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**A SEARCH FOR FRACTIONALLY CHARGED QUARKS
PRODUCED BY 200 AND 300 GeV PROTON-NUCLEAR INTERACTIONS**

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ABSTRACT

We describe an experimental search for particles with fractional charge (quarks) with mass below $11 \text{ GeV}/c^2$ 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 twelve-inch beryllium target. The experiment was performed at the National Accelerator Laboratory. The M2 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. Quarks of charge $1/3e$ and $2/3e$ are expected to exhibit ionization losses $1/9$ th and $4/9$ th that of singly charged particles. During the running period with 200 GeV incident protons the secondary beam channel was tuned to momenta of 270 GeV/c 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 feet from the production target. The momentum selected beam was bent further and subsequently brought to a second focus at the detection apparatus, 1360 feet from the production target. The beam spot size at the second focus was about $1/8$ -inch 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 $(\Delta p/p) \cdot \Delta \Omega$ acceptance of $0.4 \mu\text{sr} \cdot \%$, 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 (V0) with a 3/4" diameter hole centered on the beam axis was followed immediately by the first of the dE/dX (ionization loss) counters (E1). A pair of 1-inch cube scintillation counters (B) were located forty feet downstream. In the 40 foot region between the beam defining counters were the Cerenkov counters (C1 and C2) each 16 feet long and seven additional dE/dX counters (E2 to E8). The dE/dX counters were 1/2-inch thick, 6 x 4 inch 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 (quark-like) signals produced by Cerenkov radiation in the plastic. Two large veto counters (V1 and V2) with 2" x 3" 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 seven-inch diameter 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 Cerenkov 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,

$$N + N \rightarrow N + N + Q + \bar{Q}, \quad (1)$$

and 70 GeV/c for dissociation,

$$N + N \rightarrow N + Q(2/3) + Q(2/3) + Q(-1/3), \quad (2)$$

with 200 GeV incident protons. Particles of charge 1/3 with these momenta are bent like unit charge particles of 270 GeV/c and 210 GeV/c, respectively. The corresponding beam momenta for charge 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 2/3 particles with 300 GeV protons and a non-supermomentum secondary beam setting of 207 GeV/c. This corresponds to a charge 2/3 momentum of 139 GeV/c, which is the maximum of the 4-body phase space for process (1) with 300 GeV incident protons. Under these conditions, which accounted for most of the charge 2/3 search, there were typically 10^4 - 10^5 particles per pulse in the beam.

In order to reduce selectively the data taking rate 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 quark-like signals. A quark-like 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 10 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 $1/3$ and 90% for particles of charge $2/3$. The Cerenkov 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 $1.76 \text{ GeV}/c^2$ for charge $2/3$ 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 $\geq 95\%$ of charge $2/3$ ($\sim 100\%$ of charge $1/3$) but reduced the charge 1 background by 10. When all 8 dE/dX pulse heights were required to satisfy these cuts only 8 events survived. About 70% of the charge $2/3$ sample would be expected to remain after this cut. All 8 of these events showed signals in the Cerenkov counters. Thus, we find no candidates with mass above $1.76 \text{ GeV}/c^2$, the Cerenkov 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 $1.76 \text{ GeV}/c^2$ one event is consistent with signals expected for a charge $2/3$ 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 8 dE/dX counters.³ This would raise the upper limits by about 10. If such quarks were required to traverse only 4 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 4 of the 8 pulse heights satisfied the previously cited cuts. In this way if a fractionally charged particle interacted after 4 or more counters, it would not be lost. Again there were no candidates above $1.76 \text{ GeV}/c^2$. 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 $1/3$ candidates. However, for charge $2/3$, backgrounds are too high to analyze the data with only 4 dE/dX counters without using the Cerenkov counter rejection. Therefore for these highly interactive charge $2/3$ quarks of mass less than $1.76 \text{ GeV}/c^2$ the limits of Table I for this running condition should be increased by about 10.

We examined the data remaining if any 4 of the 8 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 8 counters to satisfy the cuts we would lose due to knock-ons no more than 25% of charge $2/3$ particles and 16% of charge $1/3$ particles.

In order to optimize conditions for charge $2/3$ 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 e^{-6P_t} , where P_t is the transverse momentum in GeV/c.

We present these two as extreme cases. For comparison similar limits from the Bott-Bodenhausen et al.⁴ experiment at the CERN ISR are also shown.

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.

REFERENCES

- ¹J. R. Orr and A. L. Read, Meson Area Design Report, NAL Internal Report (1971).
- ²This 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 $2/3$ peaks at 0.44. To be conservative we do not eliminate this event in computing the upper limit below $1.76 \text{ GeV}/c^2$ in Table I.
- ³Counting proton constituents one might expect the cross section of quarks to be about $1/3$ that of protons. Particles with cross sections as large as that of the proton would interact before transversing all 8 counters with only 20% probability.
- ⁴M. Bott-Bodenhausen, D. O. Caldwell, C. W. Fabjan, C. R. Gruhn, L. S. Peak, L. S. Rochester, F. Sauli, U. Stierlin, R. Tirlir, B. Winstein, and D. Zahniser, Phys. Letters 40B, 693 (1972).

TABLE I

90% Confidence Level Upper Limits
on Fractionally Charged Particle Production

Proton Energy	Secondary Beam Momentum*	$\frac{d\sigma}{dp d\Omega}$ (Lab)	
		$ Q = 1/3$	$ Q = 2/3$
200 GeV	-270 GeV/c	$5.6 \times 10^{-36} \text{ cm}^2/\text{GeV-sr}$	$2.8 \times 10^{-36} \text{ cm}^2/\text{GeV-sr}$
	-207	5.6×10^{-35}	2.8×10^{-35}
	-150	8.0×10^{-35}	4.0×10^{-35}
300 GeV	-270	5.1×10^{-34}	2.5×10^{-34}
	-207	1.0×10^{-34}	$5.0 \times 10^{-35}^\dagger$
	+150	4.8×10^{-33}	$8.5 \times 10^{-35}^\ddagger$ 2.4×10^{-33}

* Sign indicates polarity of beam.

† Mass $> 1.76 \text{ GeV}/c^2$

‡ Mass $< 1.76 \text{ GeV}/c^2$

FIGURE CAPTIONS

Fig. 1 Schematic drawing of experimental apparatus.

Fig. 2 Upper limits on total cross section for fractionally charged particle production:

a) Charge $-1/3$, b) Charge $-2/3$

Solid lines show limits obtained assuming four-body phase space (with an isotropic center of mass angular distribution). Dashed lines show limits with the four-body phase space constrained by a multiplicative factor of e^{-6P_t} where P_t is the transverse momentum in GeV/c. Results from this experiment and from Bott-Bodenhausen et al.⁴ at the ISR are shown.

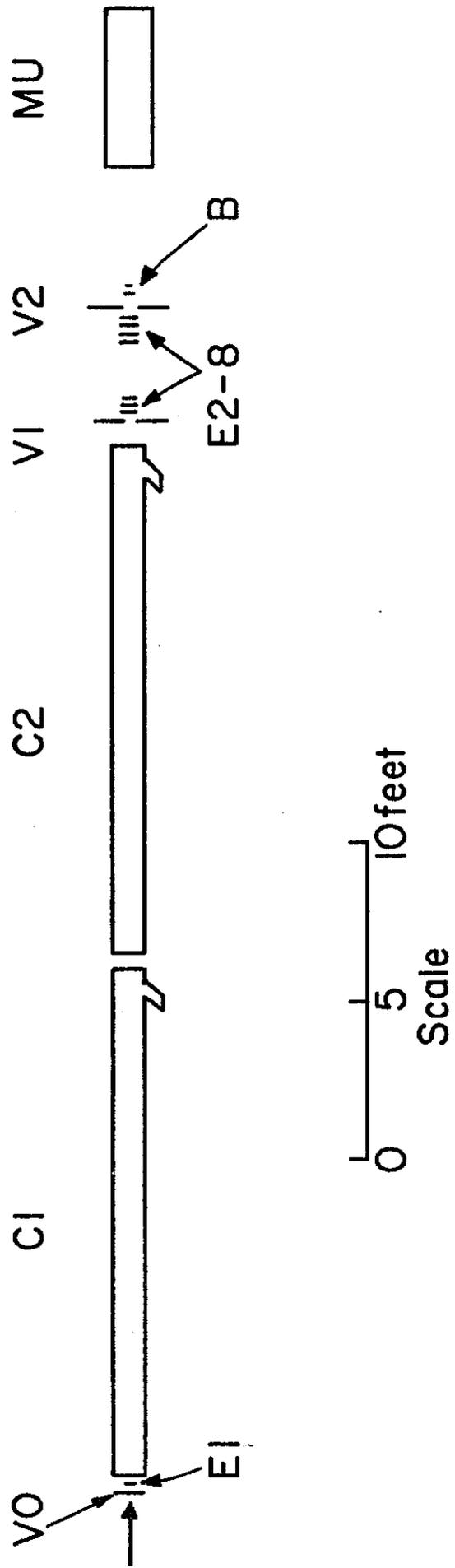


Fig. 1

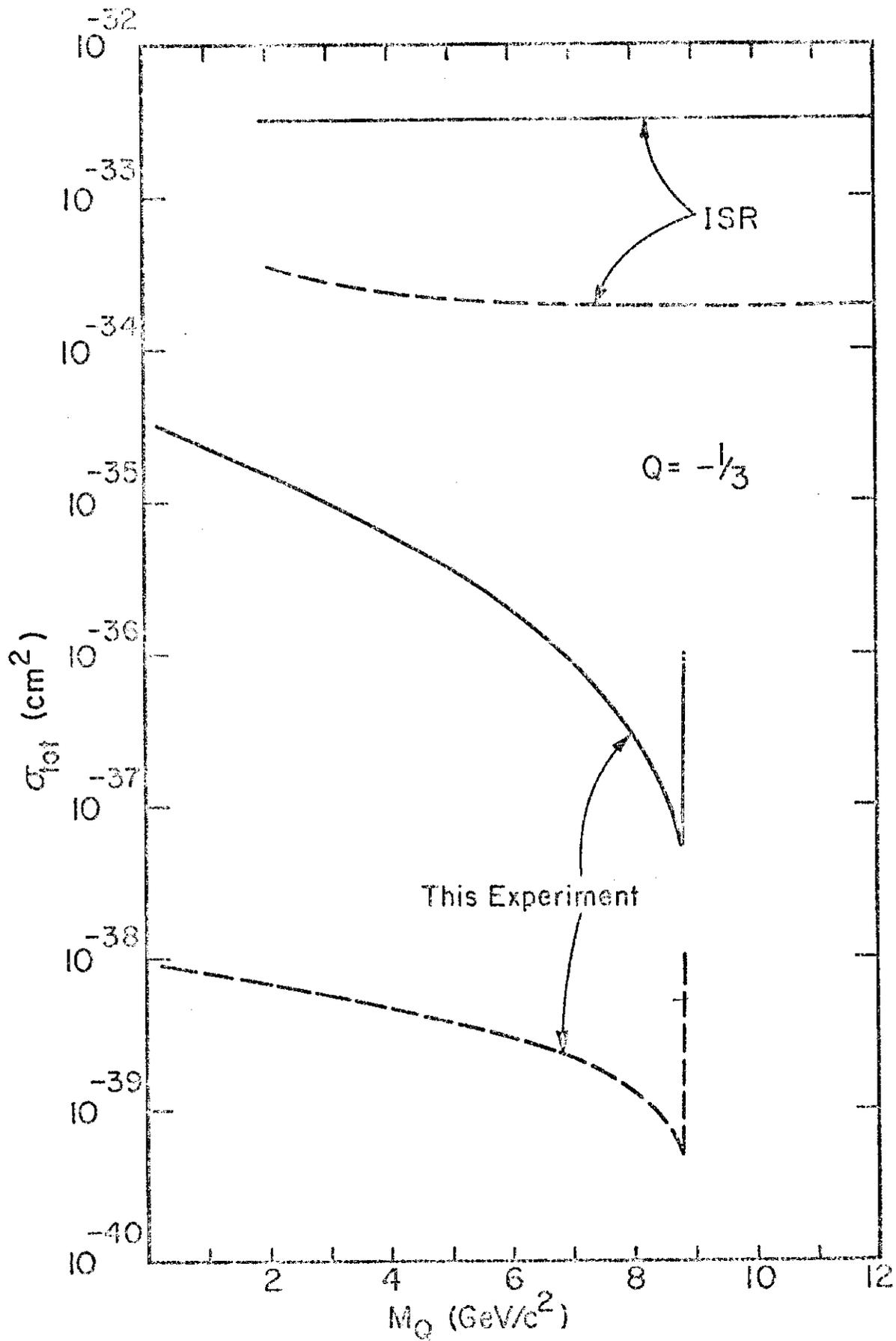


Fig. 2(a)

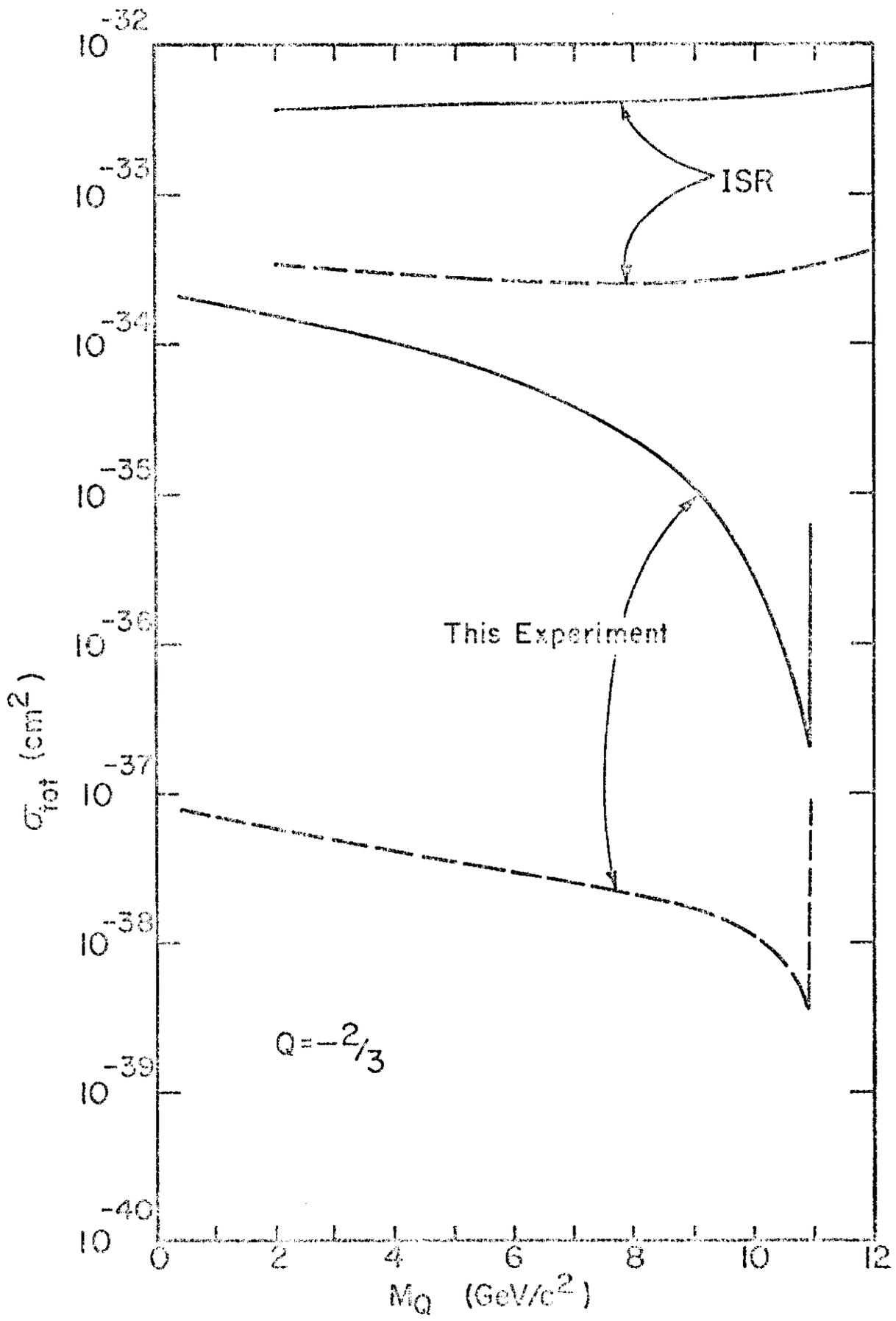


Fig. 2(b)