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CM-P00063996

THE MULTISTEP AVALANCHE CHAMBER:
A NEW HIGH-RATE, HIGH-ACCURACY GASEOUS DETECTOR

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ABSTRACT

A new particle detector relying on an unusual avalanche mechanism mainly mediated by UV photons permits multistage amplification of ionization electrons. Single electrons are detectable. Particle fluxes, orders of magnitude more intense than in wire chambers, are acceptable. Applications can be foreseen for Čerenkov light imaging, radio-chromatography, slow neutron and X-ray detection.

Geneva - 12 September 1978

(Submitted to Physics Letters B)

Progress in elementary particle physics is very sensitive to the evolution of detectors. The introduction in this field, 10 years ago [1,2], of multiwire proportional and drift chambers (MWCs) resulted in a widespread use of these instruments and, quite naturally, a stage has been reached where some experiments are limited by the properties of this detector in terms of accuracy and rate capability. Very characteristic in this respect is the recent discovery of the upsilon particle [3]: a primary beam, one order of magnitude less intense than the available one, had to be used, mainly because of the rate limitation in the multiwire chambers.

The maximum tolerable rate in MWCs is determined by two factors: the accidentals counts at high fluxes, due to the electron collection time in the gas (typical value 150 nsec), and the space-charge field distortions induced by the positive ions produced in the avalanches, with a consequent loss of efficiency [4]. To overcome these difficulties a scheme has been conceived where only a fraction f of the events, suitably selected, give rise to the full avalanche multiplication [5]. The principle of operation is illustrated schematically in fig. 1a. Electrons released by an ionizing encounter in the upper part of the structure traverse a preamplifying gap A_1 where the initial charge is multiplied by a factor M_1 ; the resulting electron swarm is then drifted in the gas by an electric field to a gate G which transmits charges only during the short time τ of application of an appropriate pulse. The second amplifying element A_2 , of gain M_2 , is then reached by the transmitted electrons. Typically, a total gain $M_1 \cdot M_2 \approx 10^6$ is desirable since it brings the amplification to the level reached by good MWCs; if, for instance, $M_1 \approx M_2 \approx 10^3$ can be obtained, such a scheme would reduce by a factor M_1 the ion accumulation in A_2 due to the direct ionizations, and by a factor f the space charge due to accepted events. The resolution time is essentially defined by the jitter of the signal detected in A_2 .

Two methods of solving the problem of preamplification were investigated, one based on secondary emission from low-density materials, and the other on a process

of gaseous multiplication and transfer [5]. Further work on the second method has led us to the observation of an unusual multiplication process that makes it possible to go far beyond the initial aim and may give rise to a new class of detectors.

As shown by the authors of ref. 5, when in a gas a region of high electric field is separated by a wire grid or mesh from a region of lower field, under suitable conditions charge multiplication can take place with considerable electron leakage into the low-field region (fig. 1b). In the original design, a preamplification and transfer element (PAT) was associated with a gated MWC following the scheme of fig. 1a. Examination of the electric field structure in the PAT element shows that a number of field lines, equal to the ratio of the fields, escape into the lower region. Electrons multiplying through a conventional avalanche process along these particular lines can be transferred into the lower field; for a typical field ratio of five to one about 20% of the charges may leak. One would, however, expect a strong position dependence of the transmission. To justify the remarkably good experimental uniformity of response and the energy resolution of the PAT element, the authors of ref. 5 had to invoke an uncomfortably large electron diffusion coefficient in the gases used (argon + alcohol and argon + carbon dioxide + alcohol) such as to obliterate the structure of the multiplying wires. Further observations have led us to suggest an entirely different avalanche propagation mechanism.

- i) Effective preamplification factors (inclusive of the transfer efficiency) above 500 have been obtained in argon to which had been added small quantities of ethyl alcohol, benzene, or acetone. Attempts to use argon + carbon dioxide or argon + hydrocarbons have failed owing to spark breakdown at very modest values of preamplification.
- ii) Mixtures of xenon with the above-mentioned vapours produced no detectable preamplification; the addition of even small quantities of argon, however,

restored the PAT behaviour. The preamplification and transfer can be obtained again in xenon, however, using in addition a vapour with very low ionization potential, as, for example, triethylamine.

- iii) Study of the localization properties of the structures for minimum ionizing particles has shown a uniform, non-modulated efficiency of detection.
- iv) A good energy resolution was measured for well-defined charge injections into the PAT structure ($\sim 20\%$ FWHM for 5.9 keV X-rays converted in a drift space above the preamplification region), approaching the values measured in the best single-wire proportional counters where transfer efficiency is not of concern.

The following mechanism is suggested to explain the previous observations. Electrons liberated in the gas by an ionizing event increase their energy in the high-field region and induce secondary light emission by inelastic collisions with the argon atoms. For the field values with which we are concerned, most of these photons are emitted in a wide band centred around $1250 \text{ \AA}$ (9.85 eV) [6], an energy high enough to efficiently photo-ionize the benzene and acetone molecules, and (although marginally) ethyl alcohol. Simple calculations, taking into account the known values of the photo-ionization cross-section for the three vapours [7-9], provide a mean free path for photons above the ionization threshold of a few hundred micrometres in mixtures containing around two percent of quencher (atmospheric pressure). Since the secondary light emission of xenon is centred at much longer wavelengths (1500 to $1950 \text{ \AA}$) [10], the secondary photo-ionization process cannot take place in these vapours, as observed. However, the use of triethylamine with an ionization potential of 7.5 eV permits the photo-ionization, and the PAT mechanism is restored.

A large secondary light yield followed by an efficient photo-ionization within a few hundred micrometres seems to explain all the previous observations. However, at this point we cannot completely disregard a conventional avalanche multiplication as partly contributing to the process; also, it should be noted that essentially nothing is known about secondary photon emission in noble gases mixed with organic vapours, which forbids a precise calculation on such a photon-mediated avalanche spread.

Several construction schemes have been tried in order to exploit the properties of the gaseous preamplification and transfer mechanism. Figure 1c shows a PAT element followed by a gated MWC, as in the original design, while in fig. 1d two identical amplification elements are separated by a transfer and drift space constituting a true multistep avalanche chamber. The best stability of operation and energy resolutions have so far been obtained when operating in argon with about 2% acetone, at atmospheric pressure. Typically we have used 3 mm multiplying gaps, followed by a transfer region of 5 mm; the preamplification grid (central electrode of the structure, fig. 1b) was made either by a grid of 50 μm diameter wires, 500 μm apart, or by a stainless-steel mesh 85% transparent, as for the other electrodes. The addition of an absorption and drift space above the PAT element allowed known quantities of charge (from soft X-ray conversions) to be moved into the multiplication volume, and a multiwire proportional chamber with two-dimensional coordinate read-out using the induced cathode pulse method [11], mounted below the structure, permitted efficiency and localization studies. At fields around 6 kV/cm, multiplication takes place in the preamplification gap, and part of the electrons continue their trip in the multiple structure. At electrical transparencies around 20%, effective preamplification factors above 400 can be obtained, implying a real gain in the preamplification gap around 2×10^3 . At this level the signal on the preamplification grid can be detected, as shown in the upper trace of fig. 2a. The lower trace shows the signal on the MWC anode (adding a further gain around 10^3), detected after a delay corresponding to the electron drift time between the PAT and MWC elements. The movement of the ions in the last avalanche also induces a positive feedback signal in the preamplification grid. The built-in controllable gaseous delay greatly simplifies the electronics of the read-out system, eliminating the need for a delay element on each cathode strip of the MWC. By itself, this seems a sufficient reward for the increased mechanical complexity over a conventional MWC. The operation of the pulsed electronic gate is shown in fig. 2b. The two oscilloscope tracks show, respectively, the pulse detected on the MWC anode in conditions of full transparency (upper trace) and of pulsed transmission in coincidence with the passage

of the electron swarm through the gate (lower trace). A residual induction of the pulsed gate appears, comfortably preceding in time, however, the appearance of the real charge signal.

Over-all multiplication factors above 10^7 can be obtained in the combined structure, although in a fully charge-saturated regime. This allows the detection of single electrons; fig. 3a shows the pulse-height spectrum for single electrons photoproduced on the upper cathode of the structure by an ultraviolet lamp. It should be noted in this context that in the gas used, the MWC alone cannot be operated at gains above 10^4 without entering a full Geiger regime. We explain this observation by the fact that, although there may be a large amount of hard photons from the head of the final avalanche, they have a negligible chance of propagating back into the preamplifying gap; they are instead reabsorbed within the MWC itself and give rise to a charge gain reduced by the factor M_1 . This is the key reason for the stable operation of multistep structures, as compared to single-gap structures with the same gain.

We have analysed the localization properties of the PAT element on minimum ionizing particles, making use of a bidimensional induced cathode pulse read-out on the terminal MWC (see fig. 1c). Two standard chambers with the same read-out, permitting track localization within $60 \mu\text{m}$ r.m.s. [11], were used in line for monitoring purposes. Full efficiency of detection could be obtained, both with and without the drift and conversion space attachment; the fact that in the latter case the efficiency is uniform in the direction perpendicular to the preamplifying wires grid is the major argument in favour of a photon-mediated avalanche spread. The coordinate localization along this direction is instead slightly modulated by the charge scraping operated by the wires; the amplitude of the modulation implies a $50 \mu\text{m}$ displacement of the measured versus real position, and the wavelength corresponds to the distance of the multiplying wires ($500 \mu\text{m}$). Despite this, a position accuracy around $150 \mu\text{m}$ r.m.s. has been measured in this direction, which corresponds to the best determined coordinate in the MWC along its anode

wires. In the perpendicular direction, where the anode wire spacing of 2.5 mm would normally introduce a large quantizing effect [11], it appears that the large avalanche spread leads to an effective charge interpolation, and an accuracy of 250 μm r.m.s. has been measured.

A complete parallel-plate avalanche chamber can be constructed with one transfer and two amplification elements, as shown in fig. 1d. Not only is this structure mechanically much simpler than the previous one (there are no thin wires, as in the MWC), but also it allows the best time resolutions on charged particles to be obtained. Operating in argon acetone, a resolution of 10 nsec FWHM has been measured for fast electrons traversing the structure. Localization in this case is obtained by recording the distribution of induced charges on the last electrodes; contrary to the normal MWC case, the electron swarm may keep drifting across as many gaps as desired, allowing coordinate measurements along an arbitrary number of directions in a succession of gaps with wires oriented at different angles. Such multidimensional read-out has been used, for example, in high-accuracy X-ray detectors associated with channel plate electron multipliers [12].

In conclusion, we have shown that it is possible to multiply electrons, and to efficiently and uniformly transfer them into a succession of gaps in order to obtain a variety of functions. All electrodes in such a structure can be made with either thick wires or meshes, thus eliminating one major source of breakdown in large detectors. The large gains, good accuracies, and time resolutions that can be obtained with the multistep avalanche chambers (MSCs) allow their use in all applications where MWCs were used so far, but with a rate capability (in the gated version) at least two orders of magnitude higher for selected events.

Besides, some new applications are allowed by the specific properties of the MSC:

- The single-electron detection allows applications to be foreseen in the imaging of ultraviolet Čerenkov radiation [13] where the velocity of relativistic particles is measured from the opening of the emitted light cone. Using the

bidimensional imaging properties of our chambers, we have simulated a Čerenkov ring (as could be obtained with suitable optics) by simple collimation of an UV light source over a cathode of the MSC (fig. 3b). Of course in this simulation, photon conversions are separated time-wise, which simplifies the pattern recognition; the diameter of the ring is 50 mm, with 1 mm thickness.

- In radio-chromatography applications, the parallel-plate characteristics of the preamplifying gap should ensure a good localization accuracy, despite the long range of emitted electrons, since the largest avalanche starts from the entrance point in the gap of the electron.
- For slow neutron detection, the use of a conversion foil with large cross-section, e.g. made of gadolinium, as the first electrode, should, for the same reasons, allow very good localization.
- In spherical drift chambers [14] a preamplifying gap at the end of the drift space should permit selection of X-ray conversions taking place within the drift space, thus in some cases eliminating the need for using xenon to reduce the background of photons converted in the transfer space or in the MWC.

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Figure captions

- Fig. 1a : Principle of the gated multistep detector. Electrons liberated by an ionizing event in A_1 are amplified by a factor M_1 and transferred to A_2 (gain M_2) under the control of the gate G .
- Fig. 1b : The gaseous preamplification and transfer element. Avalanche multiplication takes place in the high field between grids a and b , and a fraction of the electrons is transferred into the lower field region by the mechanism described in the text.
- Fig. 1c : Construction scheme of a gated multistep chamber, associating a preamplification and transfer element with a conventional multiwire proportional chamber. For X-ray detection a conversion and drift space has been added.
- Fig. 1d : A preamplification and transfer module followed by a parallel-plate element constitutes a true multistep avalanche chamber.
- Fig. 2a : Pulse detected in the structure of fig. 1c on ^{55}Fe X-rays on the preamplification grid (upper track 4 mV/div.) and on the multiwire chamber (lower track, 100 mV/div.). Amplifier sensitivity 300 mV/pC; horizontal scale 200 nsec/div.
- Fig. 2b : Multiwire chamber electronic gating. Upper trace: d.c. operation (gate open); lower trace, pulsed operation: electrons are transmitted only during the gating period. Horizontal scale: 500 nsec/div.
- Fig. 3a : Pulse-height spectrum for single electrons, photoproduced by an UV lamp on the upper cathode of the structure shown in fig. 1c, and detected on the MWC anode. The peak value corresponds to about 1 pC on the chamber.
- Fig. 3b : Simulated Čerenkov light ring, obtained by illuminating the upper cathode of the chamber in fig. 1c with an UV lamp through a ring mask, 50 mm in diameter. Sparse points correspond to background; exposure time ~ 1 min.

Fig. 1a

Fig. 1b

Fig. 1c

Fig. 1d

Fig. 2a

Fig. 2b

Fig. 3a

Fig. 3b