was also observed. Large errors in cross sections due to deuterium and normalization difficulties precluded any definite conclusions.[9] *If* we assume this peak is the same object that we observe in this experiment, then it couples not only to ωp but also to πN although our upper limit of $(\pi N)^+/(\omega p) < 36\%$ indicates that the πN coupling is small.

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[1]A 2.5-standard-deviation ωp enhancement in this mass region from the reaction $\pi^- p \to \pi^- \omega p$ at 7 GeV/c was reported by M. S. Milgram *et al.*, Nucl. Phys. B18, 1 (1970). Further observation of ωp enhancement from the reaction $K^+ p \to K^+ \omega p$ at 12 GeV/c was reported by P. J. Davis *et al.*, [Nucl. Phys. B44, 344 (1972)], but they reported no evidence for narrow structure near the threshold region.

[2]A. R. Dzierba *et al.*, Phys. Rev. D 7, 725 (1973); A. R. Dzierba *et al.*, in *Proceedings of the International Conference on Instrumentation for High Energy Physics, Frascati, Italy, 8–12 May 1973*, edited by S. Stipcich (Laboratori Nazionali del Comitato Nazionale per l'Energia Nucleare, Frascati, Italy, 1973), p. 56.

[3]In the Dalitz plots for all the data, we note that there is no kinematic overlapping region between this peak in ωp and the $B(1250)$ meson. Furthermore, the peripheral cut of $|t_{\pi \to \pi}| < 0.4$ GeV^2 removes most of the events with $M(\pi^- p) < 1.7$ GeV.

[4]We have also examined the moments where $m \neq 0$ and found them to be consistent with zero. Furthermore, distributions of the normal to the ω-decay plane are found to be uncorrelated with decay angles in the ωp rest frame.

[5]Data from 6 and 14 GeV/c were used to deduce this upper limit; 4.5-GeV/c data are not available for this comparison.

[6]Data from all three momenta were used to deduce this upper limit.

[7]See, for example, E. W. Anderson *et al.*, Phys. Rev. Lett. 25, 699 (1970).

[8]J. S. Danburg *et al.*, Phys. Rev. D 2, 2564 (1970), and earlier references therein.

[9]Further evidence for a large s-wave contribution to the $\pi^- p \to \omega n$ cross section near threshold has been reported by D. M. Binnie *et al.*, Phys. Rev. D 8, 2789 (1973).

Search for Fractionally Charged Quarks Produced by 200- and 300-GeV Proton-Nuclear Interactions

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We describe an experimental search for particles with fractional charge (quarks) with mass below 11 GeV/c^2 produced by proton-nucleus collisions at 200 and 300 GeV. No evidence for such particles was found. Limits on the quark production cross section are given.

We have searched for fractionally charged particles (quarks) among secondaries produced by 200- and 300-GeV protons incident on a 12-in. beryllium target. The experiment was performed at the National Accelerator Laboratory. The *M*2 beam of the meson area was used to select the momentum of the secondaries. The principal detector was a set of eight scintillation counters which provided ionization loss information on particles transmitted by the beam channel.

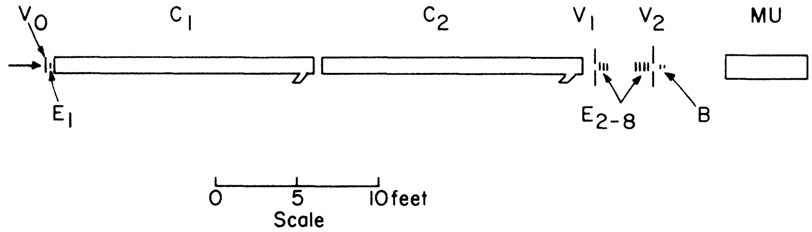

FIG. 1. Schematic drawing of experimental apparatus.

Quarks of charge $\frac{1}{3}e$ and $\frac{2}{3}e$ are expected to exhibit ionization losses $\frac{1}{9}$ and $\frac{4}{9}$ that of singly charged particles. During the running period with 200-GeV incident protons the secondary beam channel was tuned to momenta of 270 and 207 GeV/c ("supermomentum") so that only particles of fractional charge would be transmitted. We found no evidence for the existence of fractionally charged particles and report here upper limits on the production cross section.

Secondaries produced at 1 mrad were bent through 25 mrad in the $M2$ beam and focused on a collimator 650 ft from the production target. The momentum-selected beam was bent further and subsequently brought to a second focus at the detection apparatus, 1360 ft from the production target. The beam spot size at the second focus was about $\frac{1}{8}$ in. in diameter. We established the acceptance of the beam experimentally by comparing the particle flux at standard beam settings with that obtained when all the quadrupole magnets were turned off. In the latter case the aperture was precisely limited by collimators in the beam so that the acceptance could be unambiguously estimated. The result gave a $(\Delta p/p)\Delta\Omega$ acceptance of 0.4 μsr %, 30% less than the original design calculation.[1]

The experimental apparatus is shown schematically in Fig. 1. The beam was defined by a counter telescope at the second focus. A veto counter (V_0) with a $\frac{3}{4}$-in.-diam hole centered on the beam axis was followed immediately by the first of the dE/dX (ionization loss) counters (E_1). A pair of 1-in.^{3} scintillation counters (B) were located 40 ft downstream. In the 40-ft region between the beam defining counters were the Cherenkov counters (C_1 and C_2), each 16 ft long, and seven additional dE/dX counters (E_2 to E_8). The dE/dX counters were $\frac{1}{2}$-in.-thick, 6×4-in.^{2} pilot B scintillators coupled through air light pipes to 8575 phototubes. Air light pipes were used instead of the conventional plastic to avoid low-level (quarklike) signals produced by Cherenkov radiation in the plastic. Two large veto counters (V_1 and V_2) with 2-in. $\times$ 3-in. holes provide protection against particles passing through edges of the dE/dX counters and giving deceptively low pulse heights. Located at the back of the entire apparatus was a muon identifier (MU), a steel–liquid-scintillator sandwich viewed by a single 7-in.-diam phototube.

In the supermomentum mode, the trigger was simply any particle in the beam regardless of charge. When triggered, the electronics digitized and recorded pulse-height information from all eight dE/dX counters, the veto counter, the muon identifier, and the two Cherenkov counters.

Since no particles with momentum greater than 200 GeV/c are produced in 200-GeV proton-nucleon collisions, the 270- or 207-GeV/c beam channel did not transmit ordinary particles. Occasionally one might expect a muon which penetrated the shielding to stray into the beam line after the last bend and reach the detectors. Under these conditions the trigger rate was about one per 10^{15} protons on target. The energy losses in the eight dE/dX counters for the 62 events so obtained were clearly those of singly charged particles and the pulses in the muon identifier indicated that apparently all of these were indeed muons.

The optimum choice of the secondary momentum and angle at which to search for heavy objects depends on the mechanism of their production. Small production angles are favored both by kinematics (massive objects produced at rest in the center of mass must go forward in the laboratory) and dynamics (the transverse momentum in hadron collisions is limited to about 300 MeV/c). In the absence of any reliable theory for quark production we chose the beam momentum on the basis of phase-space considerations. For all quark masses, the maximum of four-body phase space for the simplest production channels occurs at a quark momentum in the laboratory system of 90 GeV/c for pair production,

$$N+N \rightarrow N+N+Q+\overline{Q}, \qquad (1)$$

and 70 GeV/c for dissociation,

$$N+N \rightarrow N+Q(\tfrac{2}{3})+Q(\tfrac{2}{3})+Q(-\tfrac{1}{3}), \qquad (2)$$

with 200-GeV incident protons. Particles of charge $\frac{1}{3}$ with these momenta are bent like unit-charge particles of 270 and 210 GeV/c, respectively. The corresponding beam momenta for charge-$\frac{2}{3}$ particles are 135 and 105 GeV/c, far from the phase-space peak. For this reason we made a more significant search for charge-$\frac{2}{3}$ particles with 300-GeV protons and a non-supermomentum secondary-beam setting of 207 GeV/c. This corresponds to a charge-$\frac{2}{3}$ momentum of 139 GeV/c, which is the maximum of the four-body phase space for process (1) with 300-GeV incident protons. Under these conditions, which accounted for most of the charge-$\frac{2}{3}$ search, there were typically 10^4–10^5 particles per pulse in the beam.

In order to reduce the data taking rate selectively, a requirement on the dE/dX counter pulse heights was added to the trigger. We required that at least two (or three depending on beam conditions) of the dynode outputs of four selected dE/dX counters give quarklike signals. A quarklike signal was defined in a window discriminator by a pulse height between 0.07 and 0.7 times that of a singly charged particle. With this requirement there was approximately one trigger for every ten accelerator pulses. In this run there were a total of $\sim 2\times 10^{16}$ protons on target, $\sim 10^9$ pions going through the detectors, and some 14 000 events taken on tape. The efficiency of this trigger for detecting particles of fractional charge was monitored frequently by inserting optical attenuators in front of the phototubes. The efficiency was better than 95% for particles of charge $\frac{1}{3}$ and 90% for particles of charge $\frac{2}{3}$. The Cherenkov counters were filled with nitrogen and kept at a pressure of 205 mm Hg, corresponding to a γ threshold of 79. This corresponds to a mass threshold of 1.76 GeV/c^2 for charge $\frac{2}{3}$ at 207 GeV/c beam momentum (real momentum of 139 GeV/c).

We examined the data for the presence of quarks by comparison with pulse-height spectra obtained with the optical attenuators in place. Cuts for each dE/dX counter were made which left $\gtrsim 95\%$ of charge $\frac{2}{3}$ ($\sim 100\%$ of charge $\frac{1}{3}$) but reduced the charge-1 background by 10. When all eight dE/dX pulse heights were required to satisfy these cuts only eight events survived. About 70% of the charge-$\frac{2}{3}$ sample would be expected to remain after this cut. All eight of these events showed signals in the Cherenkov counters. Thus, we find no candidates with mass above 1.76 GeV/c^2, the Cherenkov threshold. The upper limits at the 90% confidence level on the differential production cross section in the lab system for this and the other beam-tuning conditions are summarized in Table I. Below the mass of 1.76 GeV/c^2 one event is consistent with signals expected for a charge-$\frac{2}{3}$ particle at greater than a 1% confidence level.[2]

If quarks had a very large interaction cross section (10 times the proton-nucleus geometrical cross section as an example), most (89%) would interact before traversing all eight dE/dX counters.[3] This would raise the upper limits by about 10. If such quarks were required to traverse only four of the counters before interacting the upper limit would increase only by about 3 since 71% would interact. For this reason we examined the data which remained if the first four of the eight pulse heights satisfied the previously cited cuts. In this way if a fractionally charged particle interacted after four or more counters, it would not be lost. Again there were no candidates above 1.76 GeV/c^2. Thus above this mass the upper limits of Table I should be increased by 3 for the highly interactive quarks of this example. Below this mass there are no charge-$\frac{1}{3}$ candidates. However, for charge $\frac{2}{3}$, backgrounds are too high to analyze the data with only four dE/dX counters without using the Cherenkov-counter rejection.

TABLE I. 90%-confidence-level upper limits on fractionally charged particle production.

Proton energy (GeV)	Secondary-beam momentum[a] (GeV/c)	$(d\sigma/dp\,d\Omega)_{(\mathrm{lab})}$ $\lvert Q\rvert=\frac{1}{3}$ (cm^2/GeV sr)	$\lvert Q\rvert=\frac{2}{3}$ (cm^2/GeV sr)
200	−270	5.6×10^{-36}	2.8×10^{-36}
	−207	5.6×10^{-35}	2.8×10^{-35}
	−150	8.0×10^{-35}	4.0×10^{-35}
300	−270	5.1×10^{-34}	2.5×10^{-34}
	−207	1.0×10^{-34}	5.0×10^{-35} [b]
			8.5×10^{-35} [c]
	+150	4.8×10^{-33}	2.4×10^{-33}

[a]Sign indicates polarity of beam.
[b]Mass > 1.76 GeV/c^2.
[c]Mass < 1.76 GeV/c^2.

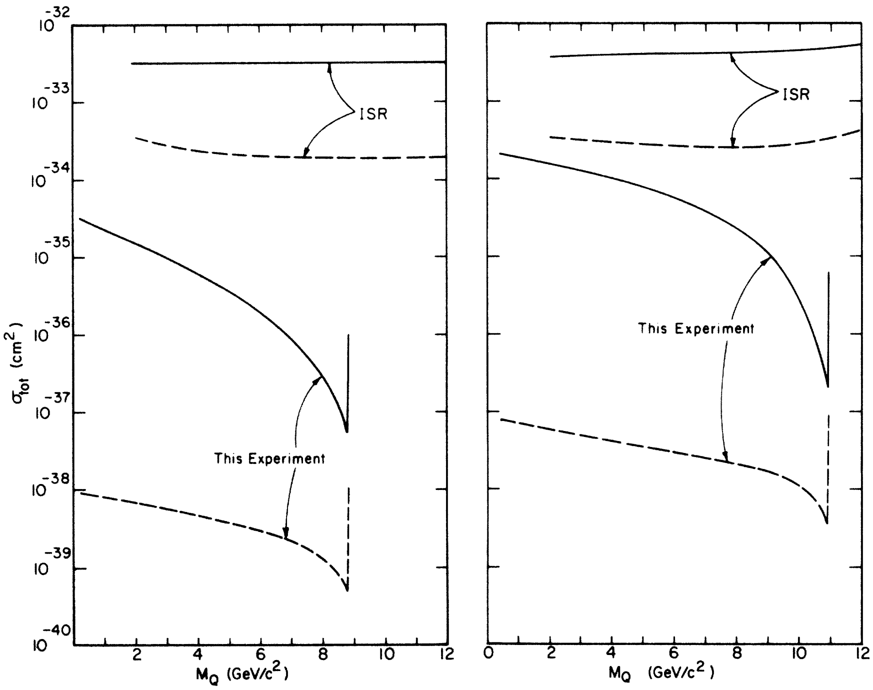

FIG. 2. Upper limits on total cross section for fractionally charged particle production. (a) Charge $-\frac{1}{3}$; (b) charge $-\frac{2}{3}$. Solid lines, limits obtained assuming four-body phase space (with an isotropic center-of-mass angular distribution). Dashed lines, limits with the four-body phase space constrained by a multiplicative factor of $\exp(-6P_t)$, where P_t is the transverse momentum in GeV/c. Shown are results from this experiment and from Bott-Bodenhausen *et al.* (Ref. 4) at the CERN intersecting storage rings.

Therefore for these highly interactive charge-$\frac{2}{3}$ quarks of mass less than 1.76 GeV/c^2 the limits of Table I for this running condition should be increased by about 10.

We examined the data remaining if any four of the eight counters satisfied the cuts, for evidence that fractionally charged particles were missed because of knock-on electrons producing large pulse heights in one or more counters. We could find no indication that this happened. We have calculated that even requiring all eight counters to satisfy the cuts we would lose due to knock-ons no more than 25% of charge-$\frac{2}{3}$ particles and 16% of charge-$\frac{1}{3}$ particles.

In order to optimize conditions for charge-$\frac{2}{3}$ quark production by dissociation, some data were taken with a 150-GeV/c positive beam. Similar analysis to that described above was applied and yielded no quark candidates. Data were also taken with 200-GeV protons and a 150-GeV/c secondary momentum as well as 300-GeV protons and 270-GeV/c secondary momentum. No candidates were observed in any of these runs.

In order to derive upper limits on the total cross section for quark production we must assume some plausible production model. In Fig. 2 are shown the total-cross-section limits obtained by assuming four-body phase space for pair production (isotropic center-of-mass angular distribution), and four-body phase space constrained by a multiplicative factor of $\exp(-6P_t)$, where P_t is the transverse momentum in GeV/c. We present these two as extreme cases. For comparison we also show similar limits from the Bott-Bodenhausen *et al.*[4] experiment at the CERN intersecting storage rings.

We wish to acknowledge the contribution of Dr. T. White during the design stages of this experiment. We also thank Jack Upton for his tireless work in constructing and installing the experimental equipment and Cordon Kerns for his assistance in electronics design. Finally, we are grateful to the Meson Laboratory personnel for their help.

*Operated by Universities Research Association Inc. under contract with the U. S. Atomic Energy Commission.

[1]J. R. Orr and A. L. Read, Meson Area Design Report, NAL Internal Report, 1971 (unpublished).

[2]This event has a confidence level of $\lesssim 10\%$ and the following pulse heights (normalized to the pulse height of a charge-1 particle): 0.78, 0.71, 0.56, 0.70, 0.71, 0.56, 0.80, 0.69. The distribution for charge $\frac{2}{3}$ peaks at 0.44. To be conservative we do not eliminate this event in computing the upper limit below 1.76 GeV/c^2 in Table I.

[3]Counting proton constituents one might expect the cross section of quarks to be about $\frac{1}{3}$ that of protons. Particles with cross sections as large as that of the proton would interact before transversing all eight counters with only 20% probability.

[4]M. Bott-Bodenhausen, D. O. Caldwell, C. W. Fabjan, C. R. Gruhn, L. S. Peak, L. S. Rochester, F. Sauli, U. Stierlin, R. Tirler, B. Winstein, and D. Zahniser, Phys. Lett. 40B, 693 (1972).

Electron-Positron Annihilation into Hadrons and Landau's Hydrodynamic Model*

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The multiplicity and inclusive single-particle distribution for $e^+ + e^- \to \pi + X$ are calculated for Landau's hydrodynamic model. At 3 and 5 GeV the collective motion is less important than the thermal motion. The average pion energy obtained in the Stanford linear-accelerator colliding-beam experiment is consistent with either an ultrarelativistic equation of state or one based on the observed hadron spectrum.

We propose that e^+e^- annihilation proceeds in two phases. First, a field-theoretical mechanism generates a prematter state that is essentially in thermodynamic equilibrium at a high temperature T_0 and confined to a volume V_0 small in comparison with the volume needed to contain N free hadrons ($V_0 \ll NV_\pi$, $V_\pi = 4\pi/3m_\pi^3$). Second, the prematter expands according to the hydrodynamical model[1,3] until the energy density is consistent with one pion per hadronic volume V_π, at which time it condenses into pions. The first phase determines T_0, V_0, and the total cross section. In this paper we examine how the hydrodynamic motion controls the multiplicity and single-particle distribution in terms of T_0 and V_0.

The expansion process is described by the relativistic four-velocity field $u^\mu(x)$ of the collective motion. We assume that the fluid is in local statistical equilibrium described by a temperature field $T(x)$. The number of pions becomes well defined when the temperature reaches a critical temperature $T_c \approx T_\pi = m_\pi c^2/k$. This happens on a three-surface σ determined by $T(x) = T_c$. We assume that the residual dynamics at breakup is described by an ideal Bose gas. The momentum distribution is calculated as an integral over σ and the role of the hydrodynamic equations is to determine σ. The number of particles having momenta in the range d^3p crossing σ is given by the invariant[4]

$$E\, dN/d^3p = \int_\sigma g(\bar{E}(x), T(x)) p^\mu d\sigma_\mu, \qquad (1)$$

where $p^\mu = (E, \vec{p})$ is the particle momentum in the c.m. frame, $\bar{E}(x) = p_\mu u^\mu(x) = \gamma(x)[E - \vec{p}\cdot\vec{v}(x)]$ is its energy in the co-moving frame, and

$$g(\bar{E}, T_c) = g_\pi (2\pi)^{-3}[\exp(\bar{E}/kT_c) - 1]^{-1}. \qquad (2)$$

For a spherically symmetric expansion the volume element $d\sigma_\mu$ takes a simple form and the surface can be parametrized by fluid rapidity $\eta = \operatorname{artanh} v$, so Eq. (1) becomes

$$E\, dN/d^3p = 4\pi \int_0^{\eta_{\max}} g(\bar{E}(x), T_c) r(\eta)^2 (E\, dr/d\eta - p\cos\theta\, dt/d\eta)\, d\cos\theta\, d\eta, \qquad (3)$$

where $\tanh\eta_{\max}$ is the maximum speed reached by the fluid on σ. The total energy and number of particles can be found by integrating Eq. (1) or Eq. (3):

$$N = \int dN = n_c V_c, \qquad (4)$$

$$E_{\text{c.m.}} = \int E\, dN = (\epsilon_c + p_c) V_c \langle\gamma\rangle - p_c V_0, \qquad (5)$$

where n_c, ϵ_c, and p_c are, respectively, the number density, energy density, and pressure