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LETTERE AL NUOVO CIMENTO VOL. 29, N. 8 25 Ottobre 1980

Results of the Quark Search Experiment in High-Energy Neutrino Interactions.

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In the past two decades the experimental search for free-quark production has been, and still is, one of the most fundamental research lines of high-energy physics.

It was pointed out a few years ago (1) that, in spite of the large number of experiments in this field (2), none had been carried out using weak-interacting probes. These

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(1) M. Basile, G. Cara Romeo, L. Cifarelli, P. Giusti, T. Massam, F. Palmonari, G. Valenti and A. Zichichi: *Lett. Nuovo Cimento*, **18**, 529 (1977).

(2) For a recent review see G. Barbiellini, G. Bonneaud, R. J. Cashmore, G. Coignet, J. Ellis, M. K. Gaillard, J. F. Grivaz, C. Matteuzzi, R. D. Peccei and B. H. Wiik: DESY preprint 80/42 (May 1980); L. Lyons: Oxford University preprint OUNP 80-38 (June 1980).

could be the most efficient for kicking a constituent out of the nucleon via a high-momentum-transfer interaction.

The result of the first experimental search for quark production in high-energy neutrino interactions was a 90% C. L. upper limit of $(5.0 \pm 1.7) \cdot 10^{-3}$ per neutrino interaction, for the flux of relativistic fractionally charged quarks (³).

In this letter we report the results of the WA44 experiment located in the CERN Super Proton Synchrotron (SPS) neutrino beam line, especially designed to reach a higher sensitivity in the search for free quarks.

The experimental set-up has been optimized to fulfil the following requirements: i) high detection efficiency, ii) high background rejection, iii) high spatial resolution and simultaneously good $\mathrm{d}E/\mathrm{d}x$ measurement accuracy, so that quarks could be detected even if they were produced in high-multiplicity events.

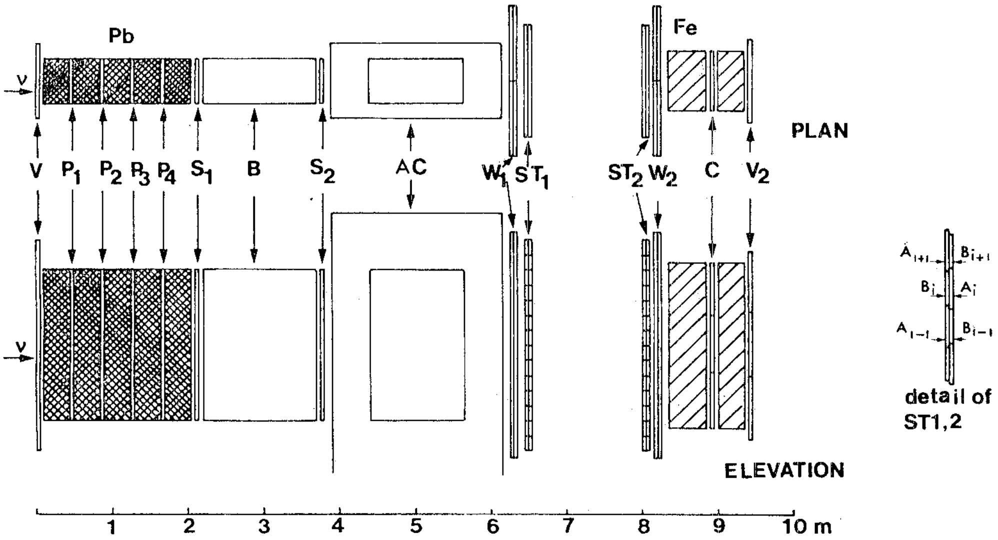

Fig. 1. – Experimental set-up: Pb: lead target; V: veto counter; P1, P2, P3, P4, S1, S2: neutrino interaction tagging scintillation counters; *B*: sweeping magnet; AC: avalanche chamber; W1, W2: wire chambers; ST1, ST2: low $\mathrm{d}E/\mathrm{d}x$ trigger scintillator hodoscopes; C, V2: μ range telescope scintillation counters.

As shown in fig. 1, the apparatus consists of

i) a 23 ton lead target with a cross-section area of $(200 \times 60)\ \mathrm{cm}^2$ and a total thickness of 170 cm segmented in five slices;

ii) a set of scintillation counters (V, P1, P2, P3, P4, S1, S2) to tag the neutrino interaction inside the target;

iii) a 0.4 T·m magnet (B) to sweep away very-low-momentum particles, mainly due to cascade processes in the target;

(³) M. Basile, G. Cara Romeo, L. Cifarelli, A. Contin, G. D'Ali, P. Giusti, T. Massam, F. Palmonari, G. Sartorelli, G. Valenti and A. Zichichi: *Nuovo Cimento A*, **45**, 281 (1978); see also D. R. O. Morrison: *Proceedings of the XIX International Conference on High-Energy Physics* (Tokio, 1978), p. 345.

iv) a large-volume $\left((2.35\times 1.25\times 0.6)\ \mathrm{m}^3\right)$ avalanche chamber (AC-235) to measure the specific ionization of all particles independently of multiplicity; events are recorded on film by three cameras equipped with light amplifiers;

v) two double-layer hodoscopes (ST1, ST2) with 14 horizontal scintillation counters $\left((150\times 20\times 2)\ \mathrm{cm}^3\right)$ per layer, to select events at the fast-trigger level according to the $\mathrm{d}E/\mathrm{d}x$ of single «isolated» particles;

vi) four proportional wire chambers (W1, W2), $(1\times 3)\ \mathrm{m}^2$ each, with multihit capability for track geometric reconstruction and timing;

vii) a μ range telescope with scintillation counters (C, V2) interspersed between iron blocks, to select muons of known momentum for calibration purposes.

A description of the characteristics and performance of the basic detector used in this experiment, namely the avalanche chamber, and of the methods used to analyse the pictures can be found elsewhere ([4,5]).

The electronic trigger was designed to accept three types of event:

i) those with a pre-selection of fractional charges, by requiring low pulse height on the scintillator hodoscopes ST1, ST2;

ii) those with a selection of high multiplicity, by requiring high pulse height on the sum of the counter S1 and S2 just behind the target;

iii) events with no bias in the trigger, *i.e.* requiring only a neutrino interaction in the target, namely just two counters hit (S1, S2) immediately following the (Pb) target.

The last type of trigger was activated after a fixed fraction of the beam spill had passed without producing either of the two selective triggers, so that the apparatus was used at maximum efficiency for all kinds of neutrino interactions.

TABLE I. – *Summary of the results on quarks with* $Q = \frac{2}{3}e$ *and* $\beta \geqslant 0.8$, *and with* $Q = \frac{1}{3}e$ *and* $\beta \geqslant 0.4$.

Beam			ν wide band	$\bar{\nu}$ wide band
total no. of protons on target (400 GeV)			$(0.8\ \pm 0.08)\cdot 10^{18}$	$(1.76\pm 0.18)\cdot 10^{18}$
no. of ν ($\bar{\nu}$) interactions			$(5.7\ \pm 0.80)\cdot 10^{-5}$	$(2.5\ \pm 0.35)\cdot 10^{5}$
90% C.L. quark flux upper limit	leptonic case	$Q = \frac{1}{3}e$	$(1.38\pm 0.25)\cdot 10^{-5}$	$(3.14\pm 0.57)\cdot 10^{-5}$
		$Q = \frac{2}{3}e$	$(1.57\pm 0.28)\cdot 10^{-5}$	$(3.58\pm 0.65)\cdot 10^{-5}$
	hadronic case	$Q = \frac{1}{3}e$	$(2.16\pm 0.43)\cdot 10^{-5}$	$(4.93\pm 0.99)\cdot 10^{-5}$
		$Q = \frac{2}{3}e$	$(2.47\pm 0.49)\cdot 10^{-5}$	$(5.63\pm 1.13)\cdot 10^{-5}$

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(4) M. BASILE, J. BERBIERS, G. CARA ROMEO, L. CIFARELLI, A. CONTIN, G. D'ALI, P. DI CESARE, B. ESPOSITO, L. FAVALE, P. GIUSTI, I. LAAKSO, C. MARRIAN, T. MASSAM, R. NANIA, F. PALMONARI, F. ROHRBACH, V. ROSSI, G. SARTORELLI, M. SPINETTI, G. SUSINNO, G. VALENTI, L. VOLTANO and A. ZICHICHI: CERN preprint EF 80-1 (July 17, 1980), to appear in *Proceedings of the International Conference on Experimentation at* LEP, *Uppsala, 1980* (*Phys. Scr.*).

(5) M. BASILE, G. CARA ROMEO, A. CASTELVETRI, L. CIFARELLI, A. CONTIN, G. D'ALI, P. DI CESARE, B. ESPOSITO, L. FAVALE, P. GIUSTI, I. LAAKSO, C. MARRIAN, M. MASETTI, T. MASSAM, R. NANIA, F. PALMONARI, F. ROHRBACH, V. ROSSI, G. SARTORELLI, M. SPINETTI, G. SUSINNO, G. VALENTI, L. VOLTANO and A. ZICHICHI: Bologna University preprint IFUB 80-14 (July 1980), to appear in *Proceedings of the International Conference on Experimentation at* LEP, *Uppsala, 1980* (*Phys. Scr.*).

Table I gives the integrated number of protons on target, corrected for dead-time, for the neutrino and antineutrino wide-band beams.

The analysis reported in this letter refers to events where fractionally charged quarks were produced « isolated », *i.e.* not accompanied by a jet of particles. In this case we can do a fast electronic analysis using the pulse height and the time information of the two hodoscopes ST1, ST2 to select events with « isolated » tracks releasing anomalously low dE/dx in one double-layer scintillator strip of each hodoscope.

For each counter hit in the two hodoscopes, the observed pulse heights in its two photomultipliers were used to correct their time information, which gives the horizontal impact position of the particle along the counter and the mean time of traversal. The two pulse heights, normalized to the value expected for a minimum-ionizing unit-charge particle crossing the centre of the counter, were added and their sum was corrected for attenuation in the counter. Pulse height spectra of minimum-ionizing muons were collected, for each counter, during special calibration runs.

The two counters of each strip were required to give the same traversal position and pulse height information within limits compatible with the known resolution of the pulse height and time measurements.

For each pair of double-layer strips in the two hodoscopes, having the four normalized pulse heights smaller than 0.95 and a correct time-of-flight difference, the mean value ($\overline{\text{PH}}$) and the root square deviation (RSD) of the four pulse height measurements were calculated. A typical mean pulse height ($\overline{\text{PH}}$) spectrum for strip pairs with RSD less than 0.4 is shown in fig. 2.

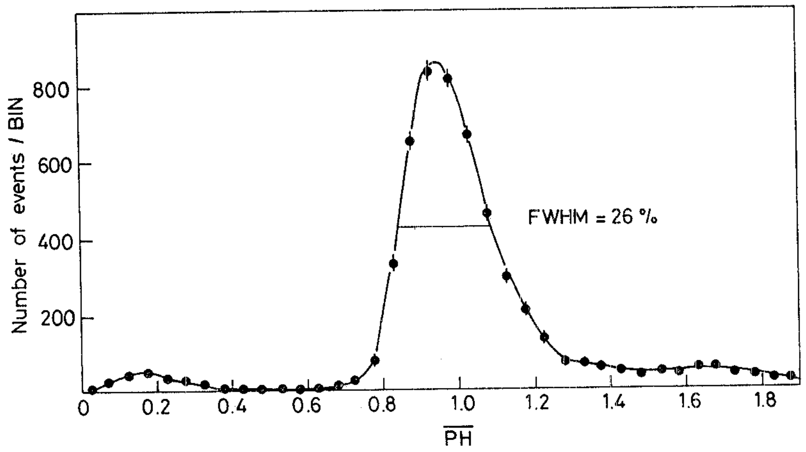

Fig. 2. – Typical mean pulse height spectrum of four strips with RSD < 0.4.

For all strip pairs with RSD < 0.4 and $\overline{\text{PH}} < 0.7$ the vertical position of each strip in the two hodoscopes and the horizontal impact points along the strips, determined by the electronic-time difference between the two photomultipliers at the extremities of each counter, were used to roughly define a candidate track direction. The intersection point of the extrapolated track with the plane defined by the exit face of the magnet B was then required to fall inside a fiducial region which took into account the bending effect of the magnet.

These cuts reduced to 102 and 38 the candidate tracks in the ν and ν̄ wide-band-beam data sets, respectively. The scattergrams of RSD *vs.* $\overline{\text{PH}}$ for these candidates are shown in fig. 3.

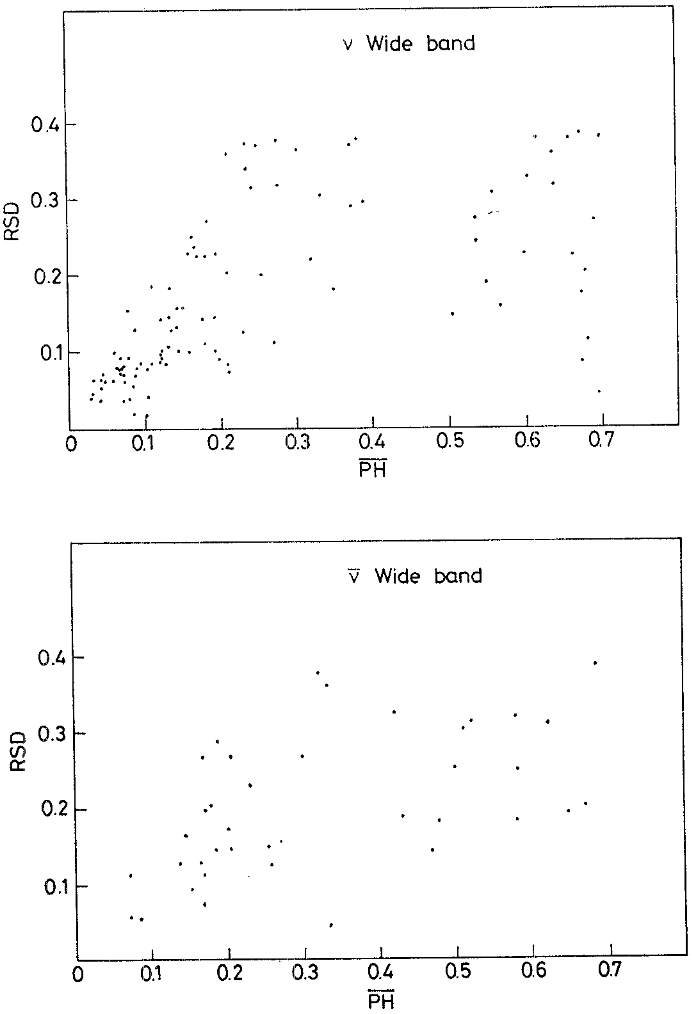

Fig. 3. - RSD *vs.* $\overline{\text{PH}}$ scattergram of the electronic analysis candidate tracks.

The avalanche chamber pictures corresponding to the events containing the candidate tracks were then visually scanned, searching for anomalously low-ionizing tracks. In a few doubtful cases some pictures were also scanned with automatic devices to measure (5) the specific ionization of all tracks visible on the picture and to compare it with the corresponding value obtained by a manual physicist eye streamer counting method. As a result of the avalanche chamber picture analysis, no electronic analysis candidate track was found, giving an anomalous ionization in the avalanche chamber.

We have analysed about 200 000 ν and ν̄ triggers. The acceptance range for fractionally charged particles is shown in fig. 4; it obviously depends on the velocity

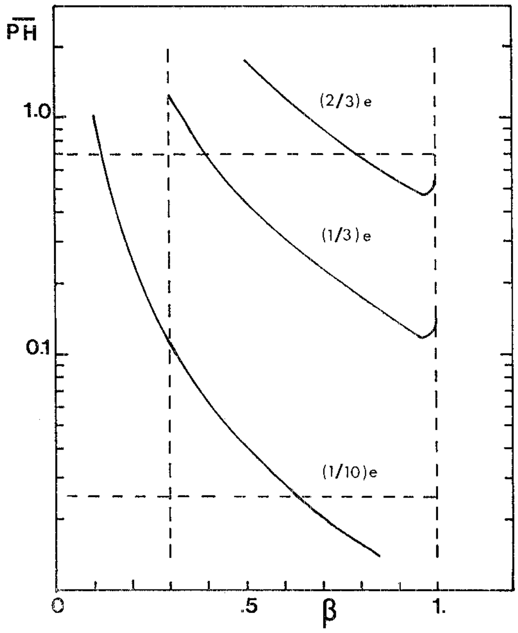

Fig. 4. – Acceptance region of fractionally charged quarks in the dE/dx (most pro bable value of $\overline{PH}$) $\beta(=v/c)$ plane.

$\beta=v/c$ of the particles. For example, if $Q=\frac{1}{3}e$, the β range is $\beta \geqslant 0.4$, while for $Q=\frac{2}{3}e$ the possible values for β are $\geqslant 0.8$.

The quark candidates searched for in the present analysis are of the « single-quark » type, *i.e.* ν interactions with a quark not being inside the jet of hadronic particles produced.

The efficiency of the cuts applied in the analysis on the pulse height and time information of the counters has been determined by the study of the counters' response to minimum-ionizing unit-charge particles during calibration runs. The estimated total efficiency is equal to (0.666 ± 0.002) for $Q=\frac{1}{3}e$ and (0.584 ± 0.002) for $Q=\frac{2}{3}e$.

The acceptance of the apparatus for quark detection was evaluated via Monte Carlo calculation by using two different hypotheses for the laboratory angular distribution of the quark:

i) one similar to that of muons produced in charged-current neutrino interactions (« leptonic » case);

ii) one similar to that of the hadrons produced in the hadronic shower and coming out of the target (« hadronic » case); we assumed that the absorption length for quarks is three times the « normal » hadron absorption length in lead.

The calculated acceptance is 0.44 ± 0.05 for the « leptonic » and 0.28 ± 0.04 for the « hadronic » cases.

The 90% C.L. upper limits for the flux of fractionally charged quarks per neutrino interaction were calculated from the effective number of ν and $\bar{\nu}$ interactions. The errors quoted for these limits come from the uncertainties in the efficiencies, in the neutrino fluxes and in the acceptance calculations quoted above.

For the « leptonic » case we have used as absorption cross-section of the produced quark the standard leptonlike cross-section, calculated assuming that the fractionally charged particle produced is a leptonlike object. The results are reported in table I and fig. 5. For the « hadronic »-like case, the sensitivity of the experiment depends on the absorption cross-section of the fractionally charged quark. Figure 5 shows how the experimental limits on $Q = \frac{2}{3}e$ and $Q = \frac{1}{3}e$ vary with the ratio

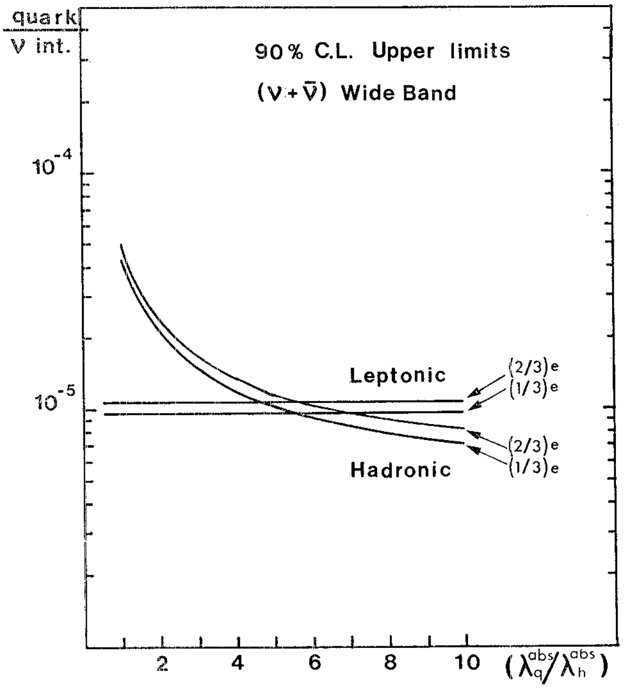

Fig. 5. – 90 % C.L. upper limits of the flux of quarks per neutrino interaction for the « leptonic » and « hadronic » cases, as a function of the ratio of the absorption length of quarks to the « normal » hadron absorption length.

$$\frac{\lambda_{\text{quark}}}{\lambda_{\text{hadion}}},$$

where λ is the hadroniclike absorption length. Notice that the limits given in fig. 5 are obtained from integrating ν and $\bar{\nu}$ interactions. In conclusion the 90% C.L. upper limits of the flux of quarks per neutrino interactions are at the 10^{-5} level, namely:

for « leptonic » quarks with

$$Q = \begin{cases} \pm\frac{1}{3}e & \leqslant (0.96 \pm 0.15)\cdot 10^{-5}, \\ \pm\frac{2}{3}e & \leqslant (1.09 \pm 0.17)\cdot 10^{-5}; \end{cases}$$

for « hadronic » quarks having $\lambda_{\text{quark}} = 3\lambda_{\text{hadrons}}$ with

$$Q = \begin{cases} \pm\frac{1}{3}e & \leqslant (1.50 \pm 0.27)\cdot 10^{-5}\,, \\ \pm\frac{2}{3}e & \leqslant (1.72 \pm 0.31)\cdot 10^{-5}\,. \end{cases}$$

When compared with a previous result on quark production in neutrino interactions (3), the limits reported in this paper represent an improvement of about two orders of magnitude.

* * *

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