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A SEARCH FOR QUARKS IN COSMIC RAY AIR SHOWERS

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SUMMARY

An experiment to search for fractionally charged particles of large mass associated with high-energy cosmic ray showers is described.

The experiment was conceived only as a test of the method and of a new electronics system; it was carried out as a side activity of the authors, using mainly borrowed counters not specifically suited for the required pulse height analysis. Therefore the results were of rather poor quality; however, we like to communicate them, since we feel that the method can be usefully improved and extended.

At an altitude of 500 m above sea-level (Geneva), showers of total energy of about $7 \cdot 10^{13}$ eV with cores landing within ≈ 80 m from the apparatus were selected. The delay and pulse height distribution for particles delayed between 50 and 1000 ns with respect to the front of the shower were studied in a telescope of plastic scintillation counters. The telescope had an overall efficiency of about 50% for particles of ionization as small as $^1/_{10}$ of the normal minimum. The experiment ran for about 36 days, during which 15 accidental events were expected, and 72 events were collected. Most of these were found to have associated delays shorter than about 250 ns, the distribution becoming flat, and the rate consistent with that expected for accidentals, at longer delays. Events with delays $\lesssim 250$ ns are interpreted as being due to protons of moderate energy belonging to the triggering shower. It was estimated from the pulse height analysis that in the central region of the selected high-energy showers the surface density of particles of charge $(^2/_3)$ e and within the selected delay interval, cannot exceed $2 \cdot 10^{-5}$ times the density of all other particles (electrons, μ mesons, etc). The limit for particles of charge $(^1/_3)$ e is $9 \cdot 10^{-5}$.

INTRODUCTION

Great interest has recently been aroused by the suggestion of Gell-Mann$^{1)}$ and of Zweig$^{2)}$ that a triplet of elementary particles (quarks) of charges $\pm {}^{1}/_{3}e$ and $\pm {}^{2}/_{3}e$ (e = electron charge) and possibly much heavier than the baryons might exist. The quarks would form the basis for the symmetry properties of the strongly interacting particle families. The fractional charge of the quarks can be used to attempt to separate them from the well-known stable or long-lived charged particles. As a matter of fact all experiments performed thus far, aiming at detecting heavy particles of fractional charge, either at the biggest accelerators$^{3-8)}$ or in cosmic rays$^{9-11)}$, failed to detect any such particles.

The accelerator experiments established that, if quarks are relatively stable (lifetime longer than about 10^{-7} sec) and if they have a mass not greater than about 2 GeV, their production total cross section in pp collisions cannot be bigger than about 10^{-35} cm^{2}. Outside this rather limited range of masses, however, the question of the possible existence of the quarks was left completely open.

Particles of mass much bigger than the nucleon mass can of course be produced in the interactions of high-energy cosmic rays. However, also the cosmic ray experiments performed so far at various altitudes$^{9-11)}$ failed in detecting the presence of particles with ionization below the minimum. These experiments established that if such fractionally charged quarks exist, their flux in the diffused cosmic radiation is smaller than a few times 10^{-8}/cm^{2} sr s. In other words, the results of these experiments established that, at various altitudes above sea level, the density of quarks is at least smaller by a factor of $\sim 10^{6}$ than the density of all the other cosmic ray particles with integer charge.

A new experimental method to search for quarks has been proposed by the Copenhagen group$^{12)}$. If heavy quarks are produced in the interactions of high-energy cosmic rays with the nuclei of the atmosphere, they should arrive at the surface of the earth sensibly delayed with respect to the front of the shower. The single hypothesis which is essential in deriving this prediction is that in the interactions of quarks with the nuclei of the atmosphere the invariant four-momentum transfer squared be not bigger than about 1 $(\mathrm{GeV}/c)^2$.

For an interaction in which a highly relativistic particle of mass M and energy E suffers an energy loss ΔE, the four-momentum transfer squared can be written, provided $(E - \Delta E) \gg M$

$$-t \approx p_T^2 + \left(\frac{\Delta E}{E} M\right)^2$$

p_T being the transverse momentum. In the interactions of high-energy protons and pions, p_T and ΔE are always found to be such that the rule $|t| \lesssim 1\ (\mathrm{GeV}/c)^2$ holds. Therefore, the above hypothesis applied to quarks appears plausible. It implies, if $M \gg 1$ GeV, $\frac{\Delta E}{E} \ll 1$. Thus, heavy quarks produced in high-energy showers in the upper atmosphere would reach the surface of the earth with still a big fraction of their original energy. In addition, they would be delayed with respect to the front of the shower. Indeed, since the spectrum of high-energy primaries is a fast decreasing function of the energy, heavy quarks would be produced mostly at the thereshold. They would therefore travel in the atmosphere with the velocity of the centre-of-mass system, and thus, after a few kilometres, have an appreciably delay with respect to the front of the shower. It can be estimated[12]) that such quarks should reach the ground with an energy and a delay roughly characteristic of their mass, the delay ranging between 50 and 1000 ns for quark masses between ~20 and ~3 GeV.

THE EXPERIMENT

We have performed a counter experiment on high-energy cosmic ray showers, to study a) the time distribution of penetrating particles, in the range between ~50 and ~1000 ns delay with respect to the front of the shower, and b) the energy release of such particles, in a telescope of scintillation counters. The experimental layout is shown in Fig. 1. Scintillation counters

C_1 , C_4 and C_5, placed approximately at the vertices of an equilateral triangle of side ~ 10 m, were connected in triple coincidence to signal the arrival of the front of extensive showers. Since these counters covered an area of ~ 3 m^2 and were at small relative distances with respect to the shower dimensions, the selected showers had a total energy of about $7 \cdot 10^{13}$ eV[13) and their cores fell at distances ≤ 80 m from the counters. Lead shielding above C_1 , though not thick enough to prevent triggering by shower particles, reduced the C_1 single counting rate due to low-energy radiation. A telescope coincidence $C_1 C_2 C_3$ signalled the passing through the telescope of a particle capable of crossing 25 cm of Pb. The delays of such particles with respect to the front of the showers and their ionizing power, were analysed as follows.

A coincidence C_{trg} from the shower counters C_1 , C_4 and C_5 triggered a gate generator whose output a) was integrated, and analysed by a pulse-height analyser, and b) was displayed on the first sweep of a double trace oscilloscope. When a delayed output pulse appeared from a coincidence C_{tel}, operated by the telescope counters C_1 , C_2 and C_3 , it passed a gate which was open from about 50 to about 1000 ns after the trigger coincidence, and stopped the gate generator. Thus, both the gate length on the scope display, and the integrated area of the gate pulse as analysed from the kicksorter, measured the delay of the telescope event with respect to the trigger. Positive pulses from the last dynodes of counters C_1 , C_2 and C_3 passed through linear gates (which were open in parallel with the gate on the C_{tel} signal) which were suitably delayed, mixed and sent to the second sweep of the oscilloscope. A camera continuously photographed the scope screen, the film being advanced after each event. An external clock was also provided to advance the film once per hour, to avoid fading.

For each event, the relevant information on the oscilloscope records were the gate length and the heights of the pulses of the telescope counters. An analysis of the correlations between delay and pulse heights was therefore possible. Care was taken to have the photomultipliers of the telescope counters (58 AVP Philips) working in linear conditions up to the last dynode. Pulse heights at the linear gates and at the scope input were kept such as to allow a proportional display up to the pulse height associated with minimum ionizing particles. Accurate matching of the transmission lines before and after the linear gates reduced the reflections to below 10%. This requirement was important to prevent the tails of telescope pulses in time with the front of the showers from passing through the linear gates and simulating small delayed pulses.

The telescope counters, placed vertically one above the other, covered an area of $\approx 0.8\ m^2$ and a solid angle of ≈ 1 sr. The counters were not specially built for this experiment, but they had an improved system of light collection*) that allowed several hundreds of useful photons to be collected by the photomultiplier screen, for minimum ionizing particles. This ensured that particles with charge $^e/3$ were signalled by each counter with an efficiency better than $\sim 80\%$ and therefore by the telescope with efficiency better than $\sim 50\%$. The gain of the photomultipliers was set in such a way that minimum ionizing particles could be detected with full efficiency when the input pulses at the C_{tel} coincidence were attenuated by a factor of ten. Therefore, the overall detection efficiency of the telescope for particles ionizing about 1/10 of the minimum was estimated to be greater than $\approx 50\%$.

The large area and the relatively small thickness of the scintillators (see Fig. 1), gave rise to a width of the pulse height distribution of $\approx \pm 25\%$ for minimum ionizing particles. This spread was mainly due to the variation of light transmission for particles passing in different points of scintillators.

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*) The light was carried to the photomultiplier by perspex bars of equal length bent in such a way as to join the scintillator side to the photomultiplier surface without changing the (rectangular) shape of the bars section.

RESULTS

During 36 days of running, about 218,000 shower triggers were obtained. Since the rate of C_{tel} was about 4,200 coincidences/minute, 15 such coincidence signals were expected to pass accidentally through the 950 ns long gate open by C_{trg}, therefore simulating a delayed event. 72 delayed events were found, the majority of which has therefore to be attributed to particles associated with the triggering shower.

In Fig. 2 the delay distribution of the above 72 telescope coincidence events is compared with the distribution obtained in the calibration runs. During the latter runs, a random external trigger at a rate of several thousands per minute was provided, with a corresponding increase of the rate of the C_{tel} events accidentally accepted by the gates. It is seen that, while the distribution obtained in the calibration runs is essentially flat, as expected for accidentals, most of the events of the production runs are grouped in the region of the small delays up to about 250 ns, thus proving that they are associated with the triggering cascades.

The nature of these events is not determined by the present experiment. Pulse height analysis (see below) shows that they are consistent with single particles of unit charge. In ref. 12, it is estimated that shower protons of a few GeV energy (which could often give rise to charged secondaries crossing 25 cm of Pb absorber as used in the present experiment) can with an appreciably probability have delays of $\approx$ 100 ns. Therefore, the most natural interpretation of these events is that they are due to such protons.

From 250 ns to 1000 ns the delayed coincidences (14 in total) are uniformly distributed, and their number is consistent with the expected contamination of accidentals (12 events).

To perform the pulse height analysis, penetrating cosmic ray particles were used to find for each counter of the telescope the amplification factor (pulse height on the film versus energy loss in the counter). This allowed to plot for each event the total energy loss in the telescope as a function of the delay. This plot is presented in Fig. 3, both for the production and for the calibration runs. In the same figure the projection of these plots on the y-axis is also given, to show the energy loss distribution. It is seen that no indication for particles ionizing $\sim {}^{1}/_{2}$ of the minimum (charge ${}^{2}/_{3}$ e) is obtained. The region of very small ionization (energy loss ~ 10 in the arbitrary scale of Fig. 4, roughly corresponding to what can be expected for particles of charge ${}^{1}/_{3}$ e ionizing $\simeq {}^{1}/_{9}$ th of the minimum) has relatively more events in the production runs than in the calibration runs. However, it is felt that such a small effect has not to be taken to seriously, because similar events are also abundant in the calibration runs. Moreover, the delay distribution for such events is roughly the same as for all the others, thus providing an indication for the apparent small energy loss being due to pulse height fluctuations in the detectors or to some other spurious effects. As a matter of fact the geometrical arrangement of the telescope counters was such that in some cases particles could possibly trigger the telescope by passing through the perspex light pipes.

From a comparison of the energy loss distribution for the 72 delayed events and for the accidental events of the calibration runs (Fig.3), the following upper limits for the quark flux can be estimated.

Particles of charge ${}^{2}/_{3}$ e should give an energy loss between ~ 50 and 80 in the arbitrary scale of Fig. 4. 3 such events are found in the production runs while about 5 are expected when comparing with the calibration runs. Therefore, no evidence at all is found for particles ionizing $\sim {}^{1}/_{2}$ of the minimum. A safe limit can be obtained by taking such events to be at most 3. By dividing by the number of triggering showers, the following limit for the density can be obtained:

$$\frac{\text{surface density of } {}^{2}/_{3}\text{ e charged quarks}}{\text{surface density of all charged shower particles}} \lesssim 2.10^{-5}$$

the quarks being accepted within a solid angle of ≈ 1 sterad around the vertical direction and within a delay band of 50 to 1000 ns with respect to the front of the showers, and the shower energy being $\sim 7\cdot 10^{13}$ eV.

Particles of charge $^1/_3$ e should give energy losses ≤ 40 (see Fig.3). Compared with the calibration runs, about 2 such particles are expected in the production runs, whereas 8 are found. Because of the above arguments this number is only used to estimate an upper limit for the flux. With a similar procedure as used for the $^2/_3$ e charged quarks, but taking also into account the 50% telescope efficiency for $^1/_3$ e charged particles, the limit obtained for the same ratio is $9 \cdot 10^{-5}$ for the conditions specified above.

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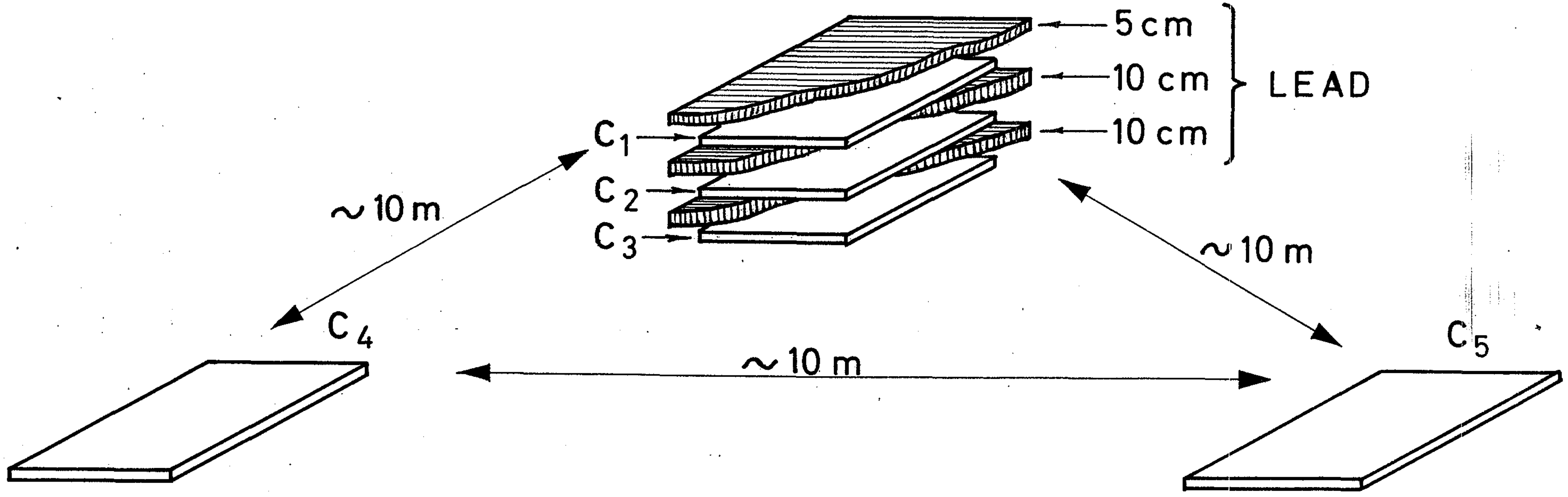
FIGURE CAPTIONS

Figure 1 : Schematic layout of the experiment.

Figure 2 : Distribution of the events as a function of the delay with respect to the front of the shower (upper section), compared with the accidentals distribution as obtained in the calibration runs (lower section).

Figure 3 : Plot of the energy loss as a function of the delay, and energy loss distribution for the events (upper section)and for accidentals (lower section).



C_1 : 90 x 90 x 1.5 cm^3

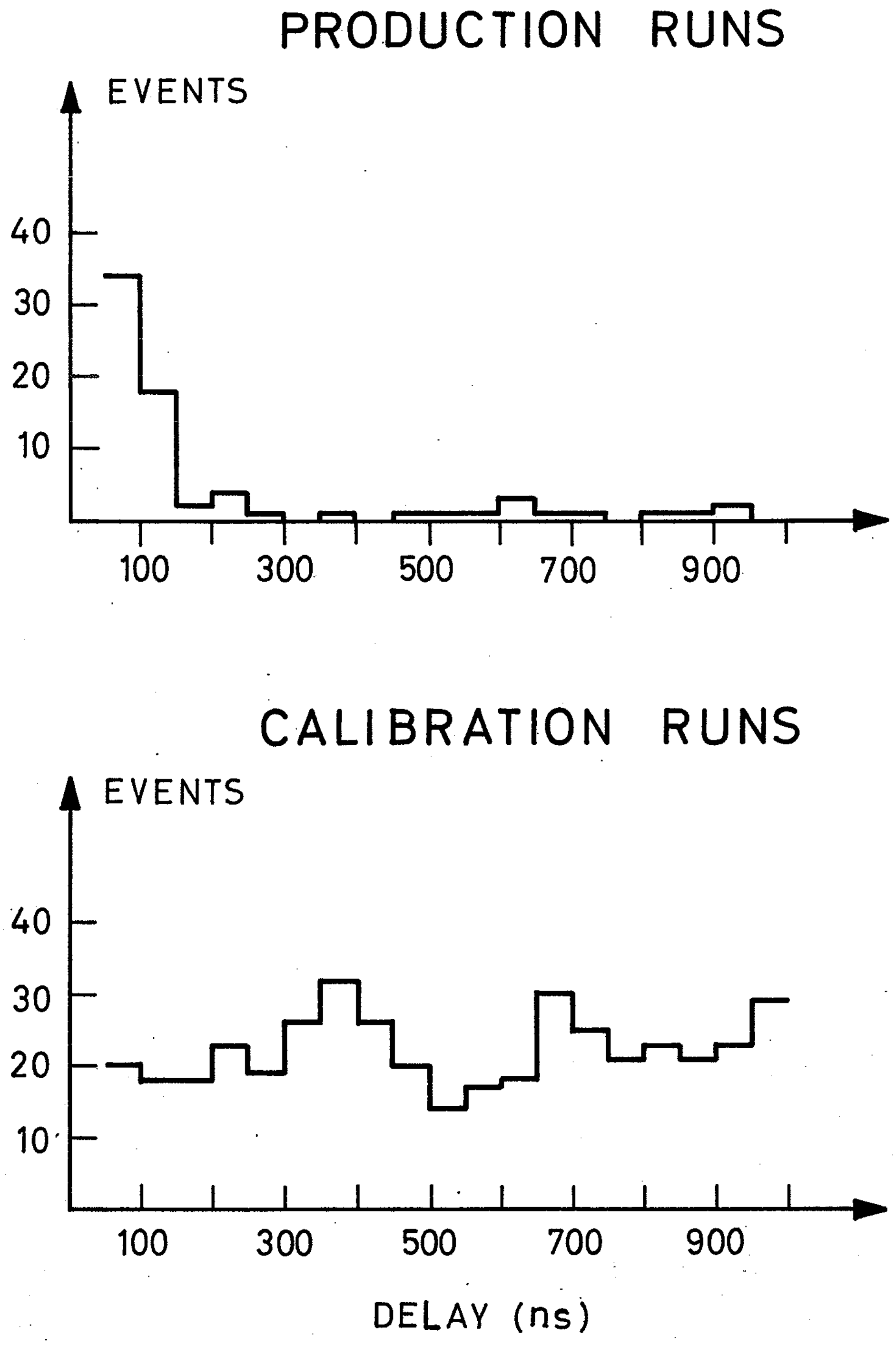
C_2 : 90 x 100 x 1.5 cm^3

C_3 : 90 x 90 x 1.5 cm^3

C_4 : 90 x 130 x 2 cm^3

C_5 : 85 x 125 x 2 cm^3

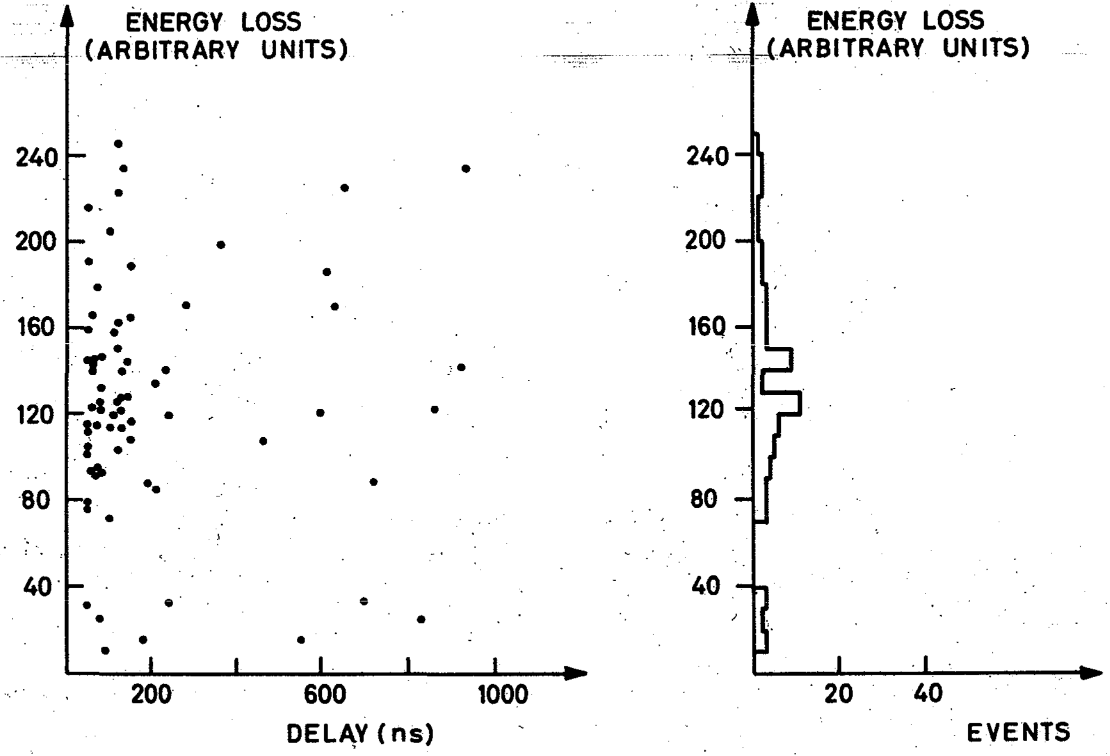
Fig. 1


PRODUCTION RUNS

CALIBRATION RUNS

Fig. 2

PRODUCTION RUNS



CALIBRATION RUNS

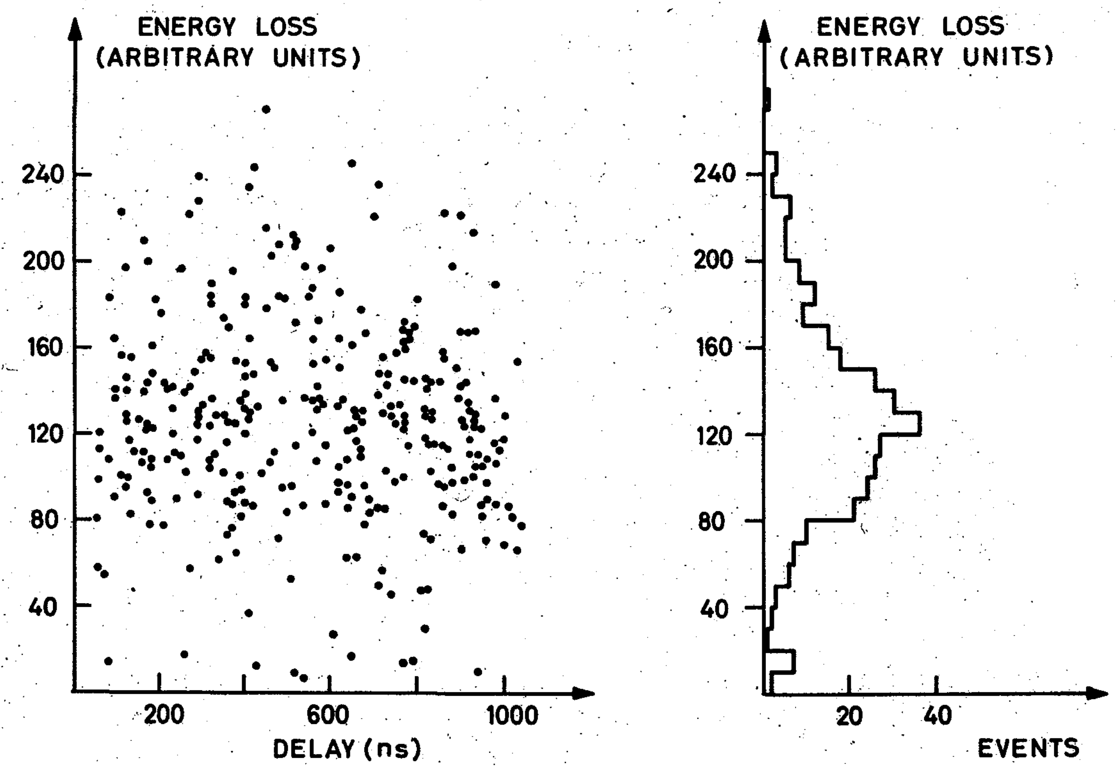


Fig. 3