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Brief Reports

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Search for fractionally charged particles in (anti)neutrino-deuterium interactions

D. Allasia,[η] C. Angelini,[ε] A. Baldini,[ε] F. Bianchi,[η] F. Bobisut,[δ] A. Borg,[ζ] P. Capiluppi,[γ] R. Cirio,[η] J. Derkaoui,[γ,(a)] M. L. Faccini-Turluer,[ζ] A. G. Frodesen,[β] D. Gamba,[η] G. Giacomelli,[γ] B. Jongejans,[α] M. Loreti,[δ] C. Louedec,[ζ] G. Mandrioli,[γ] A. Margiotta-Neri,[γ] A. Marzari-Chiesa,[η] R. Pazzi,[ε] L. Patrizii,[γ] F. Predieri,[γ] A. Romero,[η] A. M. Rossi,[γ,(b)] A. Sconza,[δ] P. Serra-Lugaresi,[γ] M. Spurio,[γ] A. G. Tenner,[α] G. W. van Apeldoorn,[α] P. H. A. van Dam,[α] N. A. M. van Eijndhoven,[α] and D. Vignaud[ζ]

[α]*Nationaal Instituut voor Kernfysica en Hoge-Energiefysica, Amsterdam, The Netherlands*

[β]*Institute of Physics, University of Bergen, Bergen, Norway*

[γ]*Dipartimento di Fisica dell'Università di Bologna and Istituto Nazionale di Fisica Nucleare, Sezione di Bologna, Bologna, Italy*

[δ]*Dipartimento di Fisica dell'Università di Padova and Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Padova, Italy*

[ε]*Dipartimento di Fisica dell'Università di Pisa and Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, Pisa, Italy*

[ζ]*Département de Physique des Particules Elémentaires, Centre d'Etudes Nucléaires de Saclay, Gif-sur-Yvette, France*

[η]*Istituto di Fisica dell'Università di Torino and Istituto Nazionale di Fisica Nucleare, Sezione di Torino, Torino, Italy*

(Amsterdam-Bergen-Bologna-Padova-Pisa-Saclay-Torino WA25 Collaboration)

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A search for relativistic fractionally charged particles in (anti)neutrino-deuterium interactions was performed using the CERN SPS wide-band neutrino beam and the Big European Bubble Chamber. The experiment established the following upper limit: quark/event $<5\times10^{-5}$ (90% confidence level) for charged particles with $0.3e<q<0.7e$, interaction length $\lambda>0.02\lambda_\pi$, and mass $m_q<0.5$ GeV. Other limits are quoted in the text.

I. INTRODUCTION

Many accelerator searches for fractionally charged particles have been made since the birth of the quark hypothesis nearly 25 years ago.[1] Searches were performed at ever increasing center-of-mass energies, mainly in hadron-hadron collisions and, more recently, also in neutrino-nucleon,[2,3] muon-nucleon,[4] and e^+e^- (Ref. 5) collisions. All searches were based on the lower ionizing power of fractionally charged particles. Many searches were sensitive to fractionally charged particles having low interaction cross sections.[2,3] These particles were assumed to pass undisturbed through considerable amounts of matter. Therefore fractionally charged particles with interaction lengths like that of a pion or smaller would not have been detected. Some authors assumed that the liberation of quarks from a nucleon could be easier in neutrino-nucleon interactions.[2]

In this paper we report a search for fractionally charged particles in high-energy neutrino and antineutrino interactions in deuterium. The search was performed using the CERN SPS wide-band (anti)neutrino beam in the Big European Bubble Chamber (BEBC). In a bubble chamber with a light liquid one may easily search with high efficiency for low-ionizing tracks produced over the whole solid angle close to the interaction vertex. This paper gives new limits for this situation, that is, for charged particles with $0.3e<q<0.7e$ and $\lambda>0.02\lambda_\pi$.

II. EXPERIMENT

The main purpose of our experiment was the systematic study of neutrino and antineutrino charged-current (CC) and neutral-current (NC) interactions on protons and neutrons. The experiment was performed in the CERN SPS West Area (anti)neutrino facility using the broadband (anti)neutrino beam into the BEBC filled with deuterium.[6]

In the first runs the chamber was equipped with the external muon identifier (EMI); in the last runs it was also equipped with an internal picket fence (IPF), a system of proportional tubes surrounding the vacuum tank, which allows better selection of NC events. For part of the data taking, a high-resolution camera was also available.

The film was scanned twice for interactions inside a large fiducial volume. The events were then checked, measured, and, when necessary, remeasured. For each interaction a systematic search of low-ionizing tracks (≤0.5 minimum) was made in all directions, starting at a

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TABLE I. Number of charged-current (CC) and of neutral-current (NC) events, average charged-hadron multiplicity, and average number of charged-hadron tracks observed in this experiment. The numbers of neutral-current events represent all NC candidates; the average charged-hadron multiplicity for NC events was found to be compatible, within large uncertainty, with that for CC events.

Collision	No. of CC interactions	CC Average charged-hadron multiplicity	No. of charged tracks	No. of NC interactions	NC Average charged-hadron multiplicity	No. of charged tracks
$\bar{\nu}$D	16 160	3.4	55 000	6 000	3.4	20 400
νD	26 400	4.5	118 800	9 000	4.5	40 500
Total	42 560		173 800	15 000		60 900

distance of 6 cm from the vertex (about 2 cm in the projected plane of the scanning tables). The search was repeated in a forward cone at a distance of 20–30 cm from the interaction vertex. The value of 6 cm corresponds in liquid deuterium to 0.018 nuclear interaction lengths.

The events were reconstructed using the standard chain of computer programs developed for the BEBC experiments. Events were retained if their interaction vertex was inside a fiducial volume of 18.14 m^3 and were assigned to the CC sample if a clear muon track was found in the two-plane EMI. The selection of NC events was more elaborate, as discussed in Ref. 6. For the purpose of this paper we used all the NC candidates, since scanning and measurements concerned all these events.

III. RESULTS AND DISCUSSION

Table I summarizes the experimental results. The table gives the number of events, the average charged-hadron multiplicity and the number of charged hadrons observed.

Because of charge conservation, particles of fractional electric charge should be liberated and/or produced in pair in each (anti)neutrino-nucleon interaction; that is the minimal reaction should be of the type

$$(\bar{\nu})+N\rightarrow q_1+q_2+X \ , \qquad (1)$$

where q_1 is a quark; q_2 is a diquark system in the case of quark liberation, q_2 is an antiquark in the case of q-$\bar{q}$ production.

In the BEBC there is a large variation of magnification; thus one needs to calibrate the ionization loss with close by tracks. In CC events there is always a muon; in NC events we require ≥ 3 tracks. We estimated that the efficiency for observing events with two fractionally charged particles should be very high, close to 100%, in any type of event present in (anti)neutrino-deuterium interactions, provided the quark tracks are longer than few centimeters. In particular there is no problem in an event of medium multiplicity. For events with a forward large jet of particles there are no problems because of the limited multiplicity of our events and because the strong magnetic field in the chamber separates cleanly the tracks. In the following we shall use a conservative efficiency $\epsilon \gtrsim 80\%$.

No serious candidate event was found. The corresponding two-standard-deviation upper limit was computed as

TABLE II. Upper limits at the 2-standard-deviation level for the production of fractionally charged particles with charge between 0.3e and 0.7e and mass smaller than 0.5 GeV.

	quark/pion (10^{-5}) CC	NC	quark/event (10^{-5}) CC	NC
$\bar{\nu}$D	5.2	14	18	48
νD	2.4	7	11	32
$\bar{\nu}$D+νD	1.7	4.7	6.8	19
$\bar{\nu}$D+νD Total	1.2		5.0	

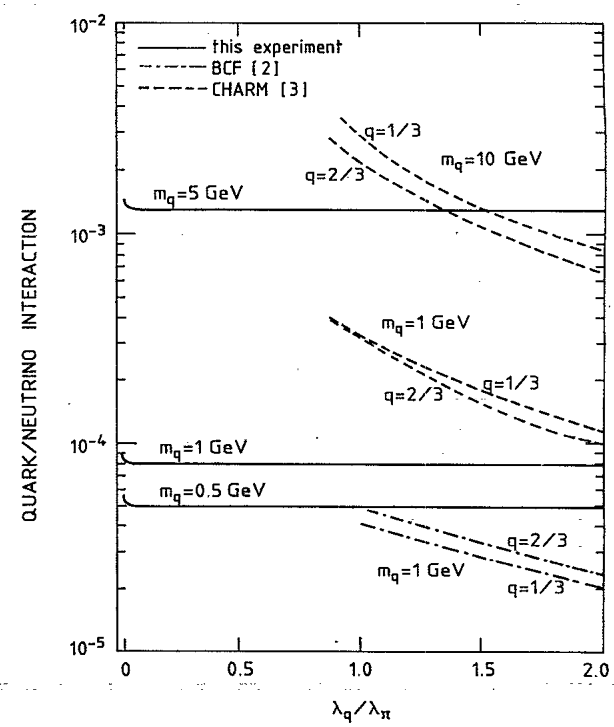

FIG. 1. Upper limits (90% C.L.) for the production of fractionally charged particles in (anti)neutrino-nucleon collisions as function of their mass and of their interaction length. Solid lines are from the present analysis, and are valid for both quark charges $\frac{1}{3}$ and $\frac{2}{3}$. Dotted and dashed lines are from Refs. 2 (BCF) and 3 (CHARM), respectively.

$$\text{quark/pion} \le 2.3/(\epsilon N_{\text{tracks}}) , \quad (2)$$

$$\text{quark/event} \le 2.3/(\epsilon N_{\text{events}}) . \quad (3)$$

Table II gives a summary of the limits obtained in this experiment for neutrino and antineutrino interactions in CC and NC events. The combined overall limit, from 57 560 events (corresponding to 234 700 charged-hadron tracks) is 1.2×10^{-5} quark/pion or 5×10^{-5} quark pair/event (90% confidence level). These limits apply to the production of any fractionally charged particle which has an interaction cross section smaller than 50 times the pion cross section (we have some sensitivity up to 200 times σ_π). In terms of mass, the minimum laboratory neutrino energy ($E_{\nu\,\text{lab}}=5$ GeV) should be sufficiently high for knocking out any u,d quark from the neutron or the proton of the deuteron. $E_{\nu\,\text{lab}}=5$ GeV corresponds for CC events to a hadronic c.m. energy of 1.5 GeV. Thus in terms of production of a quark-antiquark pair, or any particle-antiparticle pair of fractional charge, the above limits apply to quarks with masses $m_q<0.5$ GeV (thus up to s quarks). Figure 1 shows the limits. For higher masses the limits become progressively worse; the limits have been computed from the knowledge of the event distribution in the hadron energy variable.

The CERN-Hamburg-Amsterdam-Rome-Moscow (CHARM) neutrino experiment[3] was not sensitive to quarks with a mean interaction length $\lambda<0.8\lambda_\pi$. For $\lambda>2\lambda_\pi$ the experiment quoted values of quark/event $>3\times10^{-5}$ for $m_q=1$ GeV (assuming no reinteraction in the nucleus; including reinteraction the limit becomes 6×10^{-5}).

The neutrino experiment of Ref. 2 was sensitive to quarks with $\lambda>\lambda_\pi$. For $\lambda>5\lambda_\pi$ the experiment quoted the limit: quark/event $<10^{-5}$.

In conclusion we have presented new upper limits for the ejection and/or production of fractionally charged particles in (anti)neutrino-deuterium interactions. The limits are at the level of 1.2×10^{-5} quarks/pion, corresponding to 5×10^{-5} quarks/interaction (90% confidence level) for low-mass quarks with $0.3e<q<0.7e$ and with interaction lengths larger than $0.02\lambda_\pi$ (Fig. 1).

Similar limits would also apply to heavily ionizing particles, such as classical relativistic magnetic monopoles.[7]

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[a]Also at Faculty of Science, University of Oujda, Maroc.
[b]Also at Dipartimento di Fisica della Università della Calabria, Calabria, Italy.

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