geiger counters, spark chambers, etc.), and also the subsequent unsuccessful attempts to achieve a controlled discharge in liquid argon,[10] prompted us to seek an essentially new method of detecting particles in liquids.[2] Such a method, which is based on transferring the electron image of the particle track from the liquid to a gas phase with subsequent detection of the "electron ghost" of the track in the gas phase was investigated and reported on for the first time by the authors at the Conference on Filmless Spark and Streamer Chambers at Dubna in April 1969. In ref. 11 we reproduced the first photograph of α-particle tracks in liquid argon obtained in a two-phase electronic detector. Finally, in our report[12] we announced results that indicated the possibility of filmless extraction of information from such a detector.

Before we turn to a discussion of the characteristics of two-phase electronic detectors, we should mention the great successes in detecting electrons in a homogeneous liquid medium achieved by Alvarez's group.[7] They have achieved a 100% detection efficiency for α particles in liquid xenon by means of a discharge from the surface of a thin wire (diameter less than 10 μ). In a field $2 \cdot 10^6$ V/cm they obtained 100-fold multiplication of the electrons. They also established the possibility of 15-μ accuracy in the detection of α particles by collecting electrons (without their multiplication in the liquid) on thin wires arranged at a distance of 50 μ from each other and at a distance 0.7 mm from the α source.

However, the creation of liquid track detectors of large volume on the basis of the method discussed above and developed in refs. 4-8 would seem to us to be a very difficult technological problem. In contrast, it is much simpler to detect the electron image of the track in a two-phase detector, because the detection is made in the gas phase; there is then no need to use electric fields of high intensity and the characteristics of the two-phase detector are similar to those of gas-discharge detectors.

1. GENERAL CHARACTERISTICS OF TWO-PHASE ELECTRON DETECTORS

In a two-phase detector, ionizing particles are detected as follows:

1) An electric field "extracts" some of the electrons from the tracks of the ionizing particles in the liquid, so that they do not recombine with positive ions;

2) electrons that have avoided recombining in the track drift to the liquid–gas interface;

3) electrons pass through the interface and emerge from the liquid into the gas;

4) the electrons drift in the gas;

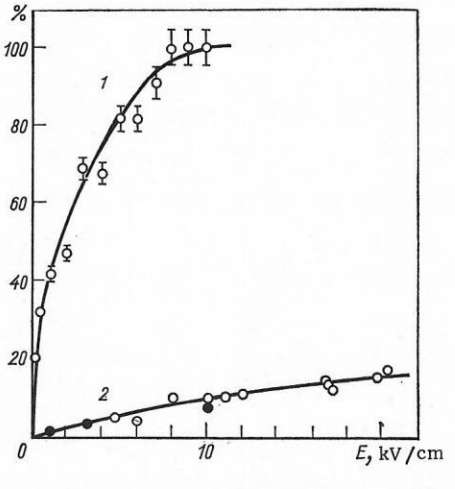

Fig. 1. Relative yield of electrons from the track of an x-ray photoelectron (1) and an α particle (2) as a function of the electric field strength in the liquid argon. For curve 2 the open circles are the results of measurements by the method of observing electroluminescence (see the text); the black circles are the results of ionization measurements in liquid argon.[16]

5) the electrons in the gas are detected by any of the known methods (for example, from a gas discharge).

The first two processes are characteristic of any liquid electronic detector; the remainder only of a two-phase detector. Since our method is based on the possibility of electrons being extracted (emitted) from the liquid phase into the gas phase, such detectors can be conveniently termed emission detectors, to distinguish them from two-phase detectors of other types (for example, Charpak's well-known liquid chamber,[13] in which the discharge occurs in gas bubbles). Let us now discuss the basic characteristics of these processes.

Extraction of electrons from the tracks of ionizing particles in the liquid. This depends on the ionizing power of the particle, the electric field strength, and the properties of the liquid. In Fig. 1 we present data obtained on the relative yield of electrons from particle tracks in a homogeneous electric field of various strengths in liquid argon. The liquid was ionized by α particles or x rays. The energy of the x rays was about 30 keV (the mean free path of the photoelectrons in the liquid was 0.002 g/cm^2); the energy of the α particles was 5.15 MeV (mean free path of about 50 μ in a liquid of density 1.3 g/cm^3).

Thus, we are dealing with ion densities per unit track length that exceed by a factor 10 (for x rays) and 300 (for α particles) the ion density per unit track length of a relativistic particle. Nevertheless, as can be seen from Fig. 1, if the field strength is 10 kV/cm, practically all the electrons are extracted from the tracks of the x-ray photoelectrons and about 10% of the electrons are extracted from the α-particle tracks. Naturally, for relativistic particles the total electron yield will be obtained in appreciably weaker fields ($\sim$1 kV/cm). In liquid xenon (density 2 g/cm^3) almost exactly the same picture is observed (as in Fig. 1) for the yield of electrons as a function of the electric field strength.[2]

It is important to note that if there is no electric field virtually all the electrons recombine in a time less than 1 μsec in the tracks of x-ray photoelectrons in liquid xenon. During this time, there is a dense plasma in the photoelectron tracks, and this prevents the escape of electrons. Experiments showed that if the electric field is about 10 kV/cm, the electrons are confined by the plasma for approximately 0.1 μsec.[2]

Drift of free electrons in the liquid. This process in the electric field is accompanied by two processes that are very important for the operation of the electron detector: diffusion and trapping of electrons by electronegative impurities. In the range of temperatures (around 100°K) and field strengths (1-10 kV/cm) of practical interest, the electrons drift in the liquid argon at a velocity $(2\text{-}3)\cdot 10^5$ cm/sec. At a lower temperature of the liquid, the drift velocity of the electrons is higher.[2]

The electron diffusion coefficient in a field of 1 kV/cm was estimated in refs. 2 and 12 and found to be $\sim$ 1 cm^2/sec. At this value of the diffusion coefficient, the electron cloud spreads by $\sim 10^{-2}$ cm when drifting in the liquid over a path of about 10 cm. The diffusion of the electrons in the liquid in strong electric fields determines the limiting accuracy with which the coordinates of a track can be determined.

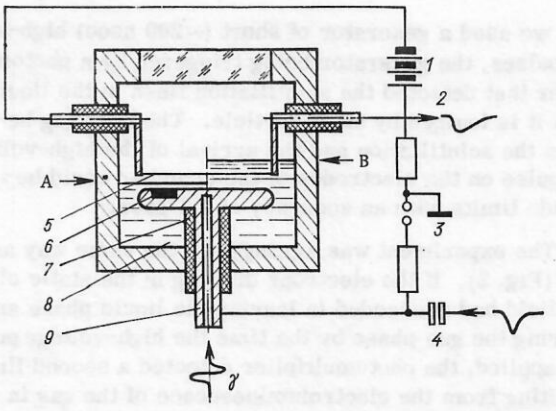

Fig. 2. Experimental chamber: A) variant of the detector with filament above the surface of the liquid argon; B) variant of the detector with heated filament immersed in the liquid argon; 1) storage batteries used to heat the filament; 2) signal output; 3) high-voltage input; 4) input of high-voltage pulse for investigation of the pulse regime of the detector (variant B); 5) wire anode; 6) α source; 7) insulator; 8) liquid argon; 9) collimator.

The probability that electrons are trapped by electronegative impurities (primarily oxygen) depends strongly on the electron energy, the impurity concentration, and the drift time. If the oxygen concentration in the liquid argon is about $2\cdot 10^{-6}$ cm^{-3} and the electric field strength is 5 kV/cm, an electron drifts about 1 cm before it is trapped. A comparatively simple purification of the argon by activated carbon increases the drift length by a factor[14] 50. In our experiments, the gaseous argon was purified by passing it through a jet of metallic calcium heated to 700°C. The walls of the detector were degassed by circulating pure gas continuously for several hours through the interior of the detector. This procedure for purifying the gas and walls of the detector before liquifaction made it possible to avoid appreciable electron losses in the detector over a drift length in the liquid up to 2 cm.

Emission of electrons from the liquid to the gas phase. This is the most important and the least studied process, and it forms the basis of the operation of the two-phase electronic detectors. It had been shown in an earlier experiment[2,12] that in a homogeneous electric field stronger than 3 kV/cm virtually all the electrons leave the liquid argon and enter the gas phase. In Fig. 1 we give additional data that confirm this conclusion. The circles on curve 2 show the number of electrons (in relative units) detected in the gas phase above the surface of liquid argon ionized with α particles. The electrons were detected by means of a photomultiplier from the electroluminescence of the gas, whose intensity is proportional to the number of electrons drifting in the gas.[15] For each field strength, the electroluminescence intensity in the gas was measured in units of the intensity to be expected at the same temperature and density but without liquid in the interelectrode gap.

It can be seen from Fig. 1 (curve 2) that the data obtained completely confirm the data of the ionization measurements in liquid argon,[16] so that the number of electrons that enter the gas phase is equal to the number of electrons in the liquid. From the electroluminescence one can also obtain time properties of the emission. For

this, we used a generator of short (~200 nsec) high-voltage pulses, the generator being triggered by a photomultiplier that detected the scintillation flash in the liquid when it is ionized by an α particle. The time lag between the scintillation and the arrival of the high-voltage pulse on the electrodes of the chamber could be varied in wide limits with an accuracy of 0.1 μsec.

The experiment was arranged in the same way as before (Fig. 2). If the electrons drifting in the static electric field had succeeded in leaving the liquid phase and entering the gas phase by the time the high-voltage pulse was applied, the photomultiplier detected a second flash resulting from the electroluminescence of the gas in the total (pulsed and constant) field.

Figure 3 shows the dependences of the number of emitted electroluminescence photons for different delay times of the high-voltage pulse (from the instant of scintillation) in static fields of different strengths. It is readily seen that these data enable one to find the drift times of the electrons in the liquid and in the gas (the time until the appearance of luminescence and the duration of luminescence, respectively) in the static field. The growth and decay time of the electroluminescence (0.4 ± 0.1 μsec) in Fig. 3 was determined by the time parameter of the electronic equipment employed. Therefore, the emission time of the electrons cannot appreciably exceed 0.1 μsec. Considering that the emission time of the electrons is also determined by the width of the electron cloud along the lines of force of the electric field, which in its turn is determined by the time, ~0.1 μsec, required by the electrons to leave the α track, we conclude that the actual process of emission of an electron through the surface of the liquid argon does not exceed 0.1 μsec.

Drift of the electrons in the gas. This is a well studied process. We shall only point out that the drift velocity of electrons in argon vapor over a liquid at an electric field strength in the range 1-10 kV/cm is $(3-4)\cdot 10^5$ cm/sec, i.e., it exceeds the drift velocity of the electrons in the liquid by a factor of less than 2. Since the energy of the electrons in the gas is much higher than in the liquid, the electron diffusion coefficient increases appreciably in the gas (cf. Einstein's well-known relation). Therefore, to ensure maximal accuracy in recording of the track coordinates in the emission chamber, it is necessary to ensure a minimal drift length of the electrons in the gas.

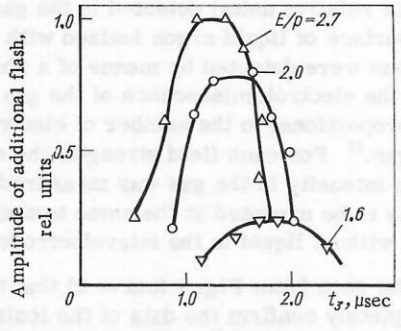

Fig. 3. Amplitude of the additional electroluminescence flash as a function of the delay time of the pulse (T = 108°K). Identical curves were observed at all temperatures from 94 to 120°K; E is the total strength of the static and the pulsed electric fields (V/cm); p is the pressure (mm Hg). The static field strength was 3, 5, and 8 kV/cm (▽, ○, △).

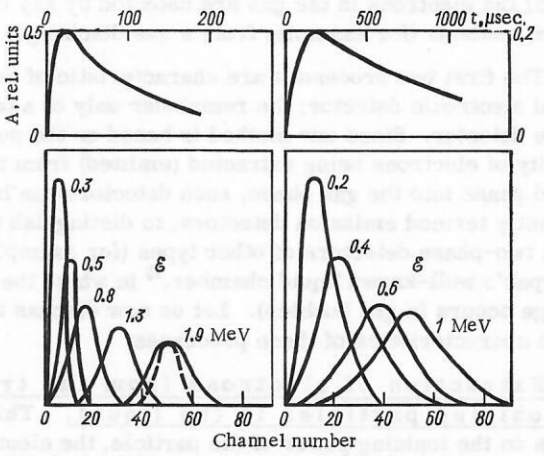

Fig. 4. Typical oscillograms of signals and the pulse-height spectra of the signals in a detector with filament above the surface of the liquid argon (on the left, filament diameter 100 μ) and under the surface of the liquid argon (on the right, filament 30 μ): --- pulse-height spectrum of the signals at an absorbed energy of about 1 MeV without gas multiplication near the surface of the filament; ionization by x rays; the adopted unit is the signal amplitude in the case of complete collection of the electrons in a capacitance of 300 pF.

trons in the gas.

Detection of electrons in the gas. As a rule, the electrons in the gas are detected by gas-discharge methods. Previously, the spark method[11,12] and also electroluminescence of the gas[2] have been used for this purpose. Below, we consider methods of detecting electrons on thin wires surrounded by the gas (see Fig. 2). The advantages of detecting electrons on wires are obvious: Filmless extraction of information about the track coordinates and the ionizing power of the particle passing through the liquid is ensured in a simple manner.

2. TWO-PHASE WIRE DETECTORS

We investigated wire detectors of three types:

A. The electrons from the track of the ionizing particle in the liquid are collected on a thin wire, the anode, which is placed above the liquid parallel to its surface. Near the surface of the wire a discharge arises in a static electric field. The discharge current is measured.

B. The same, except that the wire anode is immersed in the liquid. A gas phase is created around the anode by heating the wire with a direct electric current. The discharge develops in gas bubbles on the surface of the wire.

C. The same as B, but the wire operates in a pulsed regime.

The argon was ionized in these experiments by a pulsed beam of x rays with mean photon energy 30 keV; the x-ray pulse lasted less than 300 nsec. In addition, we used the γ-ray sources ^{60}Co (1.2 MeV) and ^{137}Cs (0.6 MeV), which were placed outside the chamber. Some of the experiments were made with an α-particle source situated on the plane cathode (see Fig. 2).

The ionization of the liquid argon by the x rays was varied by means of copper filters and measured from the ionization current. The total energy $\mathcal{E}$ absorbed in the liquid was determined from the number of ion pairs in the liquid. It was assumed that an energy[17] of 26.4 eV was re-

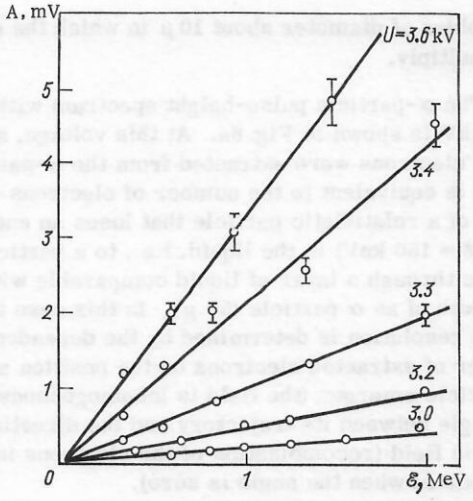

Fig. 5. Signal pulse height A as a function of the energy $\mathcal{E}$, absorbed in the liquid argon: C = 300 pF, R = 0.5 MΩ; filament diameter 100 μ; heating current 0.3 A; pressure 3.5 atm.

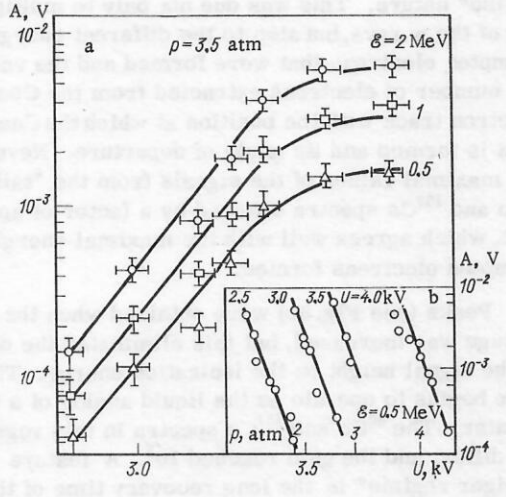

Fig. 6. Dependence of the pulse height A on the voltage U(a) and on the pressure p(b) (filament diameter 100 μ, heating current 0.3 A).

quired for the formation of one ion pair.

Figure 4 shows typical oscillograms of the signals initiated by x rays in detectors of the types A and B, and also the pulse-height spectra of the signals for different absorbed energies $\mathcal{E}$. In our experiments the pulse-height resolution was determined primarily by fluctuations in the energy of the x-ray pulses (see Fig. 4) and also by the instability of the gas pressure (see below). Figure 4 reveals a clear dependence of the signal height A on the ionization energy $\mathcal{E}$. Let us dwell in more detail on the characteristics of the detectors of each type with one wire.

A. Wire anode over the surface of the liquid. We investigated wires of diameter 30, 50, 100, and 200 μ. Since the characteristics of the detectors with different wire diameters were essentially the same, we give the results obtained for the wire anode of diameter 100 μ. To ensure stability of the results, it was necessary to heat the wire with a current of 0.3 A (a thin uncontrollable film of liquid forms on a cold wire in the electric field).

The linear dependence of the signal height A on the absorbed energy $\mathcal{E}$ at different values of the voltage U of the wire relative to the cathode is shown in Fig. 5. It should be noted that in our experiments the capacitance of the wire was very high (300 pF) because of its connection to the storage batteries. We did not take this seriously; however, if necessary, one could readily reduce the capacitance by at least an order of magnitude by making the heating circuit slightly more complicated.

An exponential dependence of the pulse height A on the working voltage U for different values of the absorbed energy $\mathcal{E}$ is shown in Fig. 6. It can be seen from Fig. 6a that at a voltage of about 3.4 kV the growth of the signal with increasing voltage is retarded and that at higher voltages the coefficient of gas multiplication hardly changes at all. The maximal value of the coefficient of gas multiplication in the regime of proportional multiplication was about 500. Figure 6b also shows an exponential dependence of the signal height A on the pressure of the argon vapor at different working voltages U. It can be seen from Fig. 6b that a change in the pressure of the gas by 0.1 atm changed the amplitude of this signal by a factor of almost 2. The strong dependence of the signal height on the pressure and the voltage means that in order to obtain a pulse-height resolution of the detector of ~10% the temperature in the chamber must be carefully controlled thermostatically ($\Delta T \approx 0.1°K$) and the voltage must be well stabilized ($\Delta U/U \approx 1\%$).

We also studied the operation of one wire in the case of a planar multiwire anode (the distance between the wires was 2 mm). The characteristics of such a detector were similar to those described above, but the working voltage was somewhat higher.

It is of interest to mention the increase of the signal height A when the current heating the wire was increased (the gain increased by a factor of 20 when the current was increased from 0.4 to 0.7 A for a wire diameter 200 μ); this effect is due to a decrease in the density of the gas next to the wire when the wire is heated.

B. Heated wire anode in the liquid. Heating a wire immersed in a liquid with an electric current is the simplest way of producing a controlled gas phase on the surface of the wire. If the electric field is turned off, one can observe a large number of gas bubbles on the surface of the heated wire. When a constant field with U ≈ 1 kV is turned on, the large bubbles disappear and, when U > 1 kV, bubbles of much smaller diameter remain.

This phenomenon can be readily explained by electrostriction effects that arise near the surface of the wire in a region of a high gradient of the electric field. First of all, an additional hydrostatic pressure arises in the inhomogeneous field; this pressure facilitates the collapse of the bubbles and their stripping from the wire surface. In addition, because of the temperature gradient, strong radial convective flows of the liquid arise near the wire and these cool the wire. We established that for successful operation of the detector it is necessary to heat wires of diameter from 30 to 100 μ with a current that ensures a power dissipation of about 1-2 W per cm of the wire length. There is an optimal heating current, which may vary in small limits (≤ 10%). The optimal value of the heating current was found experimentally in each experi-

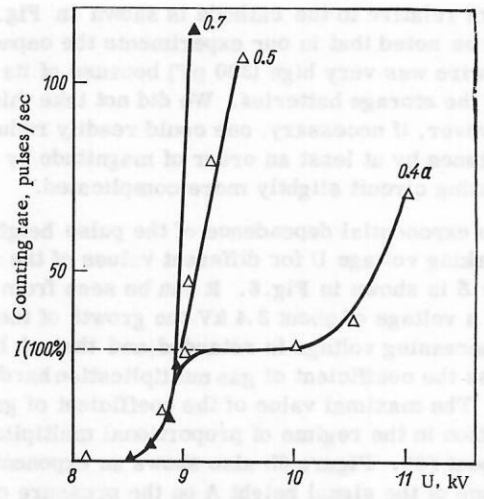

Fig. 7. Counting-rate characteristic of α-particle detector for different heating currents of the wire. In the electric fields used in the experiments, $\sim 6 \cdot 10^3$ electrons were extracted from the track of an α particle (the equivalent energy loss for a relativistic particle is ~150 keV). At a heating current of 0.3 A, there was no count right up to a voltage of 15 kV. The filament diameter was 100 μ; the pressure 4.6 atm; I (100%) is the counting rate at 100% α-particle detection efficiency.

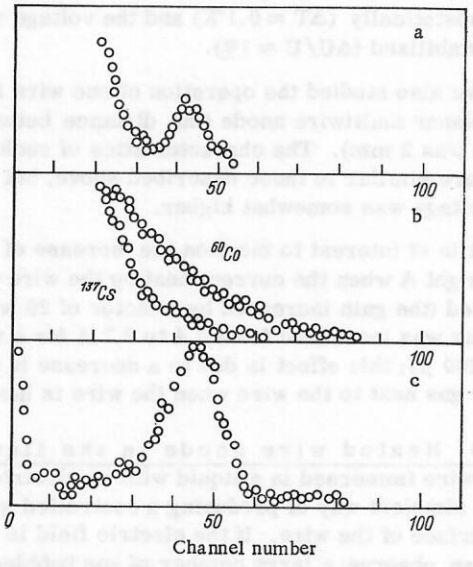

Fig. 8. Pulse-height spectra: a) from α particles (5.15 MeV); b) from ^{60}Co (~1.2 MeV) and ^{137}Cs (~0.6 MeV) γ rays under a regime analogous to the Geiger regime; gain $\sim 10^5$.

ment. In Fig. 7 we show the counting-rate characteristics of a heated wire detector of α particles; 100% efficiency of α-particle detection was obtained for a heating current of 0.4 A (the intensity of the α source was measured in advance in the gas). We shall show below that when the heating current is optimal, gas bubbles of diameter about 10 μ, in which the electrons are multiplied, remain on the surface of the wire. The minimal number of such bubbles per unit length of wire could be readily estimated; indeed, for 100% α-particle detection efficiency at least one electron that induces a discharge must enter the bubbles. The transverse diffusion of the electrons during the time they drift in the liquid argon is not greater than 10^{-2} cm; therefore, the distance between the bubbles is less than 10^{-2} cm. Thus, for each centimeter length of the wire, in the case of an optimal heating current, there exist hundreds of bubbles of diameter about 10 μ in which the electrons can multiply.

The α-particle pulse-height spectrum with voltage U = 6 kV is shown in Fig. 8a. At this voltage, a total of $6 \cdot 10^3$ electrons were extracted from the α-particle track, which is equivalent to the number of electrons from the track of a relativistic particle that loses an energy 150 keV ($\mathscr{E}$ = 150 keV) in the liquid, i.e., to a particle that passes through a layer of liquid comparable with the mean free path of an α particle (50 μ). In this case the pulse-height resolution is determined by the dependence of the number of extracted electrons on the position at which the α particle emerges (the field is inhomogeneous) and on the angle between its trajectory and the direction of the electric field (recombination of the electrons in the track is maximal when the angle is zero).

Figure 8b shows the pulse-height spectra from ^{60}Co and ^{137}Cs γ rays. Unfortunately, the spectra from the γ sources had the appearance of decreasing spectra of a "noise" nature. This was due not only to multiple scattering of the γ rays, but also to the different energies of the Compton electrons that were formed and the variation in the number of electrons extracted from the Compton-electron track with the position at which the Compton electron is formed and its angle of departure. Nevertheless, the maximal values of the signals from the "tails" of the ^{60}Co and ^{137}Cs spectra differed by a factor of approximately 2, which agrees well with the maximal energies of the Compton electrons formed.

Peaks (see Fig. 8c) were obtained when the working voltage was increased, but this eliminated the dependence of the signal height on the ionization energy. The heated wire begins to operate as the liquid analog of a Geiger counter. The ^{60}Co and ^{137}Cs spectra in this regime did not differ, and the gain reached 10^5. A feature of the "Geiger regime" is the long recovery time of the detector. When the counting rate was increased to 10 pulses/sec, the height of the signals began to decrease and at a counting rate of hundreds of pulses per sec it decreased by a

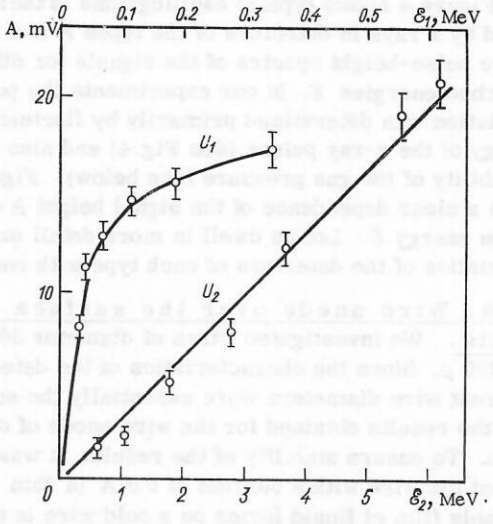

Fig. 9. Signal height A as a function of the energy $\mathscr{E}$, absorbed in liquid argon. The anode diameter was 30 μ; the heating current 0.3 A; the pressure 5.8 atm; the upper scale ε_1 corresponds to U_1 = 4.0 kV; the lower, ε_2, corresponds to U_2 = 3.5 kV.

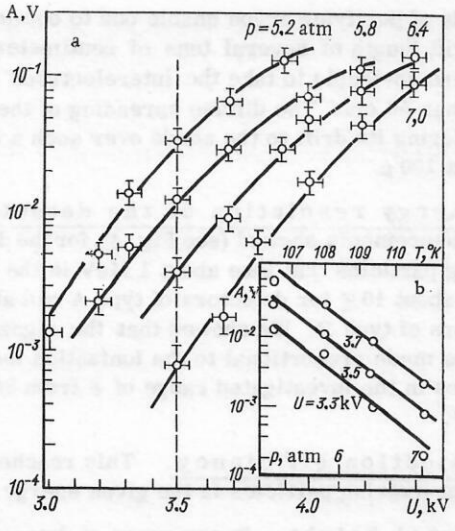

Fig. 10. Signal height A as a function of the voltage U (a) and the pressure in the chamber p (b). Filament diameter 100 μ, heating current 0.3 A; $\mathcal{E}$ = 1 MeV.

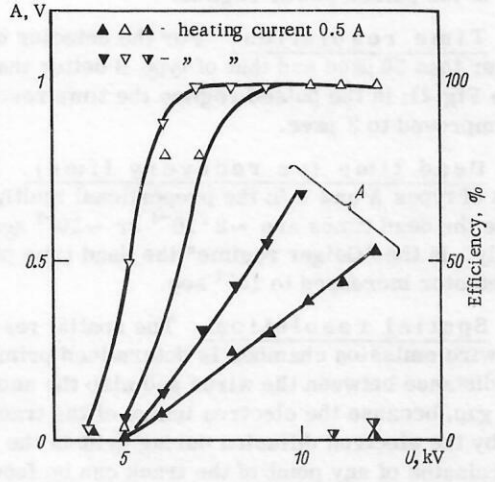

Fig. 11. Dependence of the pulse height A, the efficiency of x-ray detection, and the noise intensity on the pulse voltage (solid, open, and half-open triangles, respectively), $\mathcal{E}$ = 1 MeV, T = 108°K.

factor of 10. This effect can be explained by the long time required to "dissipate" the positive space charge on account of the low ion mobility in liquid argon[18] ($2 \cdot 10^{-4}$ $cm^2 \cdot V^{-1} \cdot sec^{-1}$). Some of the bubbles may also have "perished" in the discharge.

The clearest results indicating the possibility of proportional multiplication were obtained with an x-ray beam (see Fig. 4). It can be seen from Fig. 9 that by varying the working voltage U one can readily obtain proportional multiplication in almost any range of ionization energy. When the voltage was increased, so did the signal height, but the interval of proportional multiplication decreased. In our case the maximal signal with proportional multiplication was 60 mV (gain $2 \cdot 10^4$). From the mean gain and knowing the electric field strength within the bubble and the coefficient of impact ionization in this field, one can readily determine the mean length of the electron avalanche[19] and the bubble diameter needed for it to develop: 10 μ.

In Fig. 10a we have plotted the signal height A against the working voltage U for different gas pressures p. From these data we also plotted the signal height against the pressure for three fixed voltages (see Fig. 10b). It can be seen from the data of Fig. 10 that the signal height depends almost exponentially on the voltage and the pressure, i.e., in this regime the pressure (the temperature of the liquid) and the voltage must be well stabilized.

Finally, we should mention that in the case of proportional multiplication (electron multiplication coefficient $\sim 10^4$) the detector also has a fairly long recovery time. Thus, additional irradiation with ^{60}Co γ rays at a counting rate of about 100 pulses/sec reduced the signal height by 10%.

C. Pulsed regime. When the chamber is irradiated with x-ray pulses (see Fig. 2), one can put negative pulses of controlled voltage on the cathode (simultaneously or with a delay time). The applied pulses reach a maximum in a time of about 30 nsec and then decay in accordance with an exponential law with time constant 0.6 μsec. At the same time there is a static field with strength 1 kV/cm in the chamber.

The results of the measurements are shown in Fig. 11. A characteristic feature of this regime is the large value of the electron multiplication coefficient: $\sim 10^6$. In the controlled pulse regime with $\mathcal{E} \sim 1$ MeV the counter has a 100% detection efficiency, and this is retained for a delay time that does not exceed the time of drift of the electrons to the wire anode (the drift time is controlled by the constant voltage). A further increase in the delay time leads to a rapid decrease in the efficiency similar to the corresponding curves for ordinary spark chambers. The measured memory time of the counter is about 3 μsec.

That a high signal was obtained for a relatively low applied pulse height can be explained by the following circumstances. In a weak static field (less than 1 kV/cm) relatively large bubbles can exist on the surface of the heated wire. In such bubbles, the pulsed field initiates a discharge with a high multiplication coefficient. It is obvious that during the time of a high-voltage pulse (0.6 μsec) a large bubble does not have sufficient time to collapse or be stripped from the wire; this leads to a high gas multiplication. In addition, if the pulsed field is even stronger, there is breakdown of the liquid in the inteelectrode gap. In such a regime, the detector is transformed into a liquid spark counter, which can operate with 100% efficiency.

To conclude this section, let us consider the factors responsible for the background count in liquid electronic detectors. It arises because of radioactivity of the walls and the working liquid and because of cosmic rays; certain specific features of the liquid detector are also important: the presence of particles (both charged and neutral) suspended in the liquid and gas bubbles. In the two-phase detector, background signals can arise because of fluctuations in the surface of the liquid. Since the electric fields are higher in liquid electronic detectors than in gas-filled detectors, this facilitates the emission of electrons from microscopic edges and scratches on the cathode, etc. Such a process is the more probable because the work function for electrons going from the metal

into the liquid is less then for electrons going into a vacuum or gas (for argon by about[20] 0.4 eV).

A particularly serious cause of a background count in gas-discharge detectors is usually considered to be processes that give rise to the appearance of afterpulses that accompany the pulse initiated by the detected radiation. Such processes include the photoelectric effect and stripping of electrons when the cathode is bombarded with positive ions and also metastable excited atoms (molecules). Quenching impurities are used in gas-discharge detectors to combat these factors responsible for a background count. In liquid electronic detectors, it would be difficult to use such impurities in the necessary concentration, since almost all known quenching impurities freeze onto the chamber walls at liquid-argon temperatures and do not dissolve at all well in the liquid.

However, as our experiments have shown, the detectors described here work satisfactorily with argon of maximally high purity. This result can be readily explained. Indeed, for an electron to become free, it must overcome the potential barrier caused by the electrostatic attraction to the surface of the solid (the image potential[21]). The width of this barrier in argon in the presence of an external electric field of $E = 10^3$ V/cm is about $5 \cdot 10^{-6}$ cm, and the mean free path of an electron in the liquid is smaller by a factor of almost 10. Thus, even if an electron has an energy sufficient to overcome the barrier, there is a high probability of its returning to the cathode because of scattering by atoms of the liquid. For example, in ref. 20 the photocurrent in a cell filled with liquid argon amounted to only 10^{-1} of the photocurrent in vacuum.

We should point out that, to improve the characteristics of the detectors, we introduced certain impurities into the working volume: hydrogen, neon, nitrogen, methane, and diethyl amine $(C_2H_5)_2NH$. None of these substances had an appreciable effect except neon. Addition of neon (up to 50% in the argon vapor) facilitated the development of the discharge in regimes A and B; however, this question must be studied.

3. POSSIBILITIES OF TWO-PHASE EMISSION WIRE DETECTORS

The experimental material we have set forth here enables us to evaluate the mechanism of operation and the possibilities of emission wire detectors. Let us dwell first on the possibilities of detectors with one wire.

Working liquid. The working liquid of the detector must satisfy the following requirements: It must be a dielectric in which free electrons can exist; the electrons must be capable of being emitted in the electric field from the liquid to the gas phase. Liquid argon satisfies these requirements. There are many other liquid dielectrics (noble gases, organic liquids) which could evidently be used in emission electronic detectors if it is shown that electrons can be emitted electrostatically from their surface. As the possibility of this has not been adequately studied, we shall consider only detectors filled with liquid argon, whose emission of electrons was observed for the first time in our experiments.[2]

Working volume of the detector. Modern methods of purifying argon enable one to obtain an electron drift length of several tens of centimeters. It is therefore advisable to take the interelectrode gap not more than 50 cm. The diffuse spreading of the electron cloud during its drift to the anode over such a distance is about 100 μ.

Energy resolution of the detector. As the measurements showed (see Fig. 4), for the detection of ionizing particles that lose about 1 MeV in the liquid, this can be about 10 % for detectors of type A and about 20% for detectors of type B. We showed that the signal height could be made proportional to the ionization losses of the particles in the investigated range of $\mathcal{E}$ from 30 keV to 10 MeV.

Detection efficiency. This reaches 100% for different ionizing particles in the given energy range.

Signal height. In any range of detectable ionization loss, the signal height can be raised by an appropriate choice of the working voltage, to 10-100 mV for a capacitance of 300 pF (see Figs. 5, 6, 9, and 10), and to 1 V in the pulsed power regime.

Time resolution. For the detector of type A better than 50 μsec and that of type B better than 200 μsec (see Fig. 4); in the pulsed regime the time resolution can be improved to 3 μsec.

Dead time (or recovery time). For detectors of types A and B in the proportional multiplication regime the dead times are $\sim 2 \cdot 10^{-4}$ or $\sim 10^{-2}$ sec, respectively. In the "Geiger regime" the dead time of the type B detector increased to 10^{-1} sec.

Spatial resolution. The spatial resolution of the wire emission chamber is determined primarily by the distance between the wires and also the anode–cathode gap, because the electron image of the track is spread out by the electron diffusion during drift in the gas. Two coordinates of any point of the track can be found by means of two planar series of wires (the transparency of wire meshes for electrons in liquid is about 30% and in gas 80%).[2,11] To determine the third coordinate – in the direction of the electric field – one can measure the drift time of the electrons from the track to the wire, which is the anode.[2] In two-phase liquid track detectors one can evidently hope to achieve a detection accuracy for the coordinates of the track of about 100 μ, but this question requires further experimental study.

We should also mention a serious shortcoming of the multiwire detector: the need to heat the wires. As an example, let us consider the possibility of using liquid electronic detectors of type B to detect solar neutrinos. The requirements that such a detector must fulfill are formulated in ref. 3.

The equipment must detect electrons from the process of $\nu - e$ scattering or electrons of inverse β decay with an energy of about 1 MeV. In liquid argon, an electron with an energy of about 1 MeV has a mean free path of a few millimeters. To determine the trajectory of such an electron, one must have at least two series of wires that are separated by ≤ 1 mm (the coordinate in the field direction is determined from the drift time). On the average, about 10 wires (five points of the track) will be af-

fected by each event; the ionization energy per wire is about 100 keV. Such an energy can be efficiently detected, and each wire will operate in the proportional regime.

Since the sensitive part of the detector must contain not less than 10 metric tons of liquid argon (about 7 m^3), the total length of the wires (at an interelectrode distance of 0.5 m) must be about 10 km, and a power of about 1 MW will be required to heat the wires.

We see that the use of a two-phase detector to detect neutrinos in such an arrangement would be rather difficult. Nevertheless, the use of two-phase systems for the electronic detection of particle tracks is very promising, especially for detecting neutral radiation.

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