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NEW WAYS OF DETECTING PARTICLE TRACKS IN LIQUID AND SOLID MEDIA

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Introduction

The International Conference on Detectors, held in Dubna in 1970, clearly demonstrated the considerable interest shown by physicists in the creation of high-speed track detectors containing a solid working medium. A number of laboratories are at present carrying out intensive research into ways of solving this problem (see, for example, [1-5]). So far, however, no significant progress has been achieved in even one of the directions in which the investigations have been made. Physicists have run into major inherent difficulties due to the nature of electron multiplication directly in solid media. It is opportune, therefore, to analyse possible new ways of building track detectors in which the problem of internal amplification of the signals would not depend on the mechanism of the multiplication of the electrons immediately in the solid media. The present work is devoted to an examination of such possibilities.

Filament-type bubble hodoscope in a solid medium

The unstable electrons of most solid dielectrics have a high mobility in electric fields - up to 10^3 or 10^4 $cm^2\ V^{-1}\ sec^{-1}$. This fact can be exploited in order to accelerate the electrons which form in particle tracks, and to introduce them into gaseous bubble-cavities - frozen or polymerized in the dielectric material at the surface of the wires. If, in addition, the gas in the bubbles has a low ignition potential, the electrons injected into it may cause a discharge which produces a current pulse on the corresponding wire. Consequently, it will be seen that a collection of wires will provide a complete set of information about the place where the particle passes. It is appropriate to point out here that the idea of extracting electrons from a liquid phase into a gaseous one, in order to form in it a recorded projection of the particle track, was first considered in [6].

The successful application of this method is closely linked with the solution of three problems. The first of these

concerns the formation of uniform gas bubbles on the wire. The second is to have throughout the volume of the chamber a material which is in a mono-crystalline state in which the electrons may be freely accelerated by the electric field up to an energy sufficient to overcome the potential of electron emergence from the material into the gas. The third problem is to select the optimum relationship between the diameter of the bubbles and the gas pressure in them. These parameters determine the likelihood of initiating a discharge in the bubble by a single electron.

There are two possible ways of obtaining gas bubbles in a solid material. Thus, when obtaining bubbles with the specified gas composition, the liquid must first be injected with a suitable gas and, at the moment crystallisation takes place, it must be degassed by lowering the external pressure on the liquid. The gas in the bubbles will consist of mixture of injected gases and vapours from the frozen liquid. To generate "clean" bubbles around the wires it is sufficient to ensure that, as before, the external pressure on the liquid which is being cooled is lower than the gas/solid equilibrium pressure, or to heat up the wires for a short moment.

Bubbles of a uniform size can, it would seem, be obtained by a special preliminary treatment of the wires (e.g. by etching them), the surfaces being covered with micro-irregularities. These will then serve as a basis for the germination of "standard" bubbles. The final bubble dimension may be "corrected" by varying the speed at which the liquid is frozen and the rate at which the external pressure is reduced.

It is a more complicated matter to achieve mono-crystallisation of the liquid throughout the volume of the detector. For this, apparently, it is necessary to effect the cooling (or polymerisation) of the liquid at a very slow rate. There is, however, the danger that a slow cooling rate may be incompatible with the rate of crystallisation required to obtain bubbles of a given dimension.

For normal operation of the detector, the density of the dislocations in the crystal must not exceed $10^{14} - 10^{15}$ cm^3. If it does, the life-time of the electrons in the crystal will be considerably less than $10^{-7} - 10^{-6}$ second owing to their effective capture by the traps. A time of $10^{-7} - 10^{-6}$ second is essential for the acceleration of the electrons in the crystal and their attraction into the bubbles. In fact, the speed of the electron drift under the effect of the field is $v = \mu E$, where μ is the mobility of the electrons in crystals, $\approx 2 \times 10^3$ cm^2 V^{-1} sec^{-1}, and E is the intensity of the electric field. When $E \approx 10^4$ V/cm $V \approx 5 \times 10^7$ cm sec^{-1}. With distances of 1 - 2 mm between wires of opposite polarity the electron collection time in the bubble is $\approx 10^{-8}$ sec, which is less than 10^{-7} sec - the average life-time of electrons in a crystal up to their capture on the dislocation planes.

It was mentioned above that for the electrons to emerge from a solid substance into a gas, their kinetic energy must be greater than the emergence potential φ. Normally, for dielectric crystals φ = 5eV, and consequently the speed of the electrons must satisfy the condition

$$V \geq \sqrt{\frac{2\phi}{m}} = 1{,}8 \cdot 10^8 \text{ cm sec}^{-1}, \qquad (1)$$

where m is the electron mass. This speed may be obtained in a field

$$E = \frac{\bar{v}}{\mu} = \frac{1{,}8 \cdot 10^8}{2 \cdot 10^3} = 9 \cdot 10^4 \text{ per cm}^{-1}. \qquad (2)$$

If the diameter of the wires is taken to be 2r, the distance between them d, and the average dimension of the bubbles 2R, the voltage on the wires must be

$$U \geq E(r + 2R) \ln \frac{d}{r}. \qquad (3)$$

If we pose r = R = 0,05 mm and d = 2 mm, then, when $E = 9 \times 10^4$ per

cm^{-1}, 3kV. The field in the bubbles will then be

$$E_n = \frac{3\epsilon}{2\epsilon + \epsilon_n} E, \qquad (4)$$

where E_n is the field on the bubbles, E is the field on the crystal, ϵ_n is the dielectric constant of the gas in the bubbles, ≈ 1, and ϵ is the dielectric constant of the crystal. If we take $\epsilon = 2$, the field in the bubbles at a distance of 2R from the wire will be $E_{n1} = 9 \times 10^4$ per cm^{-1} and, on the surface of the wire, 2R = 0 and $E_{n2} = 10^5$ per cm^{-1}. The field in the centre of the bubbles can be considered roughly equal to $E_{av} = (E_{n1} + E_{n2})/2 = 10^5$ per cm^{-1}.

To calculate the required gas pressure in the bubbles at which electric discharges can effectively develop from single electrons, we shall use an empirical dependence which expresses the relationship between the breakdown voltage, the gas pressure and the size of the gap between the electrodes in the form of an implicit function

$$U = f(Pd), \qquad (5)$$

where P is the gas pressure and d the electrode gap. With regard to gas discharge in bubbles, the dependence (5) was used with success in /7/, in which the electrode gap is identified with the bubble size 2r, and the voltage on the bubble was taken to be $E_{av} = 2r$. If we assume, as above, that $d = 2r = 10^{-2}$cm and $E_{av} = 10^5$ per cm^{-1}, then $U = 10^3$V. We shall subsequently use the experimental curves from /8/ which express the dependence U = f(Pd). Thus, if the bubbles are filled with neon, there is, corresponding to the breakdown voltage $U = 10^3$V, a value $Pd \approx 60$ mm Hg. cm or $P = 60/10^{-2} \approx 8$ atm. In this way we obtain, for argon P = 4.6 atm, for helium P = 4 atm, and for hydrogen P = 1.5 atm. These data are approximate, as they were obtained on the simplifying assumptions that d = 2r and $E = E_{av}$. The degree of approximation, however, is fairly high, as is shown in /7/, where similar problems are solved. If the true gas pressure in the bubbles differs considerably from

the calculated value, this will correspondingly result in the need to correct the voltage on the wires. However, it will not be possible to allow a strong reduction in the gas pressure in the bubbles compared with the calculated value, since this will call for a marked reduction in the working voltage and it may be below the critical value required for accelerating the electrons in the crystal up to the energy of

It should be pointed out that if, in the crystals, the bubbles used are formed from the inherent gas, which will be in thermodynamic equilibrium with the walls of the bubbles, their required size may, for a given external field, be established also from the dependence (5) and from the data given in /8/. For example, the argon pressure at the triple point is 400 mm Hg, or, when converted to room temperature: the reduced pressure $-P = P_o \frac{T}{T_o} = 400 \frac{300}{83} = 2$atm. For this gas pressure and field in the bubble, namely 10^5 V/cm, the bubble size should, according to the dependence (5), be $\approx 5 \times 10^{-3}$cm. The same method is used to find the reduced pressure and the necessary bubble size for other gases. Thus, for neon the pressure is 3.5 atm, and the bubble diameter $\approx 3 \times 10^{-3}$cm correspondingly. It appears that the physical production of bubbles in the above-mentioned materials would present some difficulty.

After each gas discharge in the bubbles, their walls will acquire a surface charge. The subsequent neutralisation of the walls will mainly occur as a result of the passage of the charge on to the wire electrodes. The time constant for this process is $r \approx 6 \times 10^{-14} \varepsilon \cdot \rho$, where ε is the dielectric constant of the crystal and ρ its specific resistance. When $\varepsilon = 2$ and $\rho = 10^{16}$ cm, which is typical of solid dielectrics, $r \approx 0.3r$. This means that after each discharge the sensitivity of a bubble to recording the following particle will be restored after about one hour. This time can, however, be considerably shortened if the detector is subjected to preliminary illumination from a light in the band of the electron capture levels. Under the effect of the light the electrons will be released from the traps and acquire increased

mobility. Here we should mention generally that preliminary illumination of the crystal in the detector,in the band of electron capture levels and vacancies, will be very useful in yet another respect, namely for increasing the number of electrons collected into the bubbles by the field. This effect will increase the probability of recording particles in the detector. In addition, the light will also facilitate the "cleansing" of the volume of the crystal of positive charge-vacancies which arise in the particle tracks and become attached on the acceptor levels.

We should also mention the possibility of using a pulsed controlled field in the detector. The formation time of this field after passage of the particle must be considerably less than the life of unstable electrons in the crystal, i.e. less than 10^{-7} sec.

Filament-type bubble hodoscope with a solid scintillating material

A further development of the bubble-type crystal detector considered above could be a detector of a similar design,but containing a solid scintillator as the working material. In this detector the light quanta produced by the particle will enter the gas bubbles and give rise to electrons in them,on account of the photo-effect from the surface of the wires. These electrons, as in the case examined above, under the effect of a constant or pulsed electrical field will create, in the bubbles, a discharge in the gas and produce a current pulse on the wires.

Let us evaluate the efficiency of particle recording in this type of detector. On a unit of length in the solid scintillator the fast particle produces $\approx 4 \times 10^{4} cm^{-1}$ light quanta. If the particle track passes at a distance of 0.1 cm from a bubble measuring 5×10^{-2} cm in diameter, about 10^{2} quanta will hit it. Assuming that the diameter of the wires is 5×10^{-2} cm and the quantum output of photo-electrons from their surface is ≈ 0.01, we find that in each bubble by which a particle passes, roughly one electron will be produced. This means that the detector may

efficiently record all the particles which pass through it. Such an instrument would have a short resolving time, equivalent to the discharge development time in the bubbles, namely 10^{-7} sec. The time required to restore the sensitivity of the individual bubbles after production of the discharge in them will, on calculation, be found to be roughly one hour, as shown above. In this detector no special requirements need be placed on the degree of mono-crystallinity. It would, however, appear that the production of gas bubbles in it would be a source of considerable difficulty.

A quantum output of photo-electrons of 0.01 from the surface of the wires can be achieved by covering the surface of the wires with a special material with a low electron output potential, such as BaO, K or Na.

If this detector is used in the controlled mode, the leading edge of the pulse must be produced within several nsec. In the case of large field rise-times in the pulse, the electrons will effectively leave the gas bubbles and the probability of a discharge developing in them will, as shown in /7/, fall sharply.

The scintillation filament-type counter

In view of the successful development by industry of miniature avalanche photo-diodes capable of recording individual photons /9, 10/ with an efficiency of 0.3, it is interesting to consider the possibility of using these diodes in combined particle detectors. These detectors may be a composition of a scintillating filament /11/, or capillary filled with a scintillating liquid, and of photo-diodes optically connected to the ends of the filament or capillary.

The passage of a particle through the filament will produce in it a scintillation which may be recorded by the photo-diode. The relation of the amplitudes and times of occurrence of the pulses on the photo-cathodes of individual filaments will

provide the necessary information about the location of the particle's passage in the limits of the filament's length i.e. about the z - coordinate. The diameter of the filaments may now be made very small. There is, however a limitation here due to light losses when light is reflected a number of times from a surface. Thus, it is shown in /12/ that with a 1.6 mm diameter of the filament the light losses are e times as large over a 30 mm length of filament. These losses are mainly due, as pointed out by the authors, to the absorption of the light in micro-fissures on the surface of the filaments. When the quality of the surface was improved the light losses were reduced and a lowering of the intensity was observed only on a 80 mm length. In future it will be possible to envisage the total suppression of light absorption on the surface of the filament by covering it with a special uniform film with the same optical refraction index as that of the filament material. It will, apparently, also be possible to suppress the absorption of light on the surface by the diffusion-deposition,in the filament, of a special additive which causes a shift in the refractive index in the surface layer of the filament and creates the condition for self-focusing of the light/10/. The light in the filament is propagated along it but does not "touch" its surface. In both the last cases, the light losses will be determined only by the absorption in the volume of the filament material. These losses are usually small and in the case of modern scintillating plastics do not exceed 0.5 over a length of 1 metre.

Let us now determine the number of quanta which will reach the ends of the filament from the place where the particle passes. If we designate the angle at the vertex of a cone, - the angle which corresponds to total internal reflection -, as 2a, then

$$\text{Cos } a = \frac{n_1}{n_2} \qquad (6)$$

where n_1 and n_2 are the optical refrection factors of the surrounding medium and filament material respectively. The solid

angle of the cone, determined by the angle 2a,

$$\Omega = 2\pi(1-\cos\alpha) = 2\pi\left(1-\frac{n_1}{n_2}\right). \qquad (7)$$

For a scintillation filament surrounded for example by air, we may take $n_1 = 1$ and $n_2 = 1.5$; in that case, $\Omega = 2.4$ ster. The particle in the filament will produce, over one centimetre, about $N_0 = 4 \times 10^4$ light quanta. For a filament thickness d = 1 mm the number of quanta entering the solid angle Ω will be $N_0 d\,\Omega / 4\pi = 8 \times 10^3$. If we take the coefficient of light absorption over the length of the filament as ≈ 0.5 the number of quanta reaching its ends will be $\approx 4 \times 10^3$. With the 0.3 photon recording efficiency of the silicon avalanche-type photo-diode and an amplification coefficient of $\approx 10^3$ /9/ a current signal will be produced on the diode, with a number of elementary charges of $\approx 10^6$.

Instead of avalanche-type photodiodes it is also possible to use miniature channel-type photo-electron multipliers (CPEM) /13-15/, which have a quantum output of photoelectrons of ≈ 0.02 and an amplification factor of $10^5 - 10^9$. In this case, the output signal will have a fairly large amplitude and may be recorded by external devices without additional amplification.

Unfortunately, both the CPEM and avalanche-type photodiodes possess a noticeable background "noise" and for the normal utilisation of these elements the temperature must be low.

We have considered individual scintillation filament counters. It is obvious that these counters can be used to compose hodoscopic systems with a large volume and any desired geometry. These systems are capable of operating in the continually sensitive and pulsed (in the case of photodiodes) modes. In such a detector, filled with a liquid or solid medium, for example hydrogen, it will be possible to record not only particle tracks but also determine their ionising capacity. The spatial resolution of the

detector in the x - y plane will be determined by the diameter of the filament counters, whereas the depth (z -) coordinate will be determined by the measurement accuracy of the pulse heights and their formation time on the photo-sensitive elements, the CPEM or photodiodes. Consequently, the x - y coordinates may be resolved with an accuracy no worse than 1 mm and, for the z coordinate, no worse than 2 - 5 mm. The time resolution of the detectors will be virtually the same as that of the scintillation counters with a photo-multiplier and will not be greater than several nsec.

The channel-type multiplier as a fast-particle counter

When the first CEM's appeared they were used as detectors for slow ions and electrons /14-16/ which enter the CEM through an open end. It is, however, interesting to examine a variant for recording fast particles which intersect the CEM in an arbitrary place. In this case, when the particle passes through the CEM, secondary emission electrons should be emitted from the walls into the channel. The emission coefficient of the materials from which the CEM is made is usually 2 - 3. The electrons which enter the channel will be captured by the field, accelerated and multiplied, and produce a recordable pulse at the output of the channel. The height of this pulse will depend on the distance the avalanche travels inside the channel and consequently on the place where the particle passes. The use of a combination of CEM counters will enable the immediate recording of the coordinates of a large number of particle tracks.

A shortcoming of the counters we have been considering is, perhaps, a strong non-linear dependence of the signal amplitude on the place where the particle passes, which should lead to the appearance, on a substantial part of the CEM's length, of a zone insensitive to particles and to irregularities in the efficiency of the counter along the length of the sensitive region.

There is, however, a possibility of modernising the CEM

which will enable its efficiency to be made more even, and considerably lengthen the counter's recording range. This possibility is based on adding an extra electrode in the CEM, to limit the CEM's length to two parts, the long and short. The long part of the CEM can be fed with a low voltage, no more than 0.3 kV/cm, and be used as a particle detector. The short part, on the other hand, can be fed with a high voltage and be used as a current amplifier. By selecting the appropriate voltage fed to the recording part of the CEM it is possible to achieve in it an electron repetition coefficient close to unity, i.e. the electrons formed by a particle in the recorded part will reach the intermediate electrode with a small degree of multiplication and penetrate the amplifying part of the CEM. An amplification factor of 10^8 - 10^9 may be obtained in this part /14-16/. The output pulse in this counter will depend only slightly on the place where the particle passes within the limits of the long part of the CEM.

This counter can obviously be composed also of two separate CEMs, a long one and short - miniature - one /13/. It is true that in this case coaxial coupling of the CEMs will present some difficulty.

It will be possible to build, from long counters, hodoscope systems which have a large volume. The spatial resolution of such a system will be determined by the diameter of the CEM (of the order of a millimetre) and the time resolution by the time of collection and multiplication of the electrons, which will be 10^{-7} sec. The advantage of particle counters based on the CEM is that they are able to operate independently of the surrounding medium. This factor may prove particularly important in hodoscope systems containing a working material in a condensed state.

Brief conclusions

The purpose of this work was to analyse new proposals for recording particle tracks in detectors containing discrete particle-

sensitive elements. It is believed that detectors having filaments that are surrounded by frozen or polymerised gas bubbles will, after the necessary technological improvements, successfully compete with the gas wire-type chambers in their spatial and time characteristics and in the density of the working material. Combined detectors containing scintillating filaments, capillaries filled with a scintillating liquid and photo-multiplying elements - avalanche photodiodes or miniature CEMs - may at present be quickly constructed and tested. We may therefore expect that such detectors will soon become operational for physics experiments. In the same scheme we may consider also fast particle counters based on single CEMs. There is, at the moment, every technical reason for investigating these counters and for evaluating the prospects of developing long and flexible capillary-type particle counters.

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