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COSMIC RAY SEARCH FOR FRACTIONALLY  
CHARGED PARTICLES

by

Donald Anthony DeLise

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GRADUATE COLLEGE

I hereby recommend that this dissertation prepared under my direction by Donald A. DeLise entitled Cosmic Ray Search for Fractionally Charged Particles be accepted as fulfilling the dissertation requirement of the degree of Doctor of Philosophy

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SIGNED: Donald A. DeLine

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## ABSTRACT

A mountain altitude search has been made in the cosmic ray spectra for the hypothetical, fractionally charged particles known as quarks. These charge  $1/3 e$  and  $2/3 e$  particles have been theorized as the fundamental particles underlying one possible interpretation of the SU(3) classification schemes. A six element, liquid scintillator telescope, with the two central elements independent of the triggering requirements, was used in this search. The data were recorded in the form of differentially delayed pulses from the six photomultipliers. Using 90% confidence levels we have found upper limits to the vertical intensities of  $1/3 e$  and  $2/3 e$  quarks to be  $I_Q (1/3) \leq 8.7 \times 10^{-9} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$  and  $I_Q (2/3) \leq 1.8 \times 10^{-8} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$ , respectively. The upper limits to the production cross sections have been estimated as a function of the masses of these hypothetical particles and assumed values for attenuation mean free paths. If one assumes that the quark production cross sections are of the order of .01 mb and that the quark removal cross sections are less than 15 mb/nucleon, then  $M_Q (1/3) \geq 9 \text{ BeV}/c^2$  and  $M_Q (2/3) \geq 7 \text{ BeV}/c^2$  are the lower limits obtained in this experiment.

## 1. INTRODUCTION

The relative success in the use of unitary symmetry schemes as a method of particle classification in the field of high energy physics has led to an interesting speculation concerning fractionally charged particles. The eight dimensional representation of the special unitary group  $SU(3)$  as formulated by Gell-Mann<sup>1</sup> and Ne'eman<sup>2</sup> (The Eightfold Way) yields the multiplet  $8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus \overline{10} \oplus 27$ . The known mesons seem to group in multiplets with 1, 8, and 8 members, while the known baryons are found to fit in 1, 8, and 10 representations, but no particles have yet been identified with the  $\overline{10}$  or 27 member multiplets in the 1 to 2 BeV mass energy region.

Continuing with the search for the fundamental representation, Gell-Mann<sup>3</sup> and Zweig<sup>4</sup> observed in 1964 that  $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$ . This version of  $SU(3)$  is convenient in that the unwanted  $\overline{10}$  and 27 member multiplets are missing; this agrees with the present day assignments for experimentally observed multiplets. If, however, the elementary triplet is assigned a baryon number equal to one, then the baryons would have baryon numbers equal to three. It is also difficult to expect this elementary triplet to have unit charge, as it would then require the baryons to

carry multiple charges. A more reasonable assumption for this model is to assign the fundamental triplet fractional charges and fractional baryon numbers, that is, an isotopic spin doublet with  $Z = 2/3 e$ ,  $- 1/3 e$  and  $A = 1/3$  and the singlet with  $Z = -1/3 e$  and  $A = + 1/3$ . Gell-Mann named these candidates "quarks"<sup>3</sup> and Zweig labeled them "aces"<sup>4</sup>; we will use the term quarks in this paper. If quarks exist, combinations of quarks and antiquarks would form the known baryons and mesons. If  $q$  and  $\bar{q}$  are the symbols for quark and antiquark, then the mesons could be made up by the combinations  $(q\bar{q})$ ,  $(qq\bar{q}\bar{q})$ ,  $(qqq\bar{q}\bar{q}\bar{q})$ , etc., while the baryons would be of the form  $(qqq)$ ,  $(qqq\bar{q}\bar{q})$ ,  $(qqq\bar{q}\bar{q}\bar{q})$ , etc.

Several experimental groups have looked for quarks since it was proposed that they might actually exist. Bubble chamber experiments were performed at Brookhaven<sup>5</sup> and CERN<sup>6</sup> in which tracks with low bubble density were investigated since they could correspond to the passage of a particle with a lower charge. In these cases, the tracks were identified as early tracks either by the delta ray method or relative bubble size method. Another group, using scintillators and counters in a secondary beam of the AGS, was able to set a lower limit on the quark mass.<sup>7</sup> They concluded that quarks do not exist with a mass less than  $2 \text{ BeV}/c^2$  if they have  $1/3 e$  charge.

A cosmic ray experiment made at sea level<sup>8</sup> yielded negative results in a search for relativistic charge  $1/3 e$  particles. The mountain altitude cosmic ray search made by the University of Arizona group<sup>9</sup> led to the conclusion, with certain assumptions, that if a charge  $1/3 e$  exists and is strongly interacting and long-lived, then it will have a mass  $\geq 7 \text{ BeV}/c^2$

The experiment described in reference 9 has been improved and extended; hence, this work is concerned with the search for both the  $1/3 e$  and  $2/3 e$  quarks produced by very high energy particle collisions due to cosmic radiation. A multi-element scintillator telescope was used so that reasonable triggering rates could be used to photograph the pulses from photomultipliers. The most probable loss of energy of a relativistic, charged particle is proportional to the square of the charge of the particle; this is approximate, as there is also a slowly varying logarithmic term. Therefore, a photomultiplier output is approximately proportional to the square of the charge of a particle which passes through it; in fact, for relativistic particles the output is sensitive only to the charge. By altering the signal produced by a relativistic, charge  $1 e$  particle, we can simulate a fractionally charged particle and thus have a method of calibrating the apparatus.

## 2. APPARATUS

Figure 1 shows the arrangement of the six element, liquid scintillator telescope used in this experiment. Each of the scintillators was approximately  $18 \times 18 \times 2.5 \text{ in}^3$ , and was viewed by a 5 inch photomultiplier tube. The area-solid angle acceptance was  $237 \text{ cm}^2 \text{ ster}$ . The  $18 \times 18 \text{ inch}^2$  dimension was selected, as it affords a fairly large area which may still be viewed with uniform light collection efficiency by one 5 inch photomultiplier tube. The total vertical dimension was reduced by introducing mirrors to fold the optical path, greatly improving the solid angle acceptance of the equipment.

It was possible to operate with two of the photomultiplier tubes' signals independent of the triggering signal described below by increasing the number of scintillator units to six; the previously reported University of Arizona experiment had five units. The last dynode signals of the six photomultiplier tubes were differentially delayed in multiples of about 250 nsec so that the pulses would appear at separate positions when connected to the vertical display of an oscilloscope. Signals from the anodes of PM tubes 1, 2, 5, and 6 became inputs to a 4-fold coincidence circuit and to a 4-input mixer (OR) circuit, followed by a

discriminator, into the anticoincidence input. The resolving time of the coincidence circuit was about 100 nanoseconds. The anticoincidence was activated by a pulse corresponding to  $dE/dx \approx .7$  in units of  $(dE/dx)_{\min}$  by means of the anticoincidence discriminator. A 4-fold coincidence-anticoincidence requirement was found necessary so that the triggering rate would be low enough ( $\sim 4$  events/min) to make camera cycling and the quantity of raw data reasonable. With a 3-fold coincidence-anticoincidence high trigger rates are caused by cosmic ray showers and fluctuations in the pulse height response to charge 1 e particles. A block diagram illustrating the electronics is shown as Figure 2. The oscilloscope and the recording camera were triggered by this circuit whenever counters 1, 2, 5, and 6 simultaneously received signals which correspond to  $.03 < dE/dx < 0.7$ , again in units of  $(dE/dx)_{\min}$ . Scintillator units 3 and 4 were not connected to the triggering circuit and, hence, have pulse height distributions which are unaffected by possible triggering biases.

The experiment was carried out on a nearby mountain range at an elevation of 7800 feet; this reduces the atmospheric depth to about  $760 \text{ gm/cm}^2$ . The apparatus was housed so that approximately  $0.5 \text{ gm/cm}^2$  of material was overhead. A vertical path through all of the material of the apparatus would traverse approximately  $48 \text{ gm/cm}^2$ , mostly due to the

toluene of the liquid scintillators. The data were collected during a sensitive time of about 1,100 hours.

### 3. DATA ANALYSIS

The pulses from the six photomultiplier tubes were photographed as displayed on an oscilloscope. The 35 mm film was then scanned and measured on a digitized measuring projector. The system was calibrated at intervals throughout the running period by the use of two sets of masks which allowed only  $1/9$ th or  $4/9$ ths of the incident light to strike the photocathode of each photomultiplier. These masks consisted of a large number of apertures distributed uniformly over the area that corresponds to the photocathodes. The uniformity assures that the pulse height factor will not be altered due to variations in photocathode efficiency. The two sets of masks reduced the scintillator light by factors of  $1/9$ th and  $4/9$ ths and narrowed the widths of the pulse size distributions by the same factors. The most probable energy loss distributions have been calculated by the method of Symon<sup>10</sup> for the cases of charge  $1 e$ ,  $2/3 e$ , and  $1/3 e$  traversing one of our scintillators; these are shown in Figure 3a. These distributions are displaced by 7.9, 3.5, and 0.8 MeV, respectively, which are the most probable energy losses for the three charges. In Figure 3b we have displayed the results of altering the charge  $1 e$  distribution; the coordinates of points on the curve were

reduced by factors  $1/9$  and  $4/9$ ths for the abscissas and expanded by factors  $9$  and  $9/4$ ths for the ordinates. The resulting curves are centered at  $3.52$  and  $0.88$  MeV for the  $2/3 e$  and  $1/3 e$  cases. The corresponding distributions are quite alike. Since the calibration pulses are produced by attenuating the light striking the phototubes, the effects of photon counting statistics, electron multiplier fluctuations, and system noise should be identical for calibration pulses and true quark pulses. Hence, the use of the previously described photomultiplier masks with the charge  $1 e$  flux of cosmic rays (obtained by disabling the anticoincidence) closely simulates the passage of charge  $1/3 e$  and  $2/3 e$  particles through the scintillator.

The  $2/3 e$  calibration distribution was used to set an upper limit pulse height for traces suitable for measurement such that all quark events would have been accepted. Other criteria used to eliminate traces during the scanning were the following: a) no overlapping traces could be used; b) each pulse from positions 1, 2, 5, and 6 had to be non-zero and within  $\pm 40$  nanoseconds with respect to their mean positions on the trace; c) the pulses from positions 3 and 4 had to be within  $\pm 40$  nanoseconds of their mean positions if they were non-zero; d) every candidate for measurement must have had no extra pulses. If a trace satisfied all of the conditions, it was measured, and the data were automatically recorded on punched cards.

Computer programs were used to reduce the data. First, the calibration data were analyzed by a pulse height distribution program. This allowed the assignment of a set of nested limits on pulses 1, 2, 5, and 6, which were determined by subtracting equal percentages of the events from each end of the distributions. Pulse height distributions of independent units 3 and 4 were obtained with 1, 2, 5, and 6 within the assigned limits. Narrowing the limits on 1, 2, 5, and 6 tends to preferentially eliminate background events, with the assumption that the background events have a much broader distribution than the hypothetical quark events. From these data displays it can be determined whether or not further data purification by narrower limits on 1, 2, 5, and 6 will result in larger signal-to-noise ratios for pulses 3 and 4. Figure 4 shows the results of applying this purification program to the calibration data,  $1/3 e$ , as seen by counter 3. A pulse height distribution was then made on the signals from one of the independent units while the other independent unit's limits were narrowed, and vice-versa. Figure 5 shows the pulse height distribution observed by counter 3 during the charge  $1/3 e$  analysis. The selection criteria on pulses 1, 2, 4, 5, and 6 would include: (a) 91%, (b) 49%, and (c) 25% of all true quark events. Figure 6 is a similar set of distributions for the charge  $2/3 e$  analysis.

Limits on the data from the region where quark-like pulses would be expected were then set, and pulse height distributions were made on the pulses associated with the events within these limits. The shapes of these distributions are indications as to whether or not the events in the quark pulse height region are actually due to background events.

The background subtraction was made by making use of the 83% distribution, which has a large number of events. Because this distribution is nearly all background, the number of background events within the quark-like pulse region,  $N_1$ , is proportional, with coefficient  $C$ , to the number of events outside,  $N_0$ , of the interval. Then assuming that the shape of the background distribution remains the same, we can use this constant for the more highly purified distributions. In this way we can say that the mean number of quarks,  $\bar{N}_Q$ , is given by

$$\bar{N}_Q = K(\bar{N}_1 - C\bar{N}_0) \quad (1)$$

where  $K$  is a constant that depends on the fraction of true quarks expected to fall within the given interval and the fraction of events that survive the selection criteria of the five other counters.

The quark intensity limits in this paper are reported with a 90% upper confidence limit. This means that  $\bar{N}_Q$  has

been chosen such that the observed values fall at the boundary to the lower 10% tail of the distribution expected with mean,  $\bar{N}_Q$ .  $\bar{N}_i$  and  $\bar{N}_o$  have been chosen to maximize  $\bar{N}_Q$  subject to this condition. This, of course, tends to raise the upper limit on the quark intensities.

#### 4. RESULTS

A.  $Z = 1/3 e$ . The 90% confidence limit based upon the observed events combined with background corrections lead to the upper limits on the number of  $1/3 e$  quarks traversing our apparatus as shown in Table I. In this  $1/3 e$  analysis the number of events remaining in the 25% data becomes so small that the signal-to-noise ratio becomes worse than for the 49% data. The two values for  $\bar{N}_Q$  from the 49% data shown in Table I were therefore used. Since these two results are not statistically independent, an average was taken as  $(\bar{N}_Q)_{90\%}$  as seen by counters 3 and 4. These data yield an upper limit to the vertical intensity of  $1/3 e$  quarks at 7800 feet altitude,  $I_Q(1/3)$ , of  $8.7 \times 10^{-9} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$  using the 90% confidence levels. For those events that remain in the highly purified distributions of counters 3 and 4, the distribution of associated 1, 2, 5, and 6 pulses is consistent with the distribution expected for background events.

B.  $Z = 2/3 e$ . Table II shows the results for the charge  $2/3 e$ ; again we have used a 90% confidence level. The background in this case is due to the tail of the distribution of charge  $1 e$  particles. Due to the fact that some of the events above the  $2/3 e$  region deflect off-screen, the

background estimate for the  $2/3 e$  region is more uncertain than for the  $1/3 e$  case, above. The backgrounds which were used in the calculations are indicated by the smooth curves in Figure 6. The 22% purified case yields an average, from counters 3 and 4, of  $(\bar{N}_Q)_{90\%} = 17$ . This corresponds to a vertical intensity of charge  $2/3 e$  quarks at 7800 feet altitude,  $I_Q(2/3)$ , that is less than  $1.8 \times 10^{-8} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$ . If one assumes that all of the events in the interval that corresponds to  $2/3 e$  quark calibration are signal events (i.e., no background at all) the result is  $I_Q \leq 3.1 \times 10^{-8} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$ . The associated events (defined in Section A for the  $1/3 e$  case) were again distributed as expected for background events.

C. Cross sections. Upper limits to the production cross sections for hypothetical charge  $1/3 e$  and  $2/3 e$  can be estimated with certain assumptions: The quarks are long-lived, if they exist. Quarks are produced in pairs with a constant cross section per nucleon,  $\sigma_Q$ , for energies above threshold in  $NN \rightarrow NNQ\bar{Q}$  with an average of one quark of charge  $1/3 e$  or  $2/3 e$  per reaction. The cosmic ray primary proton total energy integral spectrum for  $10 \text{ BeV} < E < 10^4 \text{ BeV}$  is given by<sup>11</sup>

$$N(E) = 0.88E^{-1.5} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1} \text{ (E in BeV)}. \quad (2)$$

The attenuation mean free path,  $1/\mu_p$ , of protons in air is

120 gm/cm<sup>2</sup> and the removal of quarks from the relativistic energy region of the spectrum (where the detection scheme is sensitive) can be approximated by an attenuation mean free path  $1/\mu_Q$ . The attenuation of protons and the buildup of quark intensity can be described by a simple one dimensional diffusion equation in which each air nucleus is taken equivalent to 6 free nucleons. The resulting dependence of the quark production cross section,  $\sigma_Q$ , on the observed vertical intensity,  $I_Q(Z)$ , at atmospheric depth,  $x$ , is

$$\sigma_Q = (4.1) 10^3 I_Q(Z) (\mu_P - \mu_Q) \left[ 2(1 + M_Q/M_P)^2 - 1 \right]^{3/2} e^{M_Q x} \times \left[ 1 - e^{-(\mu_P + \mu_Q)x} \right]^{-1}. \quad (3)$$

The 90% upper confidence levels on  $\sigma_Q$  given by equation 3 are plotted in Figures 7 and 8 for the 1/3 e and 2/3 e cases, respectively;  $\sigma_Q$  is displayed as a function of the assumed quark mass ( $M_Q(1/3)$  or  $M_Q(2/3)$ ) for several choices of the quark nucleon removal cross section,  $\sigma_{QN}$ .

## 5. CONCLUSIONS

If quarks exist and are strongly interacting, then their production cross section might be  $\sim .01$  mb by analogy to the production of strange particles. From the accelerator experiments it was determined that the hypothetical quark would be a particle, whose mass  $\geq 2 \text{ BeV}/c^2$ , and since a fractional charge cannot be carried away in a collision with an electron or a nucleon, it is probably a fair assumption that the effective cross section for quark removal from the relativistic region is less than 15 mb per nucleon. With these assumptions we have the following lower limits on the masses of the  $1/3 e$  and  $2/3 e$  long-lived quarks, if they exist:

$$M_Q(1/3) \geq 9 \text{ BeV}/c^2 \text{ and } M_Q(2/3) \geq 7 \text{ BeV}/c^2.$$

The apparatus was sensitive for over 1100 hours as compared with about 240 hours in the previous experiment; the area-solid angle acceptance, however, was reduced by about 30% in this experiment. Even with the increased statistics and the additional independent counter we have not increased  $M_Q(1/3)$  very much (to  $9 \text{ BeV}/c^2$  from  $7 \text{ BeV}/c^2$  with the same assumptions). However, data from the new arrangement did yield a new and significant result for the

$2/3$  e quark intensity. In order to obtain an order of magnitude improvement on the results of this experiment it would not suffice to perform the obvious improvements as the size of scintillators and to extend the running time; the problem is to increase the signal-to-noise ratio, and this will demand much more selective triggering requirements. This is especially true for a  $2/3$  e search, since the charge 1 e distribution is so large that its tail may infringe on the  $2/3$  e distribution's interval.

TABLE I

	LIMIT SET 49%	LIMIT SET 25%
Counter 3	11.9	14.3
Counter 4	4.4	12.5

Upper limit on the number of  $1/3$  e quarks,  $N_Q(1/3)$  using a 90% confidence level on the observed events.

TABLE II

	LIMIT SET 55%	LIMIT SET 22%
Counter 3	24	13
Counter 4	45	21

Upper limit on the number of  $2/3$  e quarks,  $N_Q(2/3)$  using a 90% confidence level on the observed events.

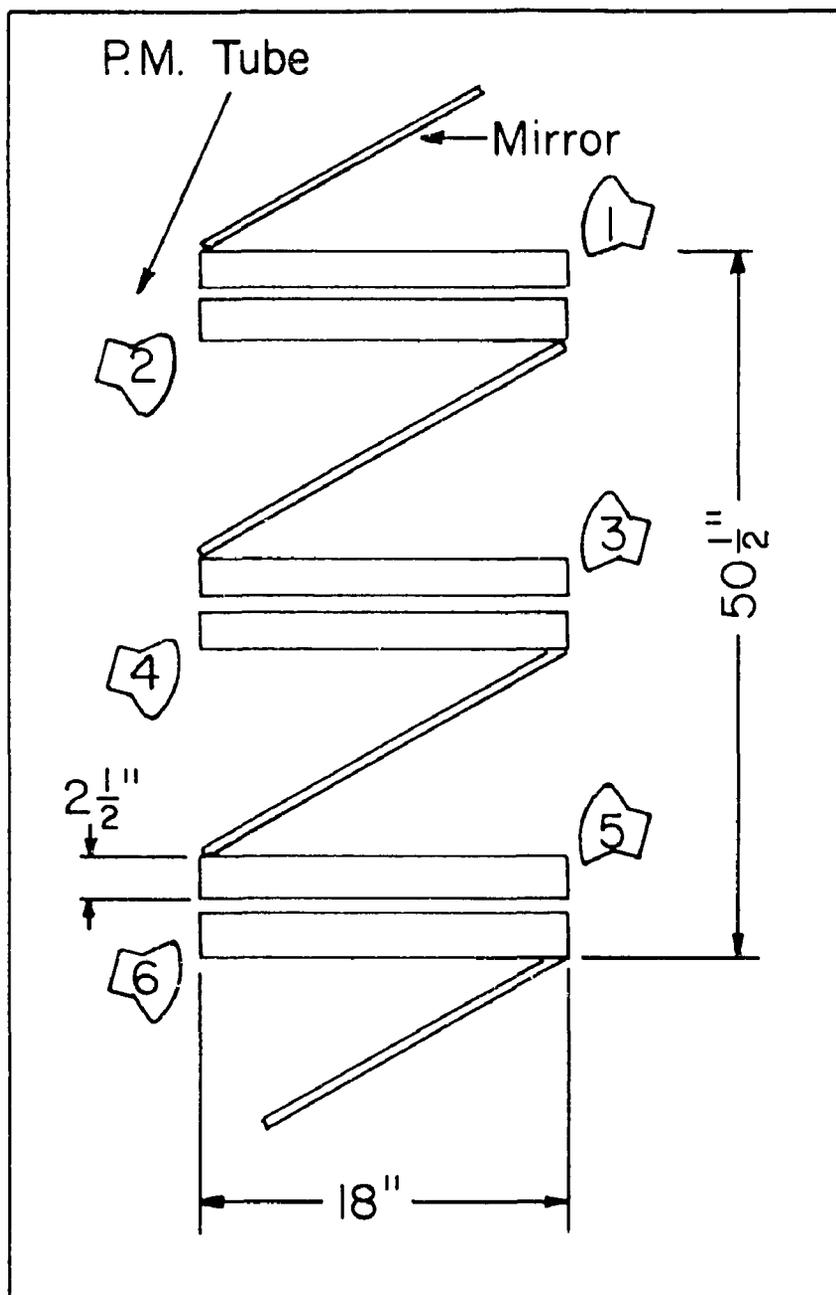


FIGURE 1. ARRANGEMENT OF SCINTILLATORS

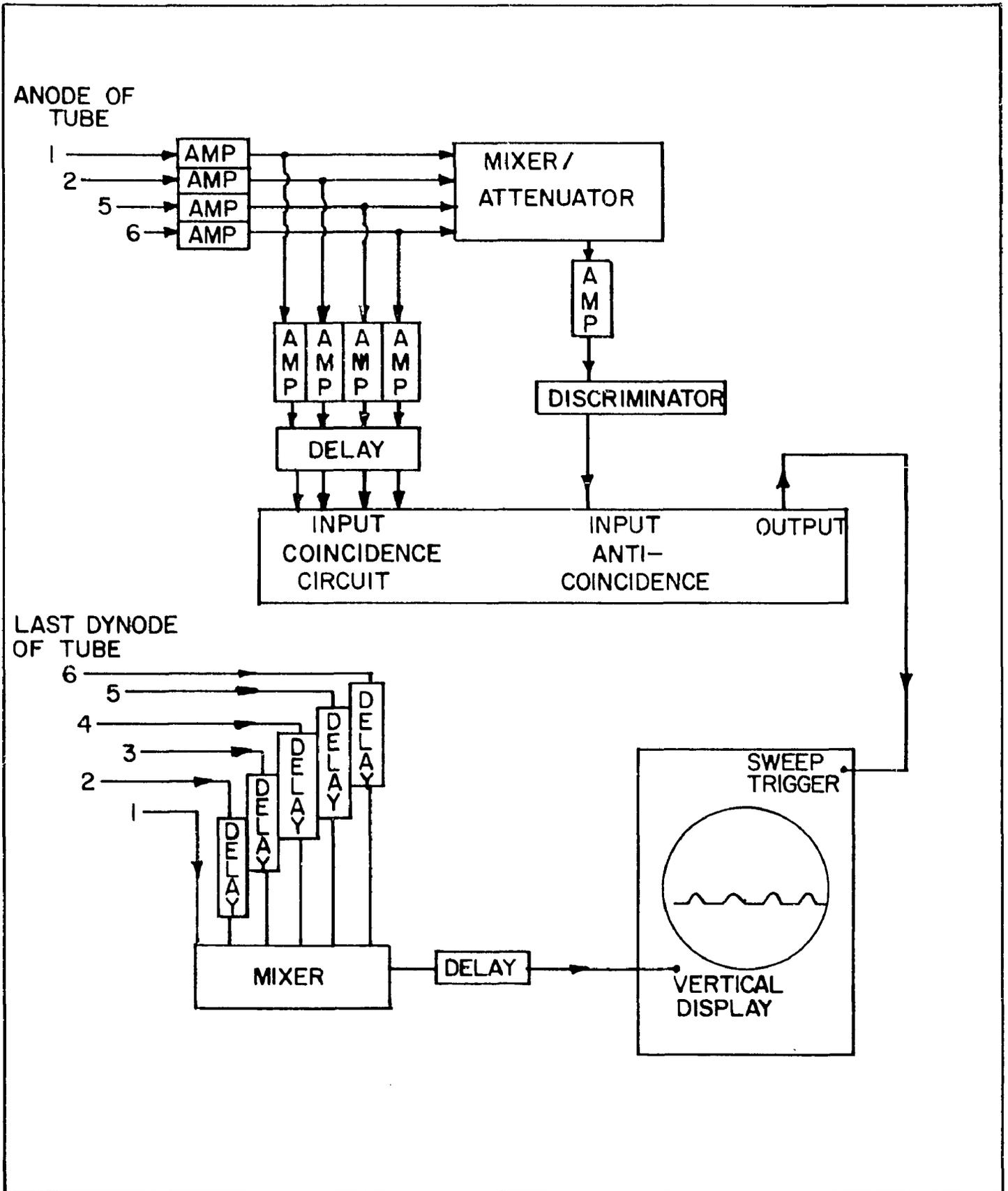


FIGURE 2. BLOCK DIAGRAM OF ELECTRONIC APPARATUS

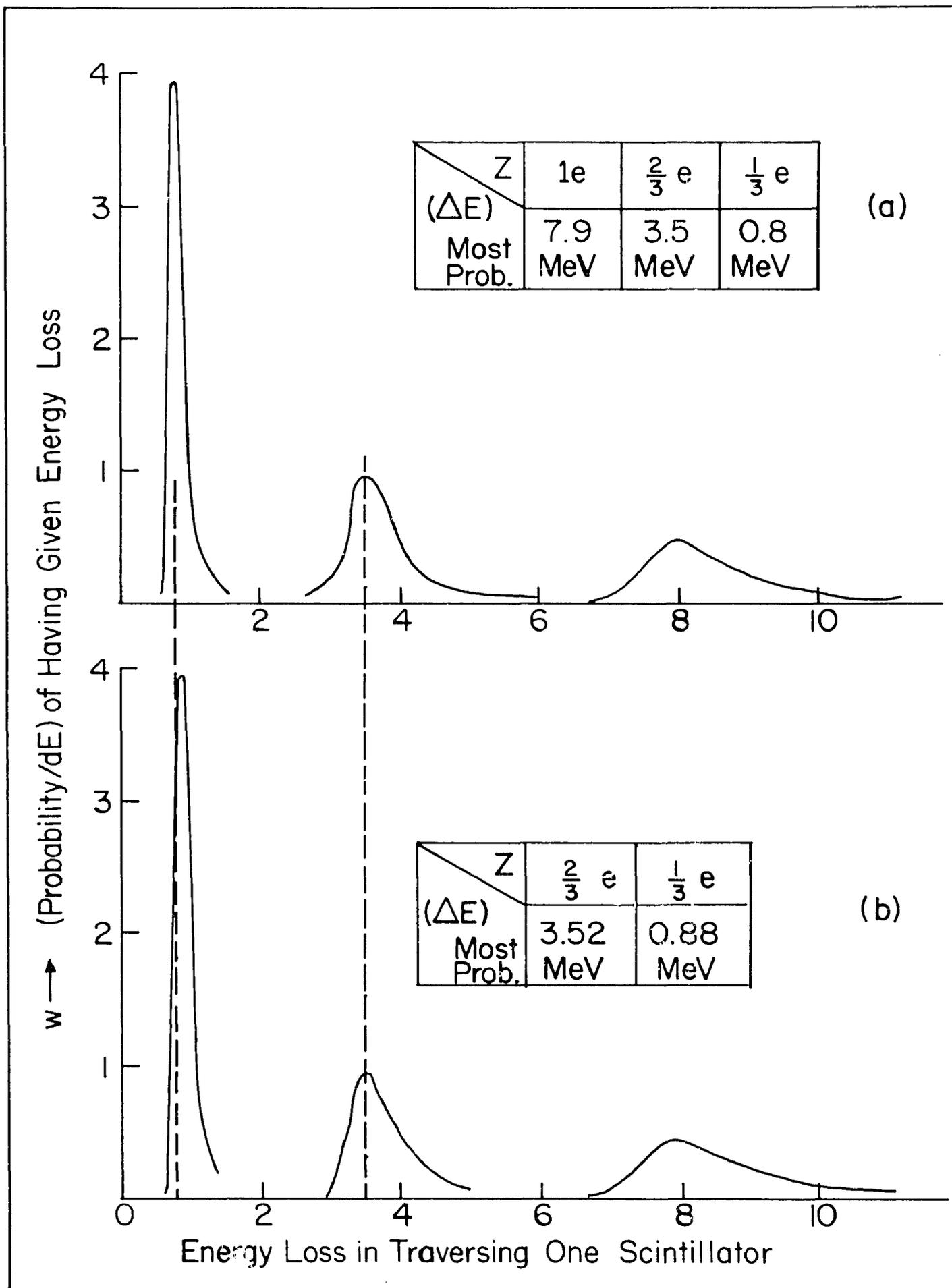


FIGURE 3. MOST PROBABLE ENERGY LOSS DISTRIBUTIONS

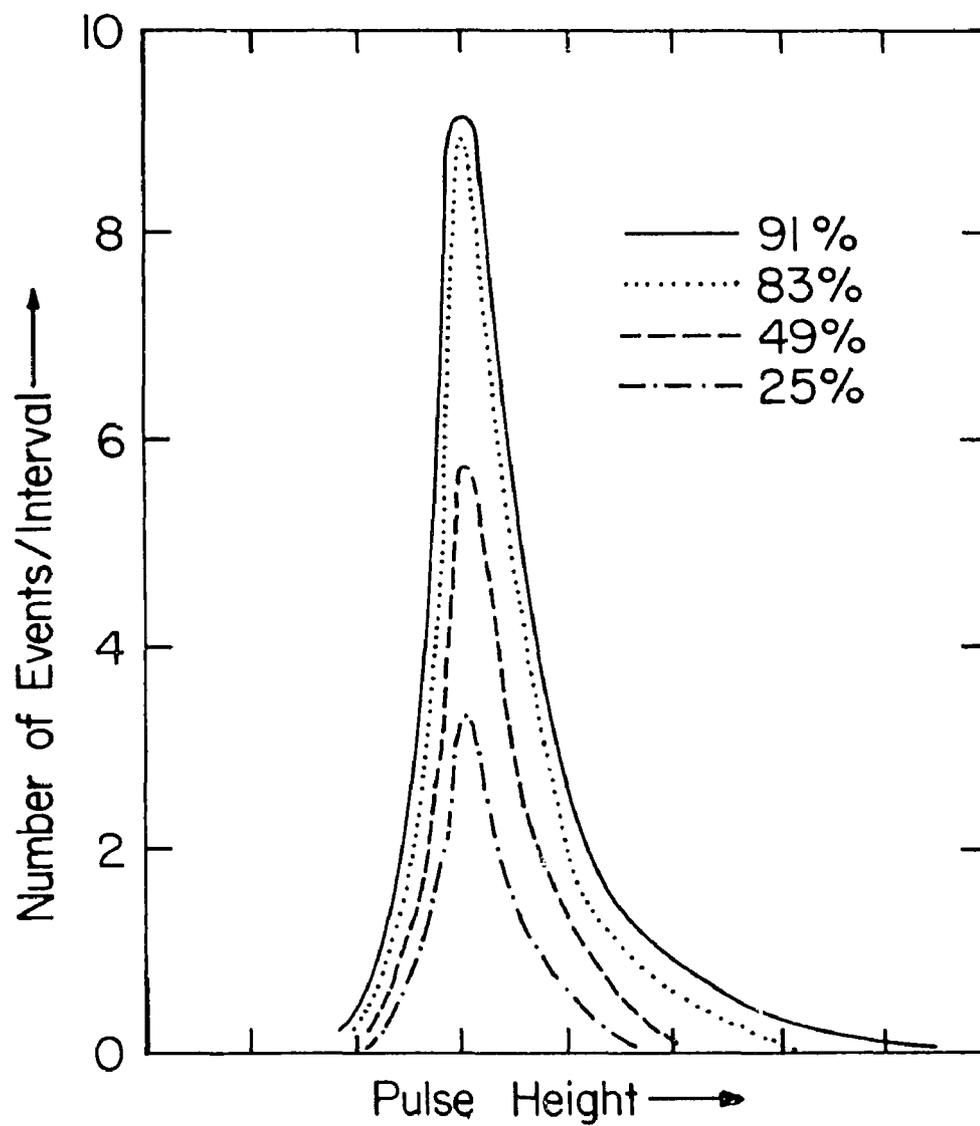


FIGURE 4. SIMULATED CHARGE  $1/3 e$  PULSE HEIGHT DISTRIBUTIONS

Figure 5. Distribution of pulses from Counter number 3 with the remaining five counters' limits set to allow the indicated percentage of true quark pulses to remain.

The shaded area (in the bottom graph) represents 50 quark-like pulses ( $Z = 1/3 e$ ) as would be seen in the 25% purified distribution.

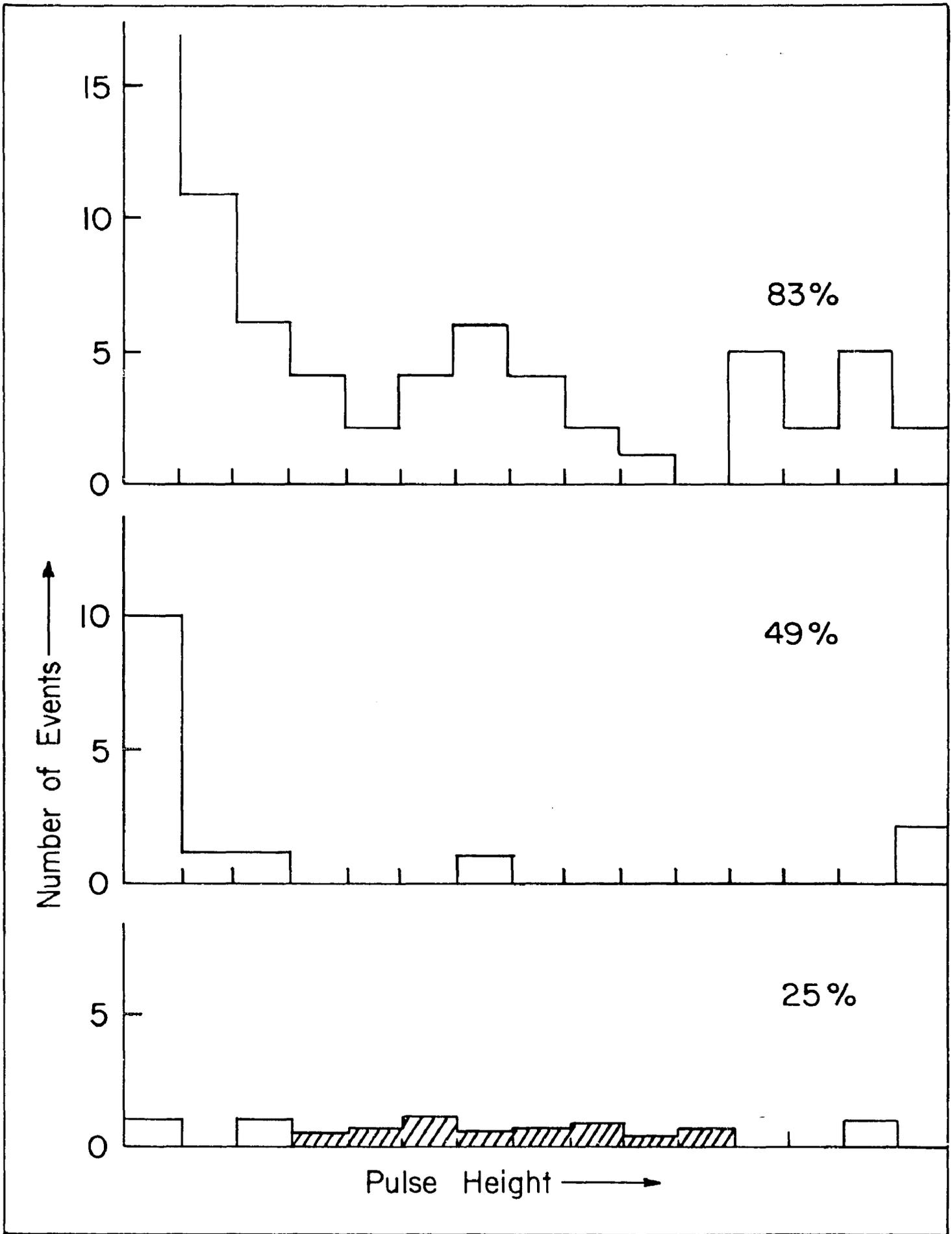


FIGURE 5. PULSE HEIGHT DISTRIBUTIONS, CHARGE  $1/3 e$

Figure 6. Distribution of pulses from counter number 3 with the remaining five counters' limits set to allow the indicated percentage of true quark-like pulses to remain.

The shaded areas represent 50 quark-like pulses ( $Z = 2/3 e$ ) as would be seen in that particular distribution.

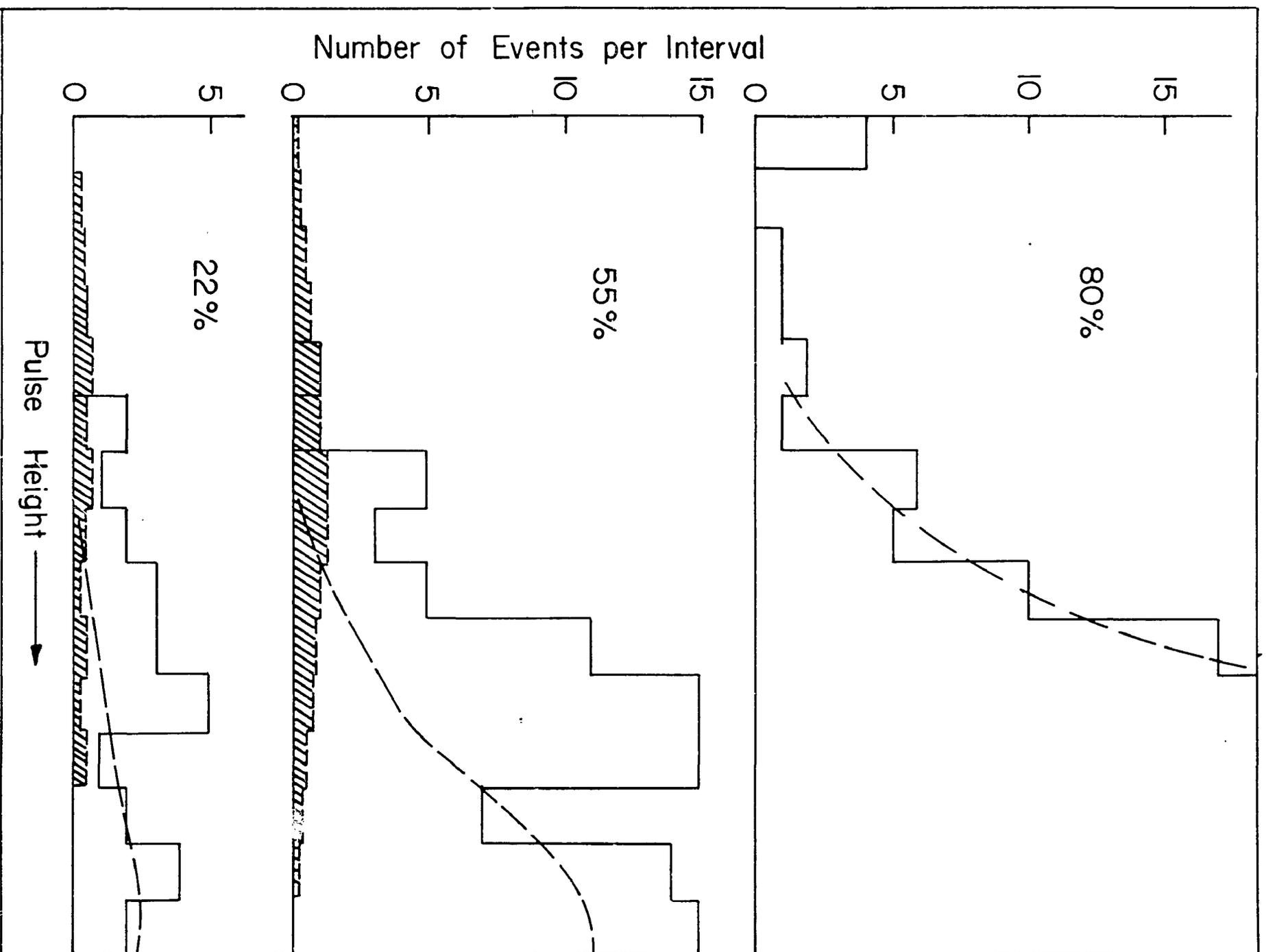


FIGURE 6. PULSE HEIGHT DISTRIBUTION, CHARGE  $2/3 e$

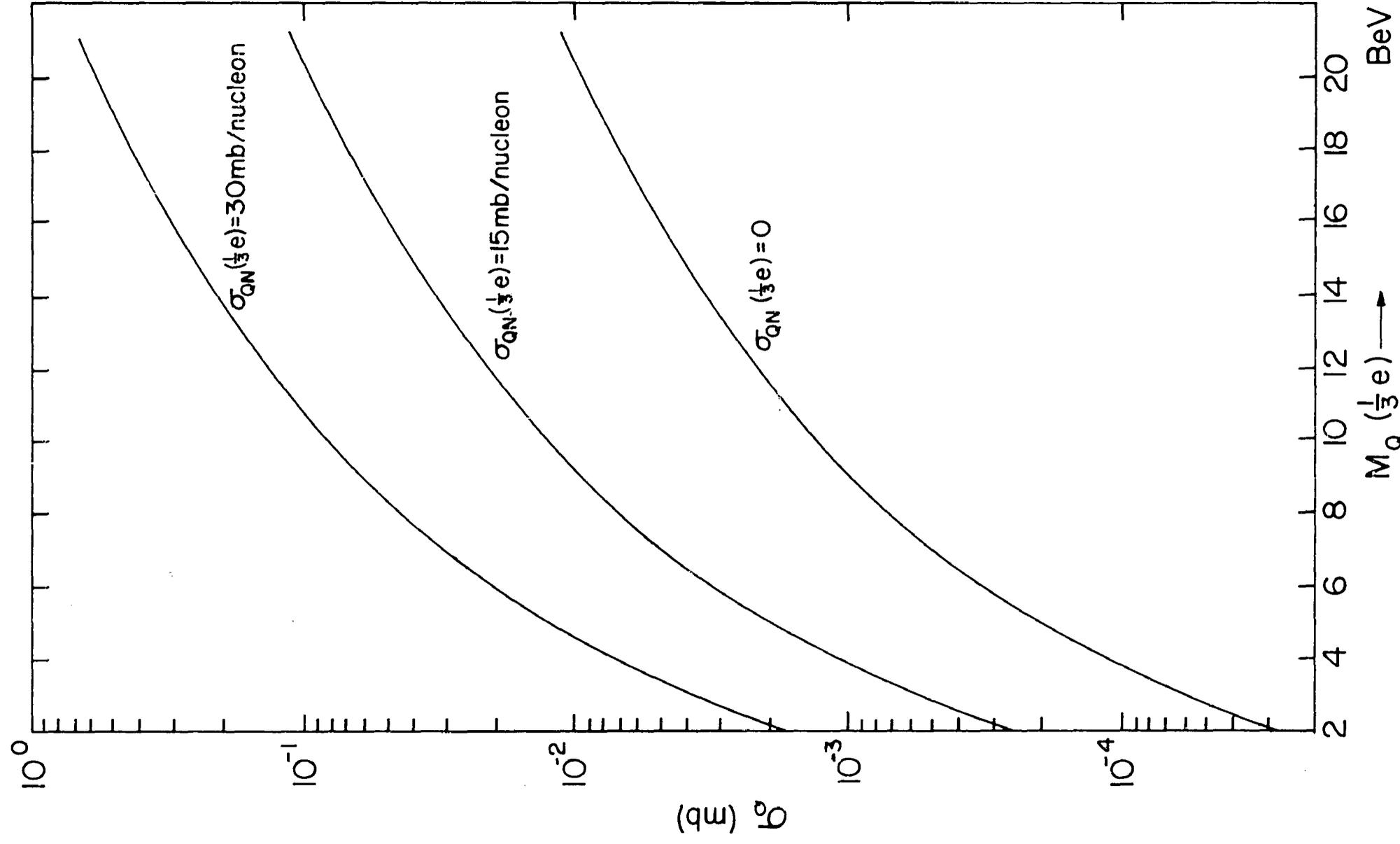


FIGURE 7.  $\sigma_Q$  vs  $M_Q(1/3)$

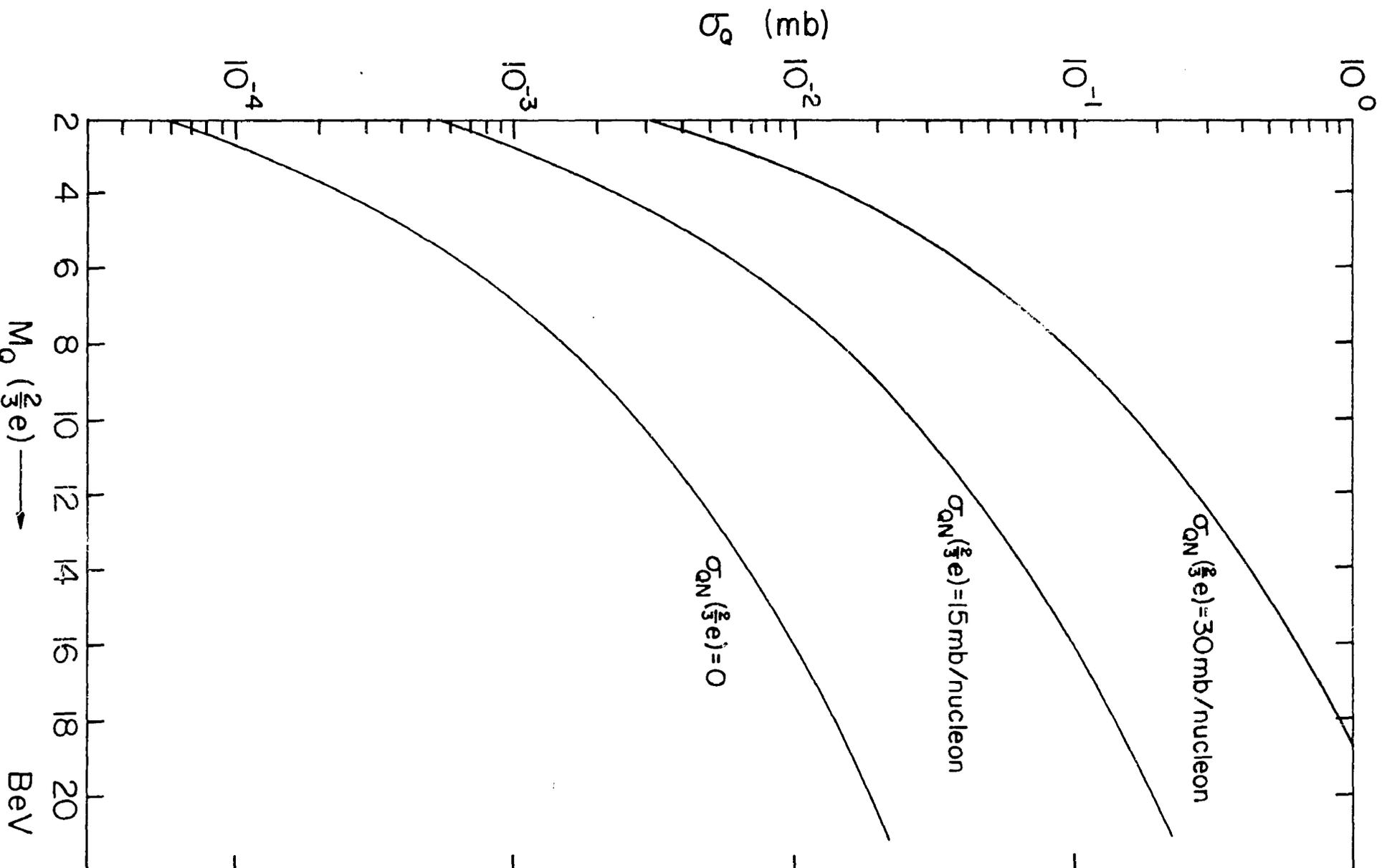


FIGURE 8.  $\sigma_Q$  vs  $M_Q(2/3)$

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