nate radius.

Hartle and Thorne[1] found, for rigidly rotating neutron stars, a maximum mass enhancement of 1.31. Their rotation was limited by equatorial shedding, rather than instability. Hence, the differential-rotation mass enhancement of 1.5 to 1.7 is only a slight increase over the rigid rotator. It may be noted, however, that the rotational enhancement found by Hartle and Thorne is strongly dependent on the equation of state and central density, while with the differential rotation the mass enhancement is a weak function of density and equation of state.

I would like to thank R. V. Wagoner, J. LeBlanc, M. Alme, and R. Ruffini for helpful discussions.

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Early Observation of Neutrino and Antineutrino Events at High Energies*

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Presented here are preliminary results of two short runs with a broad-band neutrino-antineutrino beam at National Accelerator Laboratory incident on about 120 tons of target which is part of a detector consisting of an ionization calorimeter and a muon magnetic spectrometer. These results include (i) the observed distribution in transverse muon momentum, dN/dp_μ, (ii) the average neutrino cross section at a mean neutrino energy of roughly 30 GeV, and (iii) the ratio of the antineutrino to the neutrino total cross section at a mean neutrino energy of 40 GeV.

The energy (300 GeV) and intensity ($\sim 10^{12}$ protons per pulse) of the external proton beam now available at the National Accelerator Laboratory (NAL) are sufficiently large to permit the observation of a substantial number of high-energy neutrino interactions, even without any focusing of the secondary pions and kaons which, through their decays, produce the neutrino beam. In order to provide an early description, albeit crude, of neutrino interactions in this new energy region, we report here the preliminary results of two short runs (approximately 10^{15} interacting protons on target) with such a broad-band neutrino-antineutrino beam incident on about 120 tons of target-detector.

The experimental arrangement is shown schematically in Fig. 1(a). The hadron-producing target (a collision length of iron) on which the extracted proton beam impinges is about 1400 m from the accelerator. The secondary hadrons travel unvexed through a drift region 350 m in length and 1 m in diameter. The drift region is in turn followed by a muon shield, primarily of earth, about 1000 m long, at the end of which our neutrino detection apparatus is located.

The main outlines of the target-detector are sketched in Fig. 1(b). The neutrinos are incident on an ionization calorimeter (IC) consisting of four main sections in series along the beam axis, each main section of cross-sectional area 3×3 m^2 and length along the beam of 1.8 m, and containing about 15 metric tons of mineral-oil–based liquid scintillator. Each main section is divided into four optically separated subsections viewed from two sides, as indicated in Fig. 1(b), by twelve photomultipliers (5-in. diam). There are wide-gap optical spark chambers of area 3×3 m^2 after each main section of the ionization calorimeter as shown in Fig. 1(b). Immediately downstream of the IC is a magnetic spectrometer made up of four units of toroidal iron magnets, one behind the other along the beam line, with narrow-gap optical spark chambers following each magnet unit. The toroids have an inside diameter of 0.3 m, an outside diameter of 3.6 m, and are 1.2 m long; they are driven into satura-

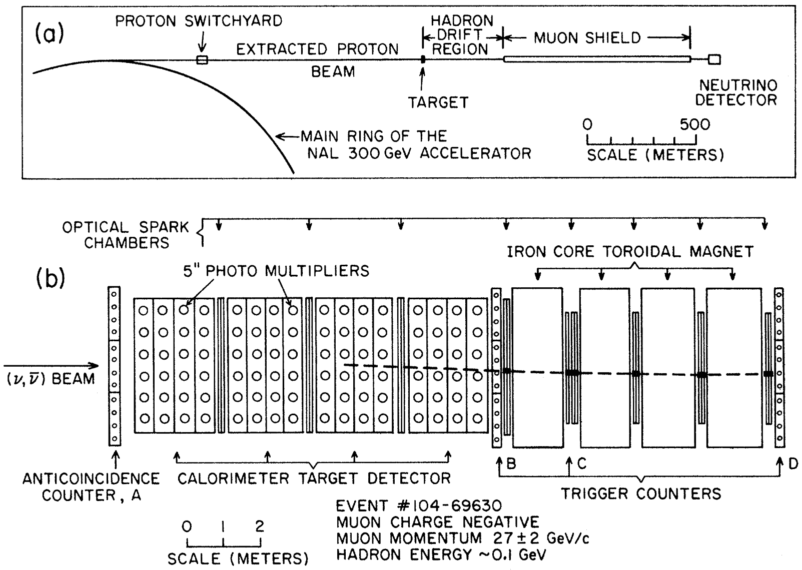

FIG. 1. (a) Experimental arrangement showing the 300-GeV accelerator, the proton beam, the hadron drift space, the muon shield, and the neutrino detector. (b) Details of the neutrino detector with quasielastic or Δ-production neutrino event superimposed.

tion and operate at an essentially constant field B of 18 kG. The narrow-gap spark chambers are 2.3×2.3 m^2 in area.

The target for neutrino interactions in the runs described here was a fiducial mass of about 60 metric tons of liquid scintillator in the ionization calorimeter plus another 60 tons of iron (part of the first unit of the magnetic spectrometer). For some of the neutrino interactions occurring in the ionization calorimeter a rough measurement of the energy of the hadron shower was made. For all events the vector momentum and sign of charge of the secondary muon was measured in the magnetic spectrometer. The detector was activated by either of the two coincidence modes CD or BC (preset minimum energy deposition in IC) [see Fig. 1(b)]. The presence of pulses in all counters and the relative times of those pulses were recorded as well as the pulse-height information from each of the sixteen subsections of the IC.

The external proton beam was obtained from the accelerator by a half-wavelength resonant extraction mode which produced a beam spill of about 300 μsec total duration. The neutrino detector was gated on by a pulse about 1 msec long coincident with the beam spill. An additional gate was opened to sample cosmic-ray events not associated with the accelerator beam. Events in coincidence with the beam were either neutrino interactions in our detector or muons emerging from the earth in front of the detector. Almost all of the latter type were neutrino induced and are therefore of interest also but we do not discuss them here. With our relatively high useful neutrino event rate, typically a few events per hour in these runs,[1] backgrounds from (i) cosmic rays, (ii) hadrons or muons leaking through the shield, and (iii) neutrino-induced events in the shield were negligible.

The salient preliminary results that we present are obtained from the directly observed distribution in transverse momentum of the secondary muons, $dN/dp_{\mu\perp}$, both positive and negative, which is shown in Fig. 2(a). We note the striking difference between the shape of the experimental distribution in Fig. 2(a) and the exponential falloff [as $\exp(-6p_\perp)$] of $d\sigma/dp_\perp$ observed in hadron-hadron collisions. Observe also that in Fig. 2 $\langle p_{\mu\perp}\rangle \approx 1.5$ GeV/c, which is to be compared with $\langle p_\perp\rangle \approx 0.3$ GeV/c obtained in hadron-hadron collisions. Furthermore, since $q^2 = p_{\mu\perp}^2 E_\nu/E_\mu$, observation of events with $p_{\mu\perp}$ as large as 6 GeV/c (the kinematic limit of the collision of a 72-GeV neutrino with a nucleon) implies values of q^2 greater than 36 (GeV/c)^2 and, on average,[2,3] about 72 (GeV/c)^2. The detection efficiency of our apparatus for such large momentum-transfer events is unrestricted.

We present in Fig. 2(b) the observed distribution in momentum, dN/dp_μ, to show that roughly $\frac{1}{6}$ of all the events have $p_\mu > 50$ GeV/c and there-

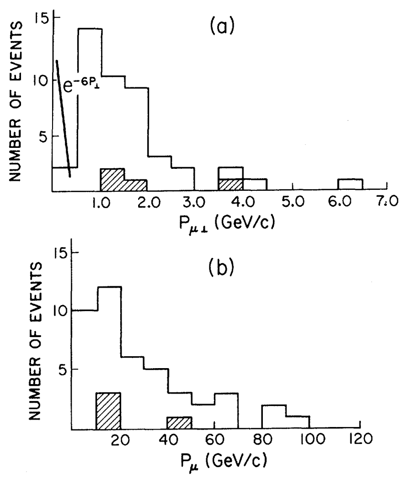

FIG. 2. (a) Distribution in $p_{\mu\perp}$. (b) Distribution in p_μ. The cross-hatched events are positive muons.

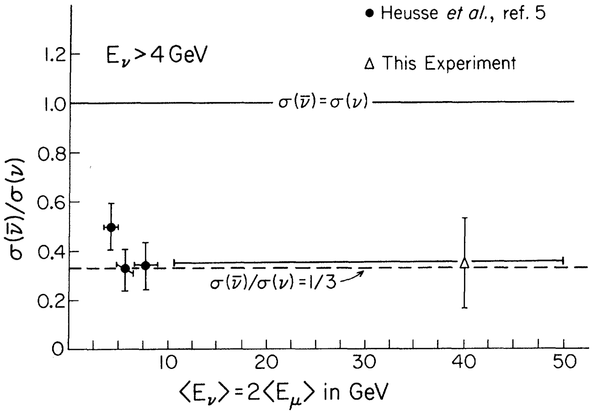

FIG. 3. Plot of the ratio $\sigma(\bar{\nu})/\sigma(\nu)$ as a function of $\langle E_\nu \rangle$. The value of $\frac{1}{3}$ is expected in the scattering of neutrinos and antineutrinos by fundamental fermions such as electrons and muons.

fore, on average,[2,3] $E_\nu > 100$ GeV. Of the twenty interactions that occur in the IC, six show *visible* hadron energies[2] between 15 and 41 GeV.

It is also of interest that there are only two events in the IC that are probably quasielastic or Δ(1238 MeV) production, as indicated by their low value of $q^2 \lesssim 0.8$ (GeV/c)^2 and low value of visible hadron energy <0.3 GeV. We take from the recent CERN–Argonne National Laboratory results[4] σ_ν(quasielastic)$+\sigma_\nu$(Δ production)$\approx(2.4\pm0.6)\times10^{-38}$ cm^2/nucleon, essentially independent of E_ν. Then σ_ν(total)$=(24\pm17)\times10^{-38}$ cm^2/nucleon at a mean neutrino energy assumed to be given roughly[2,3] by $\langle E_\nu\rangle = 2\langle E_\mu\rangle \approx 30$ GeV [see Fig. 2(b)]. This is to be compared with the value of $(21\pm4)\times10^{-38}$ cm^2/nucleon expected from the relation σ_ν(total)$=(0.7\pm0.14)E_\nu\times10^{-38}$ cm^2/nucleon observed at lower neutrino energies.[5,6]

Lastly, we note that there are 4 events with a positively charged muon, and 26 events with a negatively charged muon, as the outgoing lepton, all with 10 GeV/$c < p_\mu <$ 50 GeV/c. Above 10 GeV/c the muon detection efficiency of our apparatus is essentially charge independent. We take the ratio of the production cross sections[7] for π^+ and π^- (of momenta greater than about 75 GeV/c) by 300-GeV protons on nucleons as 2.3 and obtain

$$\frac{\sigma(\bar{\nu}+p\to\mu^+ +\mathrm{all})+\sigma(\bar{\nu}+n\to\mu^+ +\mathrm{all})}{\sigma(\nu+p\to\mu^- +\mathrm{all})+\sigma(\nu+n\to\mu^- +\mathrm{all})}=0.35\pm0.18$$

at $\langle E_\nu\rangle\approx 40$ GeV. This result is to be compared with the value 0.33 ± 0.1 observed[5] at $\langle E_\nu\rangle\approx7.5$ GeV. These data are summarized in Fig. 3. It is perhaps remarkable that the ratio $\sigma(\bar{\nu})/\sigma(\nu)$ is so close to the value $\frac{1}{3}$ at $\langle E_\nu\rangle\approx 40$ GeV when one realizes the deep inelasticity in the high-energy neutrino and antineutrino interactions that are described here. This is the numerical value of the ratio that is expected for the scattering of neutrinos and antineutrinos by fundamental fermions such as electrons and muons.

It is necessary to emphasize that our conclusions are based on few events, and therefore should not be construed as representing more than a cursory overview of a new energy region of neutrino physics. There are as yet too few events to reach any conclusion with respect to possible new phenomena, e.g., intermediate vector boson or heavy lepton production.

We wish to thank all of the dedicated people who are helping to make the National Accelerator Laboratory a scientific reality. In particular, we thank E. Bleser and Helen Edwards for their work on fast coherent extraction of the proton beam, and J. R. Orr, J. Sanford, and T. Toohig for the development of the neutrino experimental area. We are grateful to the many individuals at our respective universities whose technical skills and enthusiasm have contributed so valuably to this experimental effort. Finally, we thank Leon Lederman for the loan of the narrow-gap spark chambers.

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[1]In a subsequent short run the useful neutrino event rate has climbed to about 15 events per hour, still without focusing of the secondary hadrons.

[2]We assume that the average muon energy is $\frac{1}{2}$ of the neutrino energy. This assumption is consistent with the neutrino energy distribution determined for events observed in the calorimeter, after applying corrections for energy escape and calibration. We note that the IC has not yet been calibrated in a hadron beam. Cosmic-ray muons have been used to determine the energy loss for minimum ionizing tracks in order to calibrate crudely the visible energy measurement.

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[7]We have taken the π^+/π^- and K^+/K^- production ratio needed to determine the ratio of $\nu/\bar{\nu}$ flux from recent measurements at the CERN intersecting storage rings and proton synchrotron and interpolated the data to NAL energies. Since the π and K production approximately follow Feynman scaling in the approximate $(x, p_\perp)$ kinematic region for the NAL neutrino beam and over the s variation from proton-synchrotron to intersecting-storage-rings energies, we expect our estimate to be accurate to within ~20%. The relevant data were taken from G. Giacomelli, to be published; H. J. Muck *et al.*, Phys. Lett. 39B, 303 (1972); J. V. Allaby, F. Benon, A. N. Diddens, P. Duteal, A. Klovning, P. Meunier, J. P. Peigneux, E. J. Sacharidis, K. Schlupmann, M. Spiegel, J. P. Stroot, A. M. Thorndike, and A. M. Wetherell, CERN Report No. 70-12, 1970 (unpublished).

Comparisons of Deep-Inelastic *e-p* and *e-n* Cross Sections

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Cross sections for inelastic scattering of electrons from hydrogen and deuterium were measured for incident energies from 4.5 to 18 GeV, at scattering angles of 18°, 26°, and 34°, and covering a range of squared four-momentum transfers up to 20 (GeV/c)^2. Neutron cross sections were extracted from the deuterium data using an impulse approximation. Comparisons with the proton measurements show significant differences between the neutron and proton cross sections.

Deep-inelastic electron scattering has been used to study the structure of the proton[1,2] and neutron.[3] The investigation of neutron structure has been further extended in the present experiment. Comparisons of the proton and neutron cross sections provide important tests for many of the models suggested by the earlier proton measurements.

We have measured the differential cross section for electrons scattering from hydrogen and deuterium, detecting only the scattered electrons. Measurements were made at laboratory angles θ of 18°, 26°, and 34° and a range of scattered electron energy E' extending from that corresponding to the resonance region down to 1.5 GeV. The incident electron energy E varied from 4.5 to 18 GeV. A number of spectra, each covering a range of E' at a fixed value of E, were measured at each angle to permit model-insensitive radiative corrections to be made.

An electron beam at the Stanford Linear Accelerator Center (SLAC) passed through 7-cm-thick