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EXPERIMENTAL LIMITS ON THE PRODUCTION OF FRACTIONALLY
CHARGED PARTICLES IN PROTON-NUCLEUS AND NEUTRINO-NUCLEUS
COLLISIONS

CHARM Collaboration

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ABSTRACT A search for fractionally charged particles of different properties of interaction produced in (anti)neutrino-nucleus and in proton-nucleus collisions was performed using the scintillator system of the CHARM neutrino detector at the CERN SPS. No events of the cases considered were found. In (anti)neutrino beams production was found to be less than a few times 10^{-5} per interaction of a beam particle. In a proton beam an upper limit on the production cross section of $\sim 10^{-40}$ cm² was obtained. **1. INTRODUCTION**

The idea of considering hadrons to be composite, made of fractionally charged objects, has become nowadays universally accepted. Nevertheless the existence of isolated quarks, as ordinary particles, has never been detected so far. This negative experimental result has given origin to the belief that quarks are permanently confined inside strongly interacting particles and the theoretical developments of the last years have been consequently oriented by this prejudice. We report on a new search for fractionally charged particles performed using the CHARM neutrino detector at the 400 GeV CERN SPS. A detailed description of the experimental set-up is given elsewhere [1]. The detector consists of a fine grain target calorimeter composed of 78 identical sub-units with a cross-section of 300x300 cm², surrounded by a magnetized iron frame and followed by a muon spectrometer. The calorimeter sub-unit comprises a 8 cm thick marble absorber plate, a 3 cm thick layer of twenty plastic scintillators each with a cross-section of 15x300 cm² and a layer of proportional drift tubes with 3 cm wire spacing. The average absorption length for pions in the calorimeter is 4.65 sub-units. A

This analysis is based on the precise measurement of ionization losses of particles sampled by the scintillation counters. A charge $Q=1$ minimum ionizing particle crossing the scintillator gives an average response of 25-30 ADC counts (above a pedestal) with $\sim 20\%$ resolution (HWHM) corresponding to an energy deposition of 6 MeV. During data taking only signals exceeding the pedestal value by 2 ADC counts were recorded.

In the present analysis we have considered different possible sources, and different possible behaviours of fractionally charged particles. In Chapter 2 we describe a search for free quarks produced in (anti)neutrino-nucleus interactions within the CHARM calorimeter assuming a quark interaction cross section in the range 5 to 40 mb. Chapter 3 is devoted to a search for penetrating fractionally charged particles produced in proton-nucleus and (anti)neutrino-nucleus interactions outside the CHARM detector.

2. SEARCH FOR FREE QUARKS PRODUCED IN THE CHARM CALORIMETER

2.1 EVENT SELECTION AND EFFICIENCIES

Quark candidates were searched for in a sample of neutrino and anti-neutrino induced events collected in exposures of the CHARM detector to the wide band beam (WBB). The average energy of the beam was 31 GeV and 21 GeV for neutrinos and antineutrinos, respectively. The on-line trigger of the experiment required that at least four scintillator planes were hit and a total ionization energy larger than that produced by a 2.0 GeV shower was recorded. This trigger was fully efficient for events with visible energy above 0.5 GeV. The following criteria were applied to select events for the present analysis:

1. The primary interaction vertex must be inside the fiducial volume defined by 240×240 cm² cross-section and extending from plane 5 to plane 55 of the calorimeter (corresponding to a fiducial target weight of 70 tons);
2. The hadronic energy of the event must be larger than 2 GeV;
3. The event must not be a random superposition of two different events occurring in the time gate of the trigger. This type of events was rejected by comparing the event pattern in the proportional drift tubes (PDT's) system with the one in the scintillator system. Since the time gate of PDT's is ~ 10 times larger than the time gate of scintillators the superimposed event is normally detected only in the tube system.

About 264.000 and 104.000 neutrino and anti-neutrino induced events, respectively, were selected.

Out of this event sample two different topologies of quark candidates were searched for :

1. Events with a track emerging from the (anti)neutrino induced shower and producing a second shower ('bi-shower events'). The event pattern in the scintillators between the two showers was visually scanned.
2. Events with a single track emerging from the (anti)neutrino induced shower and detected by automatic pattern recognition in the proportional tube system ('mono-shower' events).

The signals from the scintillators hit by the fractionally charged track candidates of the above mentioned two classes were corrected for the track angles and light attenuation in the scintillators. To distinguish fractionally charged particles from $Q=1$ ones, it was required that there were at least 7 scintillators hit along the track with a mean pulse height of less than 4.5 MeV per hit.

After this selection no quark candidates remained. The background expected from charged current events (CC) in antineutrino and neutrino samples was computed by Monte-Carlo simulation and was found to be 0.1 and 0.05 events, respectively.

The efficiency of the quark candidate finding procedure was calculated in the following way:

Two real single-shower events with hadronic energy larger than 2 GeV were selected at random from a sample of (anti)neutrino induced WBB events. The first event of each pair was allowed to be either a CC or neutral current (NC) interaction, while the second one was required to be a muonless event. These events were superimposed by placing the second one at a pre-determined position with respect to the first one and their vertices were connected by a track of fractional charge generated by Monte-Carlo techniques. The quark charge and effects of multiple scattering and ionization loss in the calorimeter were taken into account. This track was assumed to simulate a fractional charged particle emerging from the first shower and producing the second one by interaction. These pseudo-events were then processed by the analysis program containing the 'bi-shower' finding and the single track finding algorithms. The efficiency of this automatic selection was computed for different combinations of hadronic energies and different relative distances between the two showers.

The computed efficiency for $Q=1/3$ particles turned out to be much lower than that for $Q=2/3$ particles because of the low detection efficiency of the proportional tubes introduced by their electronic threshold. Two showers of 10 and 5 GeV, 4 pion absorption length (λ_π) apart from each other, have a detection efficiency of 95% and 57% for quarks of charge $2/3$ and $1/3$ respectively.

These efficiencies were then used in a computer simulation program which calculated the overall acceptance of the detector for 'bi-shower' and 'mono-shower' events.

The quark production was described by Monte-Carlo generation of a value of the hadronic energy and by assuming that a fraction of this energy, Z_q , is carried away by the quark. Two types of fragmentation function were used: a constant one and one of the type $F(Z_q) = \exp(Z_q) - 1$. The quark mass and its absorption length were varied. The produced quark was tracked through the calorimeter up to the secondary interaction point where it was allowed either to be absorbed (no re-interaction case), or to interact again until its energy had been exhausted (re-interaction case). The fragmentation function that was used to describe free quark production in (anti)neutrino interactions was also assumed to govern the hadronic interactions of the quark.

Threshold effects due to the mass of the quark as well as the effect of the selection criteria described above were taken into account.

2.2. UPPER LIMITS FOR QUARK-PRODUCTION

It was assumed that only Cabibbo favoured transitions (that is, $d \rightarrow u$ in neutrino induced events and $u \rightarrow d$ in antineutrino induced events) can take place. In neutral current interactions with an isoscalar target we get a quark beam of roughly equal u and d quark composition (for $\sin^2 \theta_W = 0.22$),¹ but this effect was neglected. Therefore, having observed zero events, the 90% confidence upper limits on free quark production were calculated as follows:

$$\begin{aligned} \text{For } \nu \rightarrow \nu \quad u:d &= u_L^2 + 1/3 u_R^2 : d_L^2 + 1/3 d_R^2 \approx 0.13:0.18 ; \\ \text{for } \bar{\nu} \rightarrow \bar{\nu} \quad u:d &= u_R^2 + 1/3 u_L^2 : d_R^2 + 1/3 d_L^2 \\ &\approx 0.063:0.066 . \end{aligned}$$

$$\frac{\int \sigma(\bar{\nu} N \rightarrow d + \text{anything}) dE}{\int \sigma(\bar{\nu} N \rightarrow \text{anything}) dE} > \frac{2.3}{N(\bar{\nu} \text{ events}) \times \text{acceptance}(d)}$$

See Figures 1 and 2 for the cases of 'no-reinteraction' and of 'reinteraction', respectively ;

$$\frac{\int \sigma(\nu N \rightarrow u + \text{anything}) dE}{\int \sigma(\nu N \rightarrow \text{anything}) dE} > \frac{2.3}{N(\nu \text{ events}) \times \text{acceptance}(u)}$$

See Figures 3 and 4 for the cases of 'no-reinteraction' and of 'reinteraction', respectively.

The bands indicated on Figures 1 ÷ 4 correspond to quark mass values between 1 and 10 GeV. The upper and lower limits of these bands refer to the two types of fragmentation functions which were used in computing the acceptances. The 90% confidence upper limits for $\lambda_q = 5\lambda_\pi$ and $M_q = 1$ GeV for the re-interaction case are 2.8×10^{-5} and 2.6×10^{-5} , for d-quarks and u-quarks respectively. These upper limits are similar to those obtained by Basile et al. [2].

3. SEARCH FOR "WHITE-QUARKS"

The possible existence of penetrating fractionally charged particles (white quarks or WQ) was pointed out by Strikman and by Gribov [3]. Assuming that spontaneous colour charge screening could be caused by vacuum polarization, some properties of WQ's were predicted there, in particular : a mass of 2-5 GeV typical for gluonium states; a small cross-section for WQ-nucleon interaction, due to the small radius of vacuum fluctuations of the colour charge ($\sigma_{\text{inel}}^{\text{WQ}} \sim$

$\sigma_{\text{inel}}^{\pi} \cdot (m_{\pi}/m_{\text{glue}})^2 \sim 10^{-3} \cdot \sigma_{\text{inel}}^{\pi}$) and leading particle effects typical of heavy quark fragmentation.

We searched for WQ production in proton-nucleus and in (anti)neutrino-nucleus interactions, assuming a WQ interaction cross-section of 10 μb .

In the first case we analysed the experimental data collected in the 1982 beam dump exposure. The 400 GeV proton beam of the CERN SPS was directed onto a 3 m long copper dump which was for this case considered as a target for WQ production. A massive, $2 \cdot 10^5$ g/cm² thick, muon shield consisting mainly of iron followed the target area. This amount of material corresponds to one interaction length for $\sigma_{\text{inel}}^{\pi} = 10$ μb . Due to ionization energy losses in the shield only particles with energy greater than 45 and 180 GeV for charge 1/3 and 2/3, respectively, could penetrate and reach the CHARM detector located at the distance of 482 m from the dump target.

To trigger the detector on such events the first scintillator plane of the target calorimeter and at least two out of six scintillator planes of the muon spectrometer were required to be hit and the total energy deposited in scintillators was required to be less than 500 MeV.² The first plane of the calorimeter and the six planes of the muon spectrometer had special high voltage settings to provide an efficient trigger for fractionally charged particles. The trigger efficiencies were determined by a Monte-Carlo simulation that made use of the measured response of the scintillation counters to cosmic muons, the light attenuation properties of the scintillators, the discriminator efficiencies etc, with the results

$$\begin{aligned}\epsilon_{1/3} &= 0.49 \pm 0.03, \\ \epsilon_{2/3} &= 0.94 \pm 0.01.\end{aligned}$$

² Energy loss expected for a muon traversing the calorimeter.

The following criteria were used to select candidates for fractionally charged particles:

1. A track must hit at least 4 scintillators per projection, and not less than 16 scintillators in total. The average energy deposition is less than 4 MeV.³

2. The transverse impact point of the track must lie within a square of 270x270 cm².

The same trigger and selection criteria were applied to collect WQ candidates both in neutrino and antineutrino wide band exposures. In this case the 1000 tons CDHS detector [4] located immediately in front of the CHARM detector was considered as a target for WQ production. To escape from the CDHS detector particles produced in inclusive (anti)neutrino-iron interactions must on average traverse the amount of material corresponding to one interaction length for $\sigma^{\text{inel}} = 175 \mu\text{b}$.

3.1 LIMITS ON WQ-PRODUCTION IN PROTON-NUCLEUS COLLISIONS.

Data was taken for $2.02 \cdot 10^{18}$ protons on the target (dead time corrected). Fig. 5 shows the distribution of the observed mean energy below 10 MeV deposited per plane for 4139 selected tracks. The distribution is centered at 5.9 MeV as expected for muons traversing the target calorimeter. Only a few events populate the region where particles with charge 1/3 and 2/3 are expected to contribute. A visual scan of events with energy deposition < 4 MeV showed that small pulses came either from tracks hitting the light guides and scintillator edges, or from

³ Monte-Carlo simulation shows that this restriction should not affect the detection efficiency for particles with the charge $\geq 1/3$.

double events with wrong timing of the ADC gates. No candidate for fractionally charged particles was found.

To obtain a limit on the total cross section a production model has to be assumed. We used the following parametrization for the differential cross section:

$$E (d^3\sigma/dp^3) = (1-|x|)^{\alpha} \cdot e^{-\beta p_t}$$

In order to compare our results with other experiments [5] we considered two extreme cases:

a) limited transverse momentum, as in pion production:

$$\alpha = 3, \beta = 6 ;$$

b) unlimited transverse momentum (phase space):

$$\alpha = 0, \beta = 0.$$

The geometrical acceptance was calculated for both models by Monte-Carlo simulation. These calculations included energy loss and multiple scattering in the muon shield, as well as the deflection in the magnetic field of the Big European Bubble Chamber (BEBC), located upstream of the CHARM detector.

Fig.6 gives upper limits on the production cross section as a function of the quark mass. As one can see the limits established in this experiment for penetrating fractionally charged particles are significantly more stringent than limits obtained in conventional experiments which are, however, free from assumptions on the quark interaction cross-section.

3.2 LIMITS ON WHITE QUARK PRODUCTION IN (ANTI)NEUTRINO-NUCLEUS COLLISIONS.

During the exposure with $1.2 \cdot 10^{18}$ protons on target $2.3 \cdot 10^5$ tracks were recorded in the CHARM detector triggered as described above. $1 \cdot 10^5$ tracks survived the selection criteria applied. 956 tracks showed a restricted mean pulse height in scintillators of less than 4 MeV. No candidates remained after a visual scan.

The number of (anti)neutrino interactions with visible energy above 10 GeV in the CDHS detector ($7.9 \cdot 10^6$) was estimated by scaling the event rates observed in the CHARM detector. The geometrical acceptance was calculated assuming that all hadronic energy was carried by the fractionally charged particle. The upper limits on the production cross sections for particles with charge $1/3$ and $2/3$ for $m=2$ GeV are given in Table 1. They are quite close to published limits [2] on production of "lepton"-like quarks by neutrinos and somewhat more stringent than those for the case of antineutrinos.

4. CONCLUSIONS

In the present analysis the existence of $Q=1/3$ or $Q=2/3$ free fractionally charged quarks has been investigated in proton-nucleus and (anti)neutrino-nucleus interactions. No quark candidate has been found. Different quark production mechanisms were assumed and different values for the quark-mass and the quark interaction cross section were used in the calculation of the 90% upper confidence limits for quark production. The established upper limits are somewhat more stringent than previously published results.

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TABLE 1

Upper limits on production of penetrating fractionally charged particles with a mass of 2 GeV in (anti)neutrino-nucleus interactions.

limits at 90% c.l. (per ν interaction)			
b e a m	charge	CHARM ^{a)}	Basile et al ^{b)} [2]
neutrino	1/3	$1.0 \cdot 10^{-5}$	$1.4 \cdot 10^{-5}$
	2/3	$2.7 \cdot 10^{-5}$	$1.6 \cdot 10^{-5}$
antineutrino	1/3	$1.7 \cdot 10^{-5}$	$3.1 \cdot 10^{-5}$
	2/3	$3.0 \cdot 10^{-5}$	$3.6 \cdot 10^{-5}$

a) In calculations of the acceptance the interaction cross-section was fixed to $10 \mu\text{b}$.

b) Quarks were assumed to be non-interacting.

5. FIGURE CAPTIONS

- Fig.1 Upper limits for the production of non re-interacting $Q=1/3$ quarks in the anti-neutrino beam as a function of their mass and of their interaction length. The upper and lower limits of these bands refer to two different types of fragmentation functions which were used in computing the acceptances (constant and exponential respectively).
- Fig.2 Same as Fig.1, for the case of re-interacting quarks.
- Fig.3 Upper limits for the production of non re-interacting $Q=2/3$ quarks in the neutrino beam.
- Fig.4 Same as Fig.3, for the case of re-interacting quarks.
- Fig.5 Mean pulse height per plane for candidate tracks. Only pulse heights below 10 MeV are shown. The dashed histogram shows the same distribution with magnified scale.
- Fig.6 Upper limits at 90% confidence on production of penetrating fractionally charged particles in proton-nucleus collisions. In calculations of the acceptance the interaction cross-section was fixed to $10 \mu\text{b}$. The curve "A" refer to the limited p_t production model, the curve "B" - to the unlimited p_t production model (see the text). Limits obtained in conventional experiments [ref.5, a-g] which are free of any assumption on the quark interaction cross section are also shown.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5

Fig.6