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THE SEARCH FOR PARTICLES WITH A FRACTIONAL CHARGE (QUARKS) IN THE 70 GeV ACCELERATOR

Yu.M. Antipov, N.K. Vishnevskij, F.A. Ech, A.M. Zajtsev,
I.I. Karpov, L.G. Landsberg, V.G. Lapshin, A.A. Lebedev,
A.G. Morozov, Yu.D. Prokoshkin, Yu.V. Rodnov, V.A. Rybakov,
V.I. Rykalin, V.A. Sen'ko, B.A. Utochkin, V.P. Khromov.

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1. Experimental Lay-out

The search for particles with a fractional electrical charge (quarks) has been the subject of a large number of experimental studies, both in accelerators and in cosmic rays (see,for example, the review of ref.1). When the IHEP proton synchrotron went into operation, enabling protons to be accelerated to an energy of 70 GeV, the range of accessible quark masses was considerably increased, - when protons collide with stationary nucleons quarks with a mass of up to 4.8 GeV/sec^2 may form (paired with antiquarks), whereas for previous accelerators with an energy of 30 GeV the limit was 2.8 GeV/sec^2. The purpose of the present paper is to describe the experimental search for quarks produced by protons having an energy of 70 GeV on an internal aluminium target in the IHEP accelerator.

The measurements were made on a 50 GeV/sec beam of negative particles extracted from the accelerator at an angle of 0^o. The simplest process for forming Q quarks in nucleon-nucleon collisions is the reaction

$$N + N \longrightarrow N + N + \bar{Q} + Q. \qquad (1)$$

Figure 1 shows the results of calculations for the outputs in the laboratory co-ordinate system for the reaction (1) on the assumption that the angular distribution of quarks is isotropic in the centre-of-mass system, whereas the momentum spectrum corresponds to the Lorentz invariance phase volume. As can be seen from figure 1, if the beam channel is adjusted to a momentum of P = 50 GeV/sec for particles with a single charge e, (which corresponds to the momentum of quarks with an energy of q = 2/3e, equal to P_Q = 33.3 GeV/sec) the best conditions are achieved for the recording of quarks with a charge of 2/3e throughout the kinematically accessible range of masses. With regard to quarks having a charge of 1/3e (i.e. P_Q = 16.7 GeV/sec) the range of accesible masses is limited to a value of 4.4 GeV/sec^2 at the upper end, whilst for masses $\geqslant$ 4 GeV/sec^2 the quark outputs are much lower than the optimum. The basic experiments described in the present article were carried out with a momentum of P = 50 GeV/sec. An additional series of measurements was carried out with P = 40 GeV/sec.

2. Recording Apparatus

The arrangement of the recording apparatus on the particle beam is shown in figure 2. The same beam was used simultaneously by the IHEP-CERN group for measurement of π^-, K^--meson and antiproton production cross-sections. The cross-sectional values obtained as a result of these measurements were used to standardise the results of the present experiment.

The energy losses by ionisation in quarks with a fractional charge are substantially less that in particles with a unit charge e (twice as large when q = 2/3e and 9 times as large when q = 1/3e). This enables the quarks to be separated in the beam from the π^--mesons and other "normal" particles, by multiple measurements of ionisation losses. The relative ionisation losses were measured by means of spectrometric scintillation counters (S_1 - S_{10}) (the dimensions of the scintillators were 11 × 10 × 2 cm). The beam of particles passing through the spectrometric counters was separated with O_1 -O_3 counters (dimensions: 9 x 10 x 1 cm), and protective counters A_1 - A_3 (dimensions: 25 x 25 x 2 cm with a 9 x 9 cm aperture in the centre). In addition to the determination of ionisation losses, measurements were also made of the time of flight of the particles, on a basis of 60, between the T_1 and T_2 counters (dimensions 15 x 10 x 2 cm). To reduce the background of π^-- K^--mesons and antiprotons gas-type threshold Čerenkov counters were used ($\check{C}_1$ and $\check{C}_2$).

The spectrometric counters S_1 - S_{10} and the counters T_1 and T_2 were assembled with XP 1020 photomultipliers. In the remaining scintillation counters, where a high standard of amplitude and temporal resolution was not required, FEU-30 photomultipliers were used.

Typical amplitude spectra obtained by recording π^--mesons with a spectrometric counter are shown in figure 3. Also given here are spectra measured in a condition of optical imitation of the particles with a fractional charge q = 2/3e and q = 1/3e (the quantity of light falling on the photocathode of the photomultiplier was reduced by means of a black paper mask). As can be seen from this drawing the recording efficiency of π^--mesons and other particles with a unit charge may be sharply inhibited by maintaining a sufficiently high recording efficiency of quarks with a charge of $q = 2/3e$ (all the more so for $q = 1/3e$). So, if recordings are made only of momenta with an amplitude $A < 0.85\ A_0$ (where A_0 is the amplitude corresponding to the maximum of the spectrum for π^- mesons), the recording efficiency of particles with a charge of e, 2/3e and 1/3e is 10^{-2}, 0.96 and 1 respectively. When $A < 0.7\ A_0$ the difference in recording efficiency is greater still: 3×10^{-4}, 0.93 and 1.

The results of measuring the amplitude spectra of the $S_1 - S_{10}$ counters showed that for a preliminary selection of events with little ionisation it is sufficient to use 5 spectrometric counters at a discrimination level of $A < 0.85\ A_0$. In this case, the recording efficiency of beam particles was inhibited more than 10^6 times. The final selection of events was performed with a high-speed five-ray oscillograph, the inputs of which were supplied with the pulses from all of the counters.

The electronic circuit of the apparatus (figure 4) was made up of components from the IHEP system of logical nanosecond electronics [2]. The collision momentum produced by this circuit $[S_2 (A<0.85A_0), S_3(A<0.85A_0)\ S_4(A<0.85A_0)\ S_6(A<0.85\ A_0), S_7(A<0.85A_0), O_1, O_2, O_3]$ was used to trigger the five-ray oscillograph. By using the oscillogram measurements it was possible to make a multiple amplitude and temporal analysis of the pulses from the counters $S_1 - S_{10}$ and T_1, T_2, as well as obtain information about the operation of the counters $\check{C}_1$, $\check{C}_2$ and $A_1 - A_3$.

The high-speed five-ray oscillograph was a modified version of the equipment [5] previously used to record rare pion decay and capture processes. To increase the dynamic range of amplitudes, limited by the oscillograph's region of linearity, the pulses from each spectrometric counter were simultaneously fed to two oscillograph rays with an amplification differing by four times. The measurement of impulses with amplitudes of $A > 0.5\ A_0$ was done on a ray with less amplification, whereas at

$A < 0.5 A_0$ it was done on a ray with greater amplifcation. An analysis of the oscillogram showed that the accuracy of the temporal measurements was 0.5 - 1 nsec, and that of the amplitude measurements 5 - 10 %.

The pulses from the temporal counters T_1 and T_2, as well as from counter S_5 were fed to the inputs of the time of flight measurement circuit which was controlled by the pulse used to trigger the oscillograph. To compensate temporal scatter due to the difference in the time taken to collect the light from the various points of the scintallator, the scintillators of the T_1 and T_2 counters were scanned from two opposite ends by two photomultipliers. The time of flight measurement system included a circuit for automatic comparison of the time intervals, selecting only those events when the time of flight of the particles between the counters T_1 and S_5 and S_5 and T_2 corresponded to an identical particle speed. Time of flight data were displayed on an illuminated panel, which was photographed at the same time as the oscillograph screen. For the π^--mesons, the time of flight measurement system possessed a resolution of $2\tau = 0.5$ nsec, whilst for $q = 1/3e$ it was $2\tau = 1$ nsec (measured with light masks).

The gas-type threshold Čerenkov counters with a quartz optical system $\check{C}_1$ (with a spherical mirror) and $\check{C}_2$ /4/ had a speed resolution of $\Delta\beta = 7 \times 10^{-6}$. They were so adjusted that the recording inefficiency of π^-, K^--mesons and antiprotons was $\ll 10^{-2}$. The threshold of the Čerenkov counters corresponded to a quark mass of $M_Q = 1.2$ GeV/sec^2 when $q = 2/3e$, and $M_Q = 0.6$ GeV/sec^2 when $q = 1/3e$.

3. Measurements on the Beam

During the time of basic exposure, 0.9×10^9 particles were sent through the apparatus (99% were π^--mesons) and 706 oscillograms were produced. π^-- meson beam intensity was between 1.5 and 8×10^4 particles per cycle when the intensity of the internal beam of the accelerator was 10^{11} protons per cycle and the duration of the discharge on to the target was 300 - 400 msec.

During exposure, periodic checks were made of the efficiency of recording the particles with small ionisation. In this case, the signals at the outputs of all of the counters that fed the electronic logic system were 15 times weaker. The passage of quarks through the equipment was also imitated by means of pulsed light sources placed near the photomultipliers. Apart from this, the stability of the pulse discrimination levels was checked, the amplitude spectra of the S_1-S_{10} counter pulses were measured, and the oscillograph was calibrated by means of a quartz-stabilised generator. The entire equipment was calibrated by producing multiple oscillographs of the cases when π^--mesons passed through the equipment.

4. Analysis of the Oscillograms

The oscillograms obtained were analysed on IHEP bi-polar scanning and measurement tables working on line with a Minsk-2 electronic computer. As a result of the analysis, 38 candidate events were selected, for which the position of the pulses in time on the oscillogram coincided, to within 20 nsec, with those predicted by the calibration measurements. The great majority of the remaining events were caused by triggering of the equipment by chance collisions of after-pulses of the photomultipliers, small pulse reflection at cable connection points, etc.

When the candidate-events were analysed, the following selection criteria were used:-

1) Pulses from all of the S_1-S_{10} spectrometric counters are present on the oscillogram,

2) the amplitude of these pulses lies in the interval $0.05\ A_0 \leqslant A \leqslant 0.85\ A_0$,

3) the pulses from both the T_1 and T_2 time counters are recorded on the oscillogram,

4) each pulse is displaced not more than 5 nsec in relation to the position on the ray determined by the calibration measurements,

5) there are no pulses from the Čerenkov counters $\check{C}_1$ and $\check{C}_2$ on the oscillogram,

6) the protective counters A_1- A_3 did not come into operation,

7) the time interval comparison circuit operated .

Every one of the 38 candidate-events failed to satisfy at least 5 of the above criteria and cannot be identified with the case of a quark passing through the equipment. The selectivity of the equipment was much higher than was necessary to inhibit the background in the conditions of our experiment. If we disregard the data from the $\check{C}_1$ and $\check{C}_2$ Čerenkov counters and the T_1, T_2, A_1 - A_3 and S_8 - S_{10} scintillation counters (and at the same time do not impose a lower limit on the range of masses in which the search for quarks is made, and increase slightly the quark recording efficiency,), then in this case all the candidate-events are excluded simultaneously by two or three of the selection criteria.

5. Results of the Experiment

a) Boundary evaluation of the differential cross-section of quark production

During the time of equipment exposure in the beam, about 10^9 π^--mesons passed through it and not one quark with a charge of $q = 2/3e$ and $q = 1/3e$ was recorded. Consequently, for the relation of the outputs of quarks and π^--mesons N_Q/N_{π^-} when $P = 50$ GeV/sec we have:

$$N_Q/N_{\pi^-} < 4 \times 10^{-9}$$

(on a level of 90% reliability). The upper boundary evaluation of the differential cross-section of quark production in proton-nucleon collisions at an energy of 70 GeV and an angle of 0^o in the laboratory coordinate system $(d^2\sigma^Q/d\Omega dp)_{90\%}$ is linked with the π^--meson production cross-section $d^2\sigma^{\pi^-}/d\Omega dp$ by the relation

$$\left.\frac{d^2\sigma^Q}{d\Omega dp}\right|_{90\%} = \frac{d^2\sigma^{\pi^-}}{d\Omega dp}\frac{2,3}{N_{\pi^-}}\;\frac{e\varkappa}{q\varepsilon R} \qquad (2)$$

where ε and R take into account the difference in recording efficiency and in the absorption of quarks and π^--mesons, and the $\varkappa$ -decay of π^--mesons*). The introduction of the coefficient 2.3 in formula (2) corresponds to the 90% level of reliability of the evaluation in the absence of observed cases. The factor q/e takes into account the narrowing of the pulse interval for quarks as compared with π^--mesons (a difference of 1.5 or 3 times).

According to information obtained by the IHEP/CERN group on this same particle beam, $d^2\sigma^{\pi^-}/d\Omega dp \approx 1.4 \times 10^{-27}$ cm^2/ster GeV/sec for a pulse of π^--mesons of P = 50 GeV/sec, and $\approx 8 \times 10^{-27}$ cm^2/ster GeV/sec when P = 40 GeV/sec. The relative quark recording efficiency ε (taking into account the efficiency of the electronic equipment and the event selection criteria) is 0.72 for q = 2/3 and 0.84 for q = 1/3e. The correction value for absorption R was determined taking into account the quantity of counter material placed in the beam, and making three assumptions concerning the relationship of the total cross-section values for the interaction of quarks and π^--mesons with the material $g = \sigma_t^Q/\sigma_t^{\pi^-}$: $g = 1$, $g = 1/2$ /5/ and $g \ll 1$ (" lepton quarks" /6/. The results obtained are given in table 1.

The data set out in table 1 relate to the region of quark masses $M_Q \lesssim 4.8$ GeV/sec^2. When a proton collides with moving nucleons of a nucleus in reaction (1) quarks may be produced with an even greater mass, but the probability of quark formation decreases rapidly as their mass increases,(table 2). The data set out in table 2 may be used solely for qualitative boundary evaluations of the production cross-section of quarks with a mass of $M_Q >$ 5 GeV/sec^2, as they were obtained from measurements made by Dorfan and others /7/, who used a copper target, whereas in our case the protons were interacting with aluminium nuclei.

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*) In the present work, the evaluations of the quark production cross-sections are made for quarks with a long life ($\gtrsim 10^{-8}$ sec.). The changes in formula (2) when evaluating the production cross-sections of short-lived particles are evident.

b) Boundary evaluation of quark production total cross-section.

Evaluations of the production total cross-sections of quarks having a 2/3e and 1/3e charge in collisions of protons with nucleons $\sigma^{Q}|_{90\%}$ were determined from phase volume calculations using the data given in table 1. These calculations do not take into account the dynamics of the interaction, which may considerably reduce the angular distribution of the quarks (as occurs in other processes of particle formation at high energies) thus reducing still further the evaluation of σ^{Q}. The values of $\sigma^{Q}|_{90\%}$ are given in table 3 and figure 5. Figure 5 also shows, for comparison, the data given in other works dealing with the search for quarks in accelerators (these were taken from review ref./1/). A comparison of our results with those quoted in the works dealing with the search for quarks in cosmic rays/1/ shows that for quark masses of $M_Q < 6\text{-}7$ GeV/sec^2 when q = 2/3e and $M_Q < 5$ GeV/sec^2 when q = 1/3e the boundary established in our work for the production cross-section of quarks is considerably lower than that obtained in cosmic ray experiments.

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Table 1

Upper boundary evaluations of the differential cross-section of the production of quarks by protons with an energy of 70 GeV on nucleons at an angle of 0° in the laboratory coordinate system (90% level of reliability).

P, GeV/sec	N_{π^-}	q	P_Q,GeV/sec	ε	$\left.\frac{d^2\sigma^Q}{d\Omega dp}\right\vert_{90\%}$, cm^2/ster GeV/sec		
					$g = 1$, $R = 0{,}91$	$g = 1/2$, $R = 1{,}1$	$g \ll 1$, $R = 1{,}3$
50	$0{,}8.10^9$	2/3e	33,3	0,72	$9{,}4 \,.\, 10^{-36}$	$7{,}7 \,.\, 10^{-36}$	$6{,}5 \,.\, 10^{-36}$
		1/3e	16,7	0,84	$1{,}6 \,.\, 10^{-35}$	$1{,}4 \,.\, 10^{-35}$	$1{,}3 \,.\, 10^{-35}$
40	$1{,}3.10^8$	2/3e	26,6	0,72	$2{,}2 \,.\, 10^{-34}$	$1{,}8 \,.\, 10^{-34}$	$1{,}5 \,.\, 10^{-34}$
		1/3e	13,3	0,84	$3{,}8 \,.\, 10^{-34}$	$3{,}3 \,.\, 10^{-34}$	$3{,}1 \,.\, 10^{-34}$

ε and R are factors accounting for the difference in recording and absorption efficiency of quarks and mesons.

Table 2

Relative probability of achieving various energies in the c.m.s. due to Fermi motion of nucleons in the nucleus at a bombarding nucleon energy of 70 GeV.

Energy in the c.m.s. GeV	Relative probability	Limit value of the mass, GeV/c^2
11,5	1	4,8*)
12,5	10^{-1}	5,3
13,8	10^{-2}	5,9
14,5	10^{-3}	6,3
15,8	10^{-4}	6,9
17,1	10^{-5}	7,6

*) Collision with a stationary nucleon

Table 3

Upper boundary evaluations of the total cross-section of the production of quarks in proton-nucleon collisions at an energy of 70 GeV (90% level of reliability).

q	ϑ	$\sigma^Q \|_{90\%}$, cm^2				
		$M_Q = 2\,(GeV/sec)^2$	3	4	4,5	4,7
2/3e	1	$1{,}8.10^{-35}$	$8{,}7.10^{-36}$	$2{,}6.10^{-36}$	$7{,}6.10^{-37}$	$2{,}4.10^{-37}$
	1/2	$1{,}5.10^{-35}$	$7{,}1.10^{-36}$	$2{,}1.10^{-36}$	$6{,}2.10^{-37}$	$2{,}0.10^{-37}$
	1	$1{,}2.10^{-35}$	$6{,}0.10^{-36}$	$1{,}8.10^{-36}$	$5{,}2.10^{-37}$	$1{,}7.10^{-37}$
1/3e	1	$3{,}7.10^{-35}$	$1{,}9.10^{-35}$	$1{,}0.10^{-35}$		
	1/2	$3{,}3.10^{-35}$	$1{,}6.10^{-35}$	$9{,}2.10^{-36}$		
	1	$3{,}0.10^{-35}$	$1{,}4.10^{-35}$	$8{,}5.10^{-36}$		

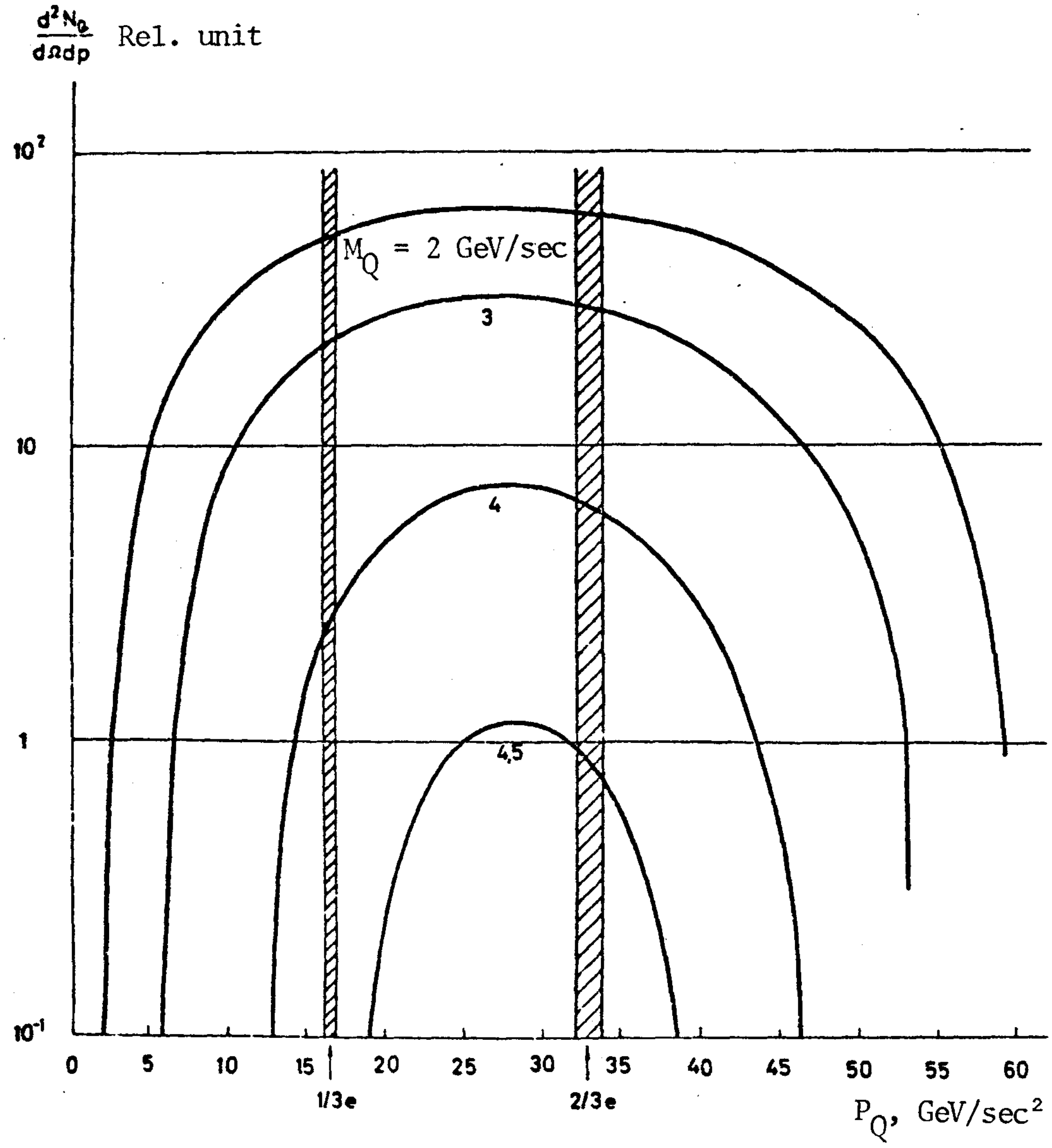

Fig. 1 Calculation of quark outputs for phase volumes. M_Q and P_Q are the mass and momentum of the quark. The shaded areas represent the pulse interval of the channel for a quark charge of q = 1/3e and 2/3e.

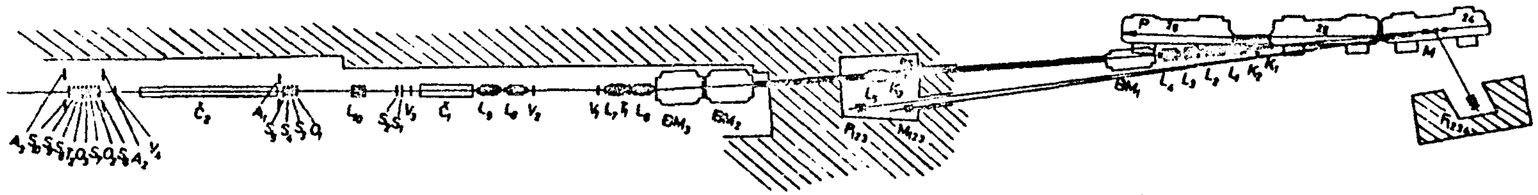

Fig. 2 Experimental layout. P: 70 GeV proton beam; m: internal accelerator target; BM_1-BM_3: deflecting magnets; L_1-L_{10}: quadrupole lenses; K_1,K_2: aperture collimators; K_3: pulse collimator; BS: beam shutter; Q_1-Q_3, S_1-S_{10}, T_1,T_2, and A_1-A_3: scintillation counters; $\check{C}_1$,$\check{C}_2$ threshold Čerenkov counters; P_{123}, M_{123} and F_{1234}: monitors for checking internal beam discharge on to the target; V_1-V_4: secondary particle beam monitor.

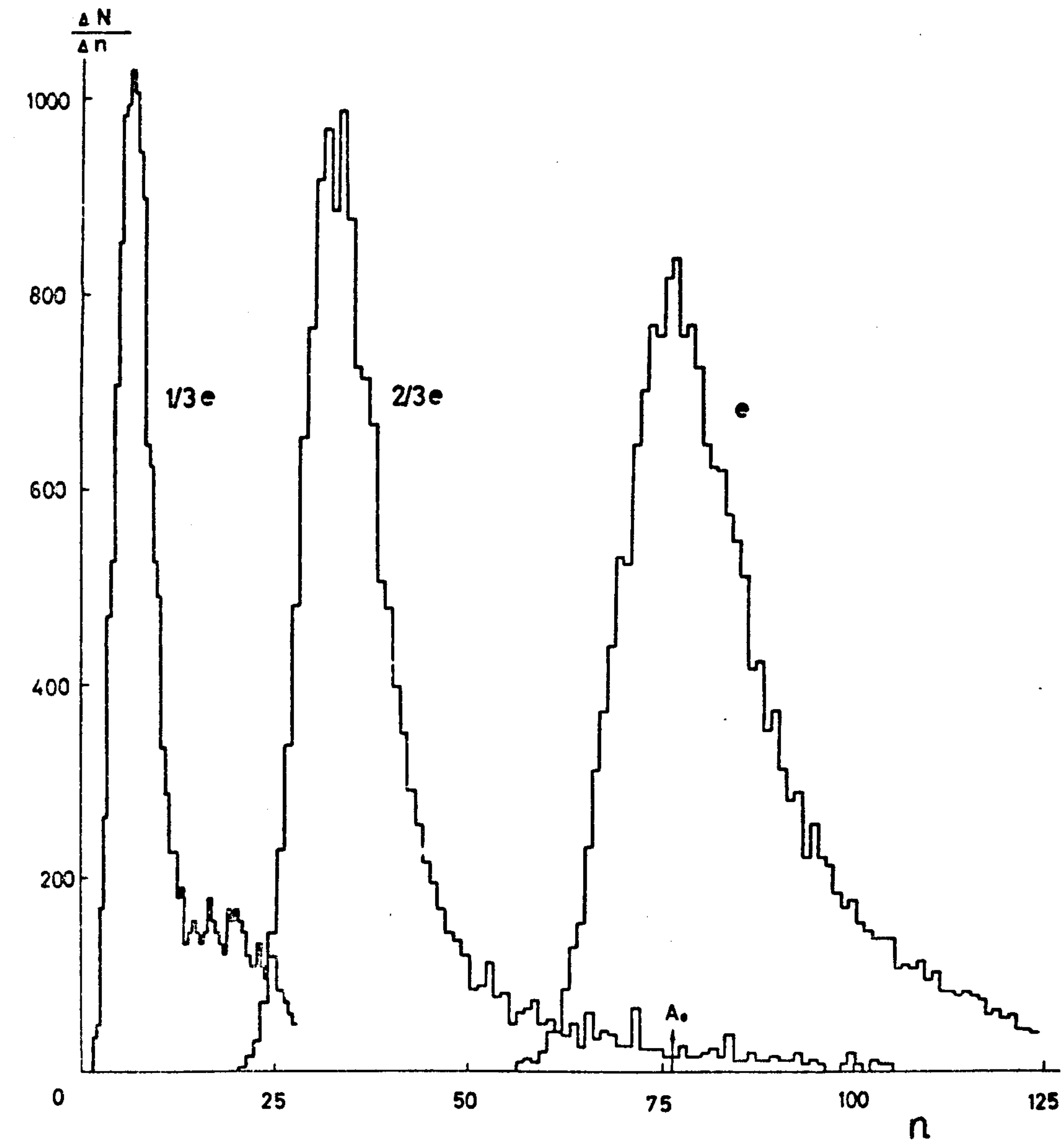

Fig. 3 Pulse amplitude spectra of the spectrometric counter S_3, measured for π-mesons and during operation to imitate quarks with a 2/3 and 1/3e charge. N: channel number of amplitude analyser; A_0: pulse amplitude corresponding to the maximum value of the spectrum for π^--mesons.

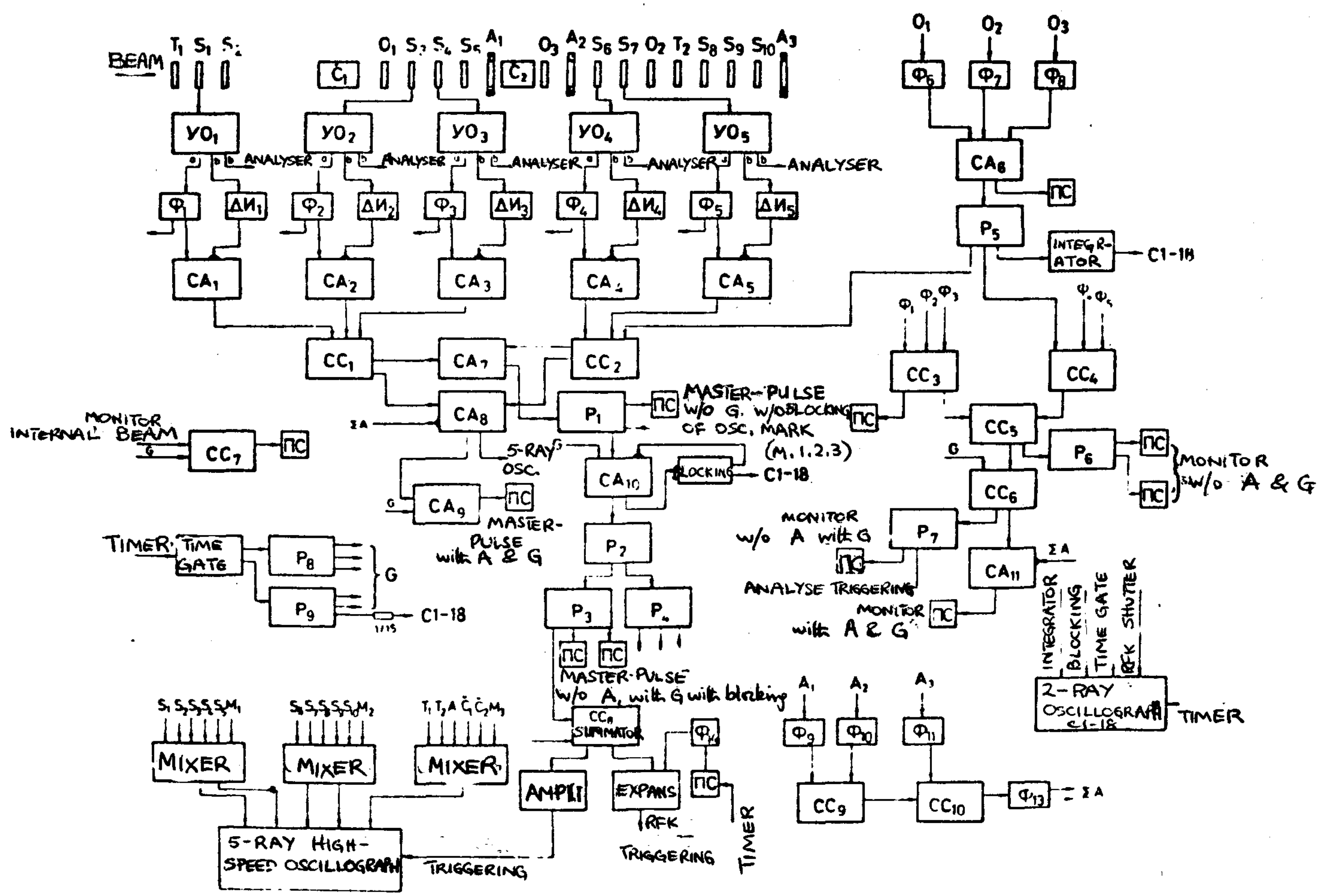

Fig. 4 Electronics block diagram. ϕ_i: shaper; YO_i: amplifier (outputs a with limitation of amplitude, b without limitation of amplitude); DU_i: amplitude discriminator; P_i: brancher; CC_i: coincidence circuit; CA_i: anticoincidence circuit; MC: scaler.