In order to utilize the proposed formalism in concrete calculations one must extend it to the case of particles with spin. The first attempts at describing the deuteron in pd-scattering in the backward direction with the help of a WF in ρ-space (neglecting the **n**-dependence and taking the spin into account nonrelativistically) were done in Ref. 16.

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Study of the detecting properties of a counter filled with solid argon

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The article reports on a study of a cylindrical filamentary counter (filament diameter 10 μ) filled with condensed argon. It is established that the ionization regime of operation is characteristic of both solid and liquid argon. In a counter filled with solid argon, a fraction of the pulses are observed to be amplified to a height exceeding the height of the ionization pulses by about 100 times. The contribution of these pulses to the total pulse-height distribution depends on the experimental conditions and the exposure time and does not exceed 30%.

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1. INTRODUCTION

In recent years many laboratories in various countries have investigated electronic methods of detecting particles in condensed noble gases.[1–10] Development of detectors using such a medium with high spatial and time resolution is necessary for solution of a number of physical problems, for example, for fast detection of neutral radiations and, particularly, neutrinos.[1,4] Most of the studies have used liquid argon or xenon as a working medium. Several studies have been made of detectors employing solid argon and xenon.[2,5,11,12]

Pisarev *et al.*[5] previously reported observation of electron multiplication (a gain up to 150 in the proportional region) near the filament in a counter filled with crystalline argon, and also with xenon. In the present article we report the results of more detailed study of the operation of the counter described previously.[5] Liquid and crystalline argon were used as the working medium.

2. EXPERIMENTAL ARRANGEMENT

The experimental apparatus included a counter, a gas purification system, a temperature regulating system, and the detecting electronics. Descriptions of the basic arrangement of the apparatus and the design of the counter have been given previously.[5] We recall that the counter had a cylindrical cathode of diameter 6 mm and the anode consisted of a gold-plated tungsten wire 10 microns in diameter. A block diagram of the electronics used in the present studies is shown in Fig. 1. The signal from the counter anode was fed to a charge-sensitive preamplifier PA with a sensitivity of 7×10^{12} volts per coulomb,[13] and then to a linear amplifier A (maximum gain 2000) in which the signal was simultaneously amplified and shaped (the integration and differentation

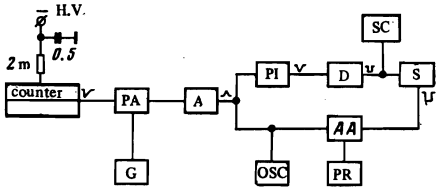

FIG. 1. Block diagram of electronics.

time constants were $\tau_{int} = \tau_{dif} = 1$ μsec). After the amplifier the signal was split; one pulse was fed directly to the input of an AI-128 pulse-height analyzer, and the other through a linear phase inverter PI, discriminator D, and amplifier-shaper S to the analyzer gate. This part of the electronics was intended to reduce the loading of the first channels of the analyzer by noise pulses and other low-amplitude pulses. The pulses from the discriminator output were fed to a scaling circuit SC. The shape of the signals was observed with an oscillograph OSC. The information from the pulse-height analyzer was fed to a digital printer PR. Pulse-height calibration of the electronic equipment was carried out with a pulse generator G through the monitoring capacitance of the preamplifier. The overall nonlinearity of the apparatus, (for a signal change at the analyzer input in the range 1–15 V) did not exceed ±1%. The energy equivalent of the noise in argon for a total input capacitance of 30 pF amounted to about 50 keV (total width at half-height).

The counter was cooled by regulation of the rate of flow of a mixture of gaseous and liquid nitrogen through the temperature stabilizer. Temperature control was accomplished by means of thermocouple and diode probes, and also by means of a wire resistor placed inside the counter. The procedure for obtaining crystalline argon is similar to that described previously,[5] but in individual experiments in order to obtain a crystal of better quality the rate of cooling was reduced to 0.2 degree per hour.

3. EXPERIMENTAL RESULTS

The studies were carried out by irradiating the counter with γ rays from various sources: ^{60}Co, ^{65}Zn, ^{54}Mn, ^{137}Cs, and ^{113}Sn. The counting rate was ~1–100 sec^{-1}, depending on the source activity and irradiation geometry. In Figs. 2 and 3 we have shown typical pulse-height distributions obtained in irradiation of counters filled with liquid and solid argon by γ rays from ^{60}Co and ^{137}Cs sources (the voltage on the cathode was $U = 4$ kV). As can be seen from the figures, the pulse-height distribution corresponding to liquid argon has the characteristic step structure associated with the spectrum of Compton electrons produced by the γ rays in the counter volume. For solid argon the main part of the distribution has the same form, but an extended tail of large pulses is distinctly visible in the spectrum. The arrows in the figures show the points (the inflection points) in the spectra which we took to correspond to the most probable pulse heights corresponding to the edges of the Compton electron spectra.

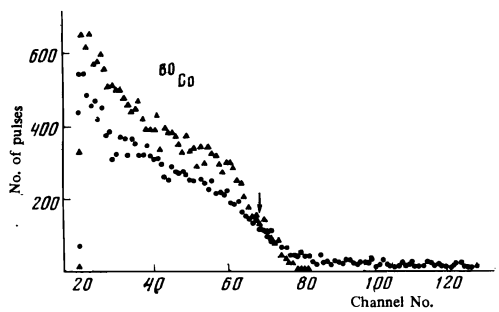

FIG. 2. Pulse-height distributions from ^{60}Co γ rays for counters filled with liquid argon (▲) and solid argon (●). The voltage on the cathode was $U = 4$ kV.

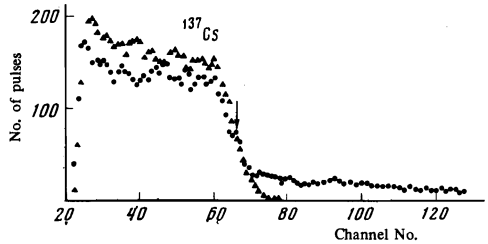

FIG. 3. Pulse-height distributions from ^{137}Cs γ rays for counters filled with liquid argon (▲) and solid argon (●). $U = 4$ kV.

In Fig. 4 we have shown these amplitudes as a function of the voltage on the counter (pulse-height characteristics), obtained by analysis of spectra taken at various voltages. The pulse-height characteristics corresponding to liquid and solid argon are practically identical. It follows from analysis of Fig. 4 that the ionization regime of operation is characteristic both for liquid and solid argon. For voltages above 4 kV, the amplitude of the ionization pulses depends weakly on the applied voltage (the curve practically reaches saturation). For a voltage of about 6 kV in liquid argon, breakdown occurred, but for solid argon no breakdown was observed up to 10 kV.

In Fig. 5 we have shown the height of the ionization pulses for liquid and solid argon as a function of the γ-ray energy, obtained on irradiation of the counter with

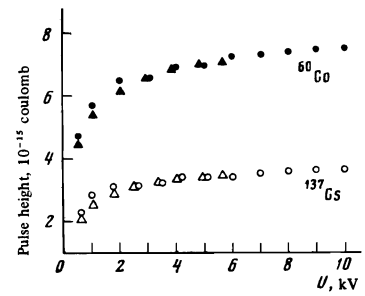

FIG. 4. Pulse-height characteristics of counters filled with liquid and solid argon, obtained in irradiation by ^{60}Co and ^{137}Cs γ rays: Δ—liquid argon, ○—solid argon (on raising the voltage), ●—solid argon (on lowering the voltage), ▲—liquid argon.

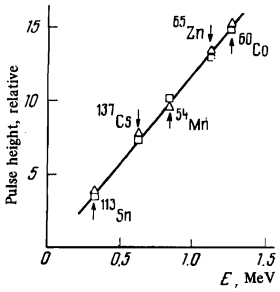

FIG. 5. Height of ionization pulses for liquid and solid argon as a function of γ-ray energy E, obtained in irradiation of the counter by γ rays from sources of ^{60}Co, ^{65}Zn, ^{54}Mn, ^{137}Cs, and ^{113}Sn ($U = 4$ kV): Δ—liquid argon, □—solid argon.

γ rays from sources of ^{60}Co, ^{65}Zn, ^{54}Mn, ^{137}Cs, and ^{113}Sn (applied voltage $U = 4$ kV). It can be seen that this dependence is linear with a high degree of accuracy.

Let us discuss in more detail the pulse-height distributions of the signals (see Figs. 2 and 3). As we noted above, in contrast to liquid argon, for the solid argon counter an extended tail of pulses of large amplitude is observed in addition to the spectrum of ionization pulses. The pulses corresponding to the tail portion of the spectrum appear at a counter voltage of about 1 kV. With further increase of the voltage the height and intensity of these pulses increase appreciably. The maximum pulse height observed for the very highest voltages reached 10^{-12} coulomb. The contribution of the tail portion of the spectrum to the pulse-height distribution is small, depends on the experimental conditions (see below), and does not exceed 30%. The intensity and height of the pulses which exceed the ionization pulses decreased appreciably with the passage of time, while the main spectrum of ionization pulses did not undergo any changes during the time of irradiation of a counter held at a given applied voltage for several hours.

Figure 6 shows counter characteristics obtained on irradiation of counters filled with liquid and solid argon by γ rays from a ^{60}Co source. As can be seen from this figure, the counter curves for solid argon have several irregularities. In particular, on raising the counter voltage, the counting rate at each value of voltage falls off with time. Thus, in Fig. 6 each vertical pair of points belonging to the upper curve was obtained with a time interval of about a minute (each lower point was taken after the upper). On reduction of the voltage the counter curve passes below the curve obtained on increasing the voltage (each upper point was taken after the lower point). The dashed line shows curves obtained on increasing the voltage from 0.5 to 6 kV (upper curve) and subsequently decreasing it from 6 to 0.5 kV (lower curve). The lack of agreement of these curves, we observed, is due to the fact that on decreasing the counter voltage the intensity of pulses in the tail portion of the spectrum drops rapidly, and also some shift of the spectrum of ionization pulses is observed toward lower pulse heights. The systematic shift of the points with time for each voltage value for the upper curve is due to the decrease in intensity of the pulses of the tail portion of the spectrum, and for the lower curve it is due to a certain recovery of the spectrum of ionization pulses.

The rise times of the ionization pulses, measured without shaping by integrating and differentiating circuits, were ~0.5 μsec for liquid argon and ~0.25 μsec for solid argon, which is in agreement with known data on electron mobility.[16] The rise time of the pulses corresponding to the tail of the spectrum for solid argon was ~0.5 μsec. The fall time of the pulses was determined by the time constant of the counter circuit and preamplifier and was ~300 μsec.

In a special experiment we checked the efficiency for detection of γ rays by different portions of the filament. Regions of the filament ~5 mm in length were irradiated with a collimated beam of ^{60}Co γ rays. We observed no variation of detection efficiency on displacement of the γ-ray beam along the counter.

It should be noted that in the various experiments, depending on the time of freezing of the liquid argon, crystalline argon of different degrees of transparency was obtained: from very transparent (crystallization time ~30 hours) to completely opaque (crystallization time ~1 hour). No important differences in the counter characteristics were observed in these experiments for the different transparencies.

In conclusion, we shall consider the important question of evaluating the purity of the argon used. As can be seen from Fig. 4, for liquid argon the maximum charge collected at the anode on bombardment of the counter by ^{60}Co γ rays is $\sim 7\times10^{-15}$ coulomb, which amounts to about 90% of the expected value calculated by the formula $Q = E/U$, where E is the energy of the γ ray absorbed in the counter, $\bar{E}(^{60}\text{Co}) = 1.25$ MeV, and U is the average energy required to form an electron-ion pair, which for liquid argon is ~25 eV. The incomplete collection is apparently due to attachment of electrons to electronegative impurities (mainly oxygen molecules).

Swan[14,15] studied the attachment coefficient as a function of the electric field strength. He found that the attachment coefficient η (in cm^{-1}) is AP_0/E, where E is the field intensity in V/cm, P_0 is the impurity concentration in parts per million, and A is a constant which for liquid argon is 8×10^3 V/cm (cm-ppm)$^{-1}$. The fraction of electrons lost as the result of attachment to impurities is

$$Q/Q_0 = \exp\left\{-\int_{r_a}^{} \eta(r)\,dr\right\},$$

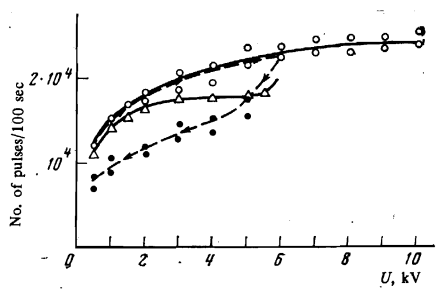

FIG. 6. Counting characteristics for counters filled with liquid argon (Δ) and solid argon (○, ●), obtained on irradiation by ^{60}Co γ rays: ○—on increasing the voltage, ●—on decreasing the voltage.

where r_a is the anode radius and r is the radial coordinate of the Compton electron. From these data we can estimate the degree of purity of the argon used by us, which turned out to be ~0.1 ppm. The value obtained agrees with the experimental results of Derenzo *et al.*,[1] who have given the height of ionization pulses corresponding to ^{65}Zn γ rays as a function of the oxygen impurity concentration in liquid argon with a counter geometry similar to ours.

4. DISCUSSION OF RESULTS

The amplification of a portion of the pulses to a height $\sim 10^{-12}$ coulomb, observed for solid argon, leads to the idea of existence near the filament of microregions in which electron multiplication occurs. These may be either microcrystalline regions in which electron multiplication is possible, or microcracks and also microbubbles (their existence in liquid argon was suggested by Derenzo *et al.*[1]), where the electrons leave the solid argon with subsequent multiplication in the gas phase. We present below a qualitative explanation of the phenomena described by us, which is acceptable for any of the hypotheses.

No mobility of positive ions in crystalline argon has been observed[16] in electric field strengths up to 10^5 V/cm. Apparently it is extremely small, and therefore on multiplication of electrons in the microregions a screening positive space charge is formed which leads to a decrease in the intensity of amplified pulses with time. The effect observed by us of a distinct hysteresis of the counter characteristic (see Fig. 6) also can be explained as follows: On reduction of the counter voltage the field strength in a microregion which is filled with space charge becomes insufficient for development of an electron avalanche, and as a result the number of amplified pulses decreases.

The fact that only a portion of the primary electrons is multiplied may be due also to the presence on the wire surface of micropoints, in the vicinity of which a high electric field strength occurs which is considerably different from the average field strength at the filament surface. Microprojections have a particularly strong effect on the nature of discharge development in the case of very thin wires, where the region of electron multiplication is small and becomes commensurate with the region of nonuniform field at the microprojections. In further studies it will obviously be desirable to subject fine wires to special additional processing in which the microprojections will be removed.

In view of the fact that in the previous work[5] no pulse-height analysis was made and the experiments utilized electronic equipment with a detection threshold several times higher than that used in the present work, the amplified portion of the pulse spectrum in the case of solid argon could not be separated from the ionization portion of the spectrum, and the electron multiplication was taken for an effect associated with the entire spectrum.

It will be of interest to carry out additional study of the operation of a counter filled with solid argon with the lowest possible counting rates. It is possible that in view of the very low mobility of positive charges in solid argon the fraction of amplified pulses will increase substantially as the counting rate is greatly reduced.

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