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A SEARCH FOR QUARKS IN THE CERN SPS NEUTRINO BEAM

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SUMMARY

Quarks and leptons are the only point-like particles known so far. However, a search for a proton-breaking mechanism in high-energy neutrino-nucleon interactions had never been performed. We present here the results of the first experiment in this field.

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1. INTRODUCTION

The limitations of previous quark search experiments have recently been reviewed¹⁾ and one of the conclusions was that so far quark production in neutrino interactions is an unexplored field. High-energy neutrino-proton interactions might prove to be the most efficient type of interaction for liberating quarks from the nucleon because the suspected elementary constituents of the nucleons, together with the leptons, are the only point-like particles at present known.

This paper describes a first measurement which was made using a simple scintillation counter telescope. The data has been used to support a proposal²⁾ for a more selective and sensitive experiment using a twenty times larger solid angle and using a streamer chamber.

2. CHOICE OF TECHNIQUE

Several techniques were considered, ranging from modifications of existing counter experiments to a scan of bubble chamber pictures with or without external tagging of fractionally charged particles. We finally concluded that a lumped target followed by low density counter telescopes and a low density visual device -- a streamer chamber -- would be the best solution.

Other counter experiments in the CERN neutrino beam are of the distributed calorimeter type, and we felt that the presence of material between the planes of scintillator would cause the accompanying normal hadronic pattern to change from plane to plane thus making quark identification difficult. On the other hand, suitable modifications of the apparatus would reduce their utility in the present neutrino program.

To make a comparison with the bubble chamber capabilities, we divided up the interactions into several classes:

- a) very low multiplicity, as would be the case for direct break-up of the proton into its constituents without the production of other particles;
- b) intermediate to low multiplicities as found in the normal neutrino interactions;
- c) very high multiplicities of a jet-like character;
- d) production of particles with charge greater than 1.

It is our opinion that bubble chamber searches are limited to type (b) interactions. In case (a) there will be no accompanying 'reference' tracks from the same interaction, and in case (c) the very high multiplicity of tracks and knock-on electron tracks would make fractional charge detection difficult. Furthermore, in any type of interaction it is doubtful if the bubble chamber is able to recognize charge $2e/3$ particles.

Note that the streamer chamber measures primary ionization and hence is far superior to both scintillation counters and bubble chambers for the detection of charges greater than 1 [class (d)].

We chose the counter technique because it gives a greater coverage of the range of interaction types, and because it can incorporate a trigger for higher selectivity and higher sensitivity. A trigger on fractional charges in the scintillators allows the selection of events from class (a) and (b) interactions. As the multiplicity increases the trigger efficiency decreases because of multiple hits in the counters. (The loss of triggers through this effect is about 30% for the average neutrino interaction.) However, a trigger could be made on type (c) events just by selecting high multiplicity in the counters, and then the streamer chamber pictures could be scanned for quarks among the jets.

In the present experiment, only the scintillation counter technique was used, and data were taken without any bias or pulse-height selection in the trigger.

3. APPARATUS

3.1 Counter layout

Figure 1 shows the counter arrangement. The axis of the neutrino beam, inclined at 43 mrad to the horizontal, left the floor of the experimental hall 10 m before counter A. The dimensions of the counters and their positions relative to counter A are given in Table 1. Counters were inclined with their faces perpendicular to the nominal beam direction so as to minimize edge effects. Veto counters were mounted to protect the light-guides of counter B, but the light-guides of counters A and C were not protected; any particle crossing counter B passed through the scintillator part of A because this completely covered both the scintillator and the light-guide of B. Each end of the five dE/dx counters was viewed by a photomultiplier: XP2020 were used for counters A and C and 58AVP for counters B, D, and E. Suffixes H and L are used to distinguish the two ends of each counter. Time-difference measurements were used to define the position of the particle and hence provide a further protection against particles crossing the light-guides.

NE110 scintillator was used for counters A and C. Counters B, D, and E were of home-made scintillator.

During the latter part of the running time, a $100 \times 40 \times 40$ cm³ block of lead was placed 250 cm before counter A, as shown in Fig. 1. A veto counter, before the lead, was used as a tag for interactions in the lead. During the greater part of the running time, the concrete floor served as the target.

3.2 Electronics and data acquisition

Figure 2 shows the electronics. Since with this apparatus the trigger rate for coincidences between photomultipliers (AH•BH•CH) was less than 0.5/burst even at the highest beam intensity, no further restrictions were placed on the trigger. This avoided background sources such as the tail of the slow component of the scintillation light from previous, vetoed particles simulating a fractional charge.

The coincidence (AH•BH•CH) provided the ADC gates and the TDC start signal. For each event, the pulse heights and relative times of all counters were recorded.

Each of the pulse heights in counters A, B, C, D, and E was measured twice using two linear channels with different gains. The high-gain channels saturated at pulse heights between 0.2 and 0.3 of minimum ionizing.

Protection against possible background situations was provided by a combination of hardware and software as illustrated by Fig. 2 and the flow diagram shown in Fig. 3. When the computer was accepting an event or was making a pedestal calibration, it provided a d.c. signal into the 'Veto OR'. The output of this circuit entered a d.c.-sensitive, up-dating discriminator which was set to a pulse length of 100 nsec and which provided the veto signal in the coincidence unit. This ensured that there was a veto present for at least 100 nsec after the removal of a signal from the OR veto. During this 100 nsec, the end of the pulse from the OR circuit was detected by RC differentiation and the resultant pulse triggered a 10 μ sec one-shot. A coincidence between this signal and any pulse from AH or CH set a flag in a pattern unit to allow a software rejection of the next event. This method ensured that there were no dead-time effects which might reduce the efficiency of the protection.

To ensure that events were time-coincident with the neutrino beam burst, a standard SPS timing pulse, provided 80 nsec before the neutrino beam spill, was used to reset a scaler which counted continuously at a rate of 10^7 /sec. When an event occurred, the contents of this scaler were read out before reading the ADCs, TDCs, and the pattern unit.

4. DATA-TAKING

Data-taking was straightforward -- whenever the neutrino beam was in operation, data was taken, irrespective of expected event rate or neutrino flux, so that data was available under a range of machine and background conditions. Calibration measurements, described in the next section, were associated with each data-taking run.

5. CALIBRATION MEASUREMENTS

Extensive calibration measurements were made firstly to ensure the quality of the counters to be used and secondly to provide run-to-run corrections for electronic drifts.

5.1 Cosmic-ray calibrations

Before the apparatus could be installed in the neutrino beam line, a first series of calibrations were made using cosmic-rays to test the counters, measure their photostatics, and set up the apparatus. Counters A and C were positioned vertically above one another and 40 cm apart so that the thick counter B could be inserted between them. The coincidence was arranged so that counter I3 could be used in the trigger instead of counter B without changing the timing of the linear pulses relative to the gate signals. This allowed a zero time (TZERO) to be determined for each photomultiplier so that after correction of the TDC signals, zero time difference between the two photomultipliers of a counter indicated a particle crossing the centre of a counter.

Slewing corrections were determined by inserting passive attenuators in the signal lines. After corrections for slewing and zero time had been made, I3 was switched out of coincidence and the time differences were used to determine the position of the particle; hence the pulse height was measured as a function of position so that a pulse-height correction factor could be determined. Pulse heights were normalized to the pulse height of a minimum ionizing particle crossing the centre of the counter.

5.2 Muon calibration

Calibrations similar to the above cosmic-ray calibrations were carried out in the neutrino beam area using background muons from a nearby external target which was used to produce secondary charged beams in the experimental hall. The angle between this "muon beam" and the neutrino beam was only 66 mrad, so the calibration could be carried out without displacing the counters. Muon calibration data were recorded with and without passive attenuators to simulate charge $1/3$ quarks electronically.

Figure 4 shows the pulse-height spectra obtained with 1 m of the counters illuminated and after correction for attenuation. Full widths at half maximum of 30% were obtained for the 2 cm thick counters A and C and 22% for the 18 cm thick counter B. In Fig. 5 is shown the time-of-flight spectrum between counters A and C. Continuous calibrations of the high pulse-height response were provided by the muon content of the neutrino beam because there was no pulse-height selection in the trigger. To obtain a clear muon signal it was sufficient to require: a) the correct synchronization of the event with the neutrino spill; b) a relativistic time of flight between counters A and C; and c) pulse heights greater than 0.5 of minimum ionizing in two counters.

5.2.1 Attenuation of the scintillator signal to simulate quarks

To obtain a good, over-all simulation of the apparatus to quarks, holes were punched in thin sheets of black PVC to give a 90% reduction in transmission, and these sheets were sandwiched between the light-guide and the photomultiplier using grease to make an optical contact. These measurements provided

- a) a check that the technique of using time differences to measure position will work for low pulse heights;
- b) a measurement of the time of flight resolution;
- c) an estimate of the photostatics and a measurement of the pulse-height resolution for quarks;
- d) a calibration of the variation in efficiency for quark detection as upper and lower pulse-height thresholds are varied simultaneously on the counters A, and B, and C.

Figure 6 shows the pulse-height spectra for counters A, B, and C with the masks mounted, and shows the electronic threshold at about 0.01, well below the lower edges of the pulse-height distributions. From the widths of the spectra, lower limits for the number of photoelectrons can be derived: there are more than 16 photoelectrons from charge 1/3 particles.

Figure 7 shows that a time-of-flight cut within ± 2.5 nsec of relativistic particles will cause negligible loss in events.

Figure 8a shows how the trigger rate varied as the signals from the masked photomultipliers were simultaneously attenuated by passive attenuators, and Fig. 8b shows how the efficiency varied as various pulse-height selection cuts were applied to the ADC values.

5.2.2 Calibrations with a polaroid filter and light-diode

Several methods might be used to calibrate the pulse height expected from a charge 1/3 particle. The method of masking the photomultiplier gave one measurement, but there was up to 20% variation observed for the reduction factor for the various photomultipliers and for repeated replacement of the masks. An alternative method is to show that the photomultiplier is linear up to the highest pulse heights and then to use the peak of minimum ionizing particles to give the pulse-height scale. Figure 9 shows the photomultiplier output as a function of the angle between two crossed polaroid filters. The diode output was adjusted to give a peak height on the oscilloscope equal to that of a minimum ionizing particle. Apart from the residual light transmission due to filter imperfections, the response is linear with the $\cos^2$ of the angle between the filters, and indicates an error of less than 3% in the pulse height if a 20 dB attenuator is used to estimate the $Q = 1/3$ extrapolation.

5.2.3 Calibration with a light-diode and masks

A third method was to measure the effect of a 90% attenuation mask without using optical grease. A pulsed light-emitting diode was viewed directly by the photomultiplier, and the voltage of the pulse to the diode was adjusted to give the pulse height of a minimum ionizing particle. The light output of the diode was varied by inserting attenuators in series with its supply cable. These measurements were repeated with the same attenuator settings but with a $\times 10$ attenuation mask before the photocathode. A plot of pulse height with mask against pulse height without mask compares the differential linearities of the photomultiplier and electronics for a factor a 10 difference in pulse height. Figures 10a and 10b show the results obtained a) for the pulse heights as measured on the oscilloscope, and b) for the pulse areas as measured on the ADC. In the ADC measurements, the data without an optical attenuator were taken with passive attenuation of the signal so as to use the same ADC channel range for both parts of the calibration. The 18% variation indicated in Fig. 10b is an upper limit to the non-linearity.

6. ANALYSIS AND METHOD

Data were corrected for attenuation in the counters and for time slewing, and then the events were filtered by requiring a) pulse heights less than 0.85 times minimum ionizing in counters A and B; b) a time of flight between counters A and C equal to that of a relativistic particle within ± 2.5 nsec. With this cut, the acceptance falls to 50% for a velocity of $\beta = 0.78$. This selection criterion was sufficient to reduce some 22,000 triggers to 706 events, which were printed out for inspection. The print-out gave the pulse heights of the five counters in the low-gain and high-gain channels, the direction of the particle, the positions in the five counters, information on the veto-counter status, and the neutrino burst synchronization clock contents. These events were examined in detail, and a further selection was made by requiring that the veto counters I2 and I4 were not hit, that the position in counter A was within ± 60 cm of the centre (i.e. the size of counter B plus a safety margin), and that the event should be in time with the neutrino beam. Most events rejected failed two or more of these tests.

Accepted events were then displayed on two scatter diagrams. The first scatter diagram gave the mean pulse height in counter A as a function of the mean pulse height in counter B, with the added selection criterion that counter C pulse height should be less than 0.85 of minimum ionizing. The second type of scatter diagram plots RSD as a function of ABC, where

$$ABC = (A + B + C)/3$$

$$RSD^2 = (A - ABC)^2 + (B - ABC)^2 + (C - ABC)^2 ,$$

(A, B, and C refer to the pulse heights in the respective counters). The results for the broad-band and narrow-band runs are shown separately in Figs. 11a and 11b, and in Figs. 12a and 12b.

The acceptance zones covering 0.5 to 1.6 of the pulse heights expected for charges $e/3$ and $2e/3$ are indicated on the scatter diagram of B against A. Only two events are accepted, marked with a circle and a square. The same symbols mark these two events in the (ABC, RSD) scatter diagram. Figure 13a, obtained by Monte Carlo simulation using the masked photomultiplier spectra as input, shows the expected distribution of charge $e/3$ events. The two events accepted in the AB scatter diagrams are indicated. Although neither event is in the most probable region, the event marked with a square cannot be excluded. Since this was a quick survey experiment, we prefer at the present time to quote only an upper limit for the quark production. The distribution of points on Fig. 12 can be understood from Fig. 13b which is a similar scatter diagram taken in a muon calibration without attenuators. The lines are the correlations for the following geometric and physical effects:

- a) two pulses equal and the third pulse bigger, for example Landau fluctuations in one counter;
- b) two pulses equal and the third one smaller, for example edge effects in counter B;
- c) counter B pulse missing or negligible;
- d) two negligible (e.g. noise) pulses in two counters, and one big pulse from noise or from a particle in the third counter.

7. BEAM INTENSITY, ACCEPTANCE, AND RESULTS

The neutrino interaction rate was calculated partly from the muon flux in the muon shield and partly from the proton beam intensity on the target, depending on the run and on the availability of this information. In both cases the total number of protons on the neutrino target was determined for each run, and then the neutrino interaction rates in the materials in front of the telescope were obtained using the calculated wide-band and narrow-band spectra.

For comparison, Table 2 gives the number of ν or $\bar{\nu}$ interactions for a 1 m wide, 40 cm high, 210 g/cm² thick target, for the different types of running conditions, together with the observed muon flux through the telescope.

The over-all acceptance was calculated using a simulation program for neutrino interactions³⁾ in the shielding. Evaluations of the acceptance is model-dependent, and the assumptions made were that the quark has a production distribution similar

to that of the muons from neutrino interactions, that the effective absorption length for quarks is 270 g/cm^2 , and that if a nucleon breaks up then it produces three quarks with charge less than unity.

With these assumptions, the product of the number of interactions times the acceptance is 450 ± 150 .

This gives a 90% confidence limit of $(5.0 \pm 1.7) \times 10^{-3}$ per neutrino interaction for relativistic quark production in, effectively, the CERN broad-band neutrino beam.

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- 3) A. Grant, EF Division CERN, private communication.

Table 1

Dimensions and positions of the counters

Counter	Width (cm)	Height (cm)	Thickness (cm)	Distance from A (centre to centre along the beam direction) (cm)
A	225	22	2	0
B	100	18	18	11
C	225	22	2	270
D	100	18	18	281
E	100	18	18	291
I2	30	30	4	22
I3	15	15	2	Variable. Used as a search counter.
I4	50	40	4	
Veto	120	50	2	-275

Table 2

Interactions and observed muon flux

Beam conditions	Integrated protons on target	Interactions*)	Integrated muons in telescope
ν wide band	9.7×10^{16}	4700	8100
ν narrow band	1.0×10^{16}	12	150
$\bar{\nu}$ narrow band	2.4×10^{17}	21	2293

*) In $1 \text{ m} \times 0.4 \text{ m} \times 210 \text{ g/cm}^2$.

Figure captions

- Fig. 1 : The counter and target arrangement relative to the nominal neutrino beam-line.
- Fig. 2 : The electronic set-up. Notation: SH = shaper, threshold 25 mV; D = delay; ATT = attenuator; TR = trigger; Amp = amplifier $\times 10$; EP = end protect.
- Fig. 3 : The data acquisition and protection-logic flow diagram.
- Fig. 4 : Pulse-height distributions obtained with muons, after correction for attenuation of light in the scintillator.
- Fig. 5 : Time-of-flight distribution between counters A and C.
- Fig. 6 : Pulse-height distributions in counters A, B, and C with optical masks in front of the photocathodes.
- Fig. 7 : Time-of-flight distribution between counters A and C with optical masks in front of the photocathodes.
- Fig. 8 : Efficiency for charge $e/3$ events simulated using optical masks on three counters. a) Showing the variation in trigger rate with simultaneous attenuation of the six pulses. b) Showing the efficiency as a function of the simultaneous upper and lower software cuts applied to the corrected pulse heights of the three counters. Thresholds are given as a fraction of the most probable pulse height for unit charge particles.
- Fig. 9 : Pulse height from the photomultiplier as a function of the relative rotation θ of a pair of crossed polaroid filters.
- Fig. 10 : Showing the effect of a 10% mask as a function of the pulse height: a) for the peak pulse height measured on the oscilloscope, b) for the pulse area measured on the ADCs.
- Fig. 11 : Scatter diagrams of the pulse heights in counters A and B. Pulse heights are normalized to the most probable pulse height for a minimum ionizing particle. Data are given for the high-gain and low-gain ADC channels. The squares show the regions for acceptance of charge $e/3$ and $2e/3$ candidates. a) Results with the narrow-band beam. b) Results with the broad-band beam.
- Fig. 12 : Scatter diagrams of the root square deviation against the mean pulse height for counters A, B, and C. Pulse heights are normalized to the most probable pulse height for a minimum ionizing particle. Data are given for the high-gain and low-gain ADC channels. a) Results with the narrow-band beam. b) Results with the broad-band beam.

Fig. 13 : Simulation of the RSD against ABC scatter diagram. a) For the high-gain ADCs, using the masked single counter spectra in a Monte Carlo calculation. b) For the low-gain ADCs using muon signals without attenuation.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

a)

b)

Fig. 10

Fig. 11

Fig. 12

Fig. 13