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TOTAL CROSS SECTIONS FOR ν_μ AND $\bar{\nu}_\mu$ CHARGED CURRENT INTERACTIONS BETWEEN 20 AND 200 GeV

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ABSTRACT

Exposures of the Ne/H_2 filled Big European Bubble Chamber (BEBC) to a dichromatic neutrino (antineutrino) beam produced by 400 GeV protons of the CERN SPS yielded 3100 events with a negative, and 1100 with a positive, muon. The neutrino flux is determined from the muon flux in the shielding. Assuming a linear energy dependence of the cross section, the values σ/E between 20 and 200 GeV are found to be 0.657 ± 0.012 (stat.) ± 0.027 (syst.) and 0.309 ± 0.009 (stat.) ± 0.013 (syst.) cm^2 (GeV . nucleon)$^{-1}$, for neutrinos and antineutrinos, respectively. The scaling variable q^2/E decreases significantly with energy both for neutrinos and antineutrinos.

The Big European Bubble Chamber (BEBC), filled with a Ne/H_2 mixture was exposed to the dichromatic neutrino beam produced by 400 GeV protons from the CERN Super Proton Synchrotron (SPS). 3100 ν_μ induced events were obtained in 262 000 photos (average proton intensity 2.2 . 10^{12} protons per pulse) and 1100 $\bar{\nu}_\mu$ induced events in 548 000 photos (3 . 10^{12} ppp). They are used to determine total cross sections for Charged Current (CC) interactions between 20 and 200 GeV neutrino energy [1]. The neutrino fluxes were determined from the muon fluxes in the shielding, measured continuously during the experiment and cross-checked with the parent flux measurements in the beam line.

The experimental layout is shown in fig. 1. The dichromatic neutrino beam originates from decay in flight of 200 GeV/c pions and kaons, produced in a 50 cm long Be target by 400 GeV protons. The fast extracted (23 μs spill) proton beam has an angle of 15.6 mr with respect to the target-detector line so as to minimize the neutrino flux from decays upstream of the decay tunnel. Secondary particles are momentum and sign selected and directed into a 300 m long evacuated pipe (1.2 m diameter, 0.1 Torr). The beam position is monitored with grid ionisation chambers along the beam line. The beam intensity is measured with a Beam Current Transformer (BCT) after the last beam element. The K/π ratios are measured with an integrating gas Cerenkov detector placed behind the BCT. They are found to be $K^+/\pi^+ = 0.146 \pm 0.003$ and $K^-/\pi^- = 0.049 \pm 0.001$ [2]. The error represents the spread of results obtained with different Cerenkov light diaphragms.

The shielding consists of steel blocks, 2.5 m diameter and 185 m long, followed by ∿ 170 m earth and rock. It contains systems of Solid State Detectors (SSD) which monitor the symmetry and intensity of the muon flux in several gaps in the shielding [3]. Fig. 2(a) shows a plot of the measured and calculated muon flux distribution in radius and depth.

The absolute flux of neutrinos is obtained from eight of the SSD's, placed on a circle of 15 cm radius situated at a depth of 30 m in the shielding. The SSD's were calibrated relative to each other with a movable set of SSD's and found to be constant to 1% or better over four years of operation. The absolute calibration of these SSD's in terms of muon flux was obtained by means of track-counting in nuclear emulsions. The emulsions were mounted on top of the SSD's with planes normal to the beam axis. A total of 4300 tracks were counted, and fig. 2(b) shows their angular distribution. The muons are peaked within 10 mr of the axis whereas the accompanying δ-rays have a flat angular distribution. Hence, the separation of muon from electron tracks contributes only $\sim$ 1% to the systematic error. The overall error of the absolute calibration is estimated to be 3.1% [7].

The muon flux measured by the SSD's must be corrected for the muons originating from π and K decays within the beam transport system. The neutrinos from such decays do not enter BEBC, but a fraction of the corresponding muons are transported along with the pions and kaons into the decay pipe. They represent (7.6 ± 1.5)% of the muon flux recorded by the SSD's (at r = 15 cm at 30 m shielding depth); the error is estimated from consistency checks between beam transport calculations [8] and measurements of the muon flux obtained when the momentum defining collimators are closed down.

The ratio of the muon flux thus measured to the pion and kaon fluxes measured in the BCT - also calibrated to ±3% - can be calculated and depends on the particle ratios in the beam line (p, π, K, e, μ), multiple scattering of the muons, and the geometry and decay kinematics. The difference between measured and expected ratios is +5% for neutrino running and -3% for antineutrino running [9]. This is reasonable agreement, considering the fact that the corrections in the case of the BCT-determined fluxes are large and uncertain (only 20% of the signal is due to neutrino parents and the δ contamination - as big as the K^- contribution - has an estimated error of ± 60%; the p/π^+ ratio has a 5% uncertainty).

The present neutrino (antineutrino) data correspond to a total corrected muon flux of $(3.16 \pm 0.11) \cdot 10^{10}$ $[(2.94 \pm 0.11) \cdot 10^{10}]$ muons per cm^2 at r = 15 cm at 30 m shielding depth. Taking account of simplifying assumptions in computing the neutrino flux in terms of the measured muon flux the total error in the absolute neutrino flux is found to be ± 4%.

The neutrino detector was BEBC filled with a Ne/H_2 mixture. The magnetic field is 35 kG. The fiducial volume (13.5 m^3) of BEBC used for this analysis is a vertical cylinder of 1.6 m height and 1.8 m radius, reduced by a 0.5 m thick curved slice at the downstream end; this part serves only for detection of neutrals and ensures a minimum length for all charged secondaries. The neutrino beam traverses BEBC at an angle of 42.5 mr with respect to the horizontal. The density of the Ne/H_2 mixture was 0.71 g/cm^3 corresponding to 0.75 mole fraction neon (41 cm radiation length) in the first part, 0.67 g/cm^3 (0.72 mole fraction neon, 44 cm radiation length) in the later parts of the experiment.

Events were found using double scanning, with a measured efficiency of 99%. These events were retained for the total cross section analysis if (a) the interaction vertex occurred inside the 13.5 m^3 fiducial volume; (b) at least one muon of more than 5 GeV/c momentum was identified; (c) the total visible energy in secondaries exceeded 8 GeV; (d) the picture was taken during stable experimental conditions.

Muons were identified with the two plane External Muon Identifier (EMI). Its detection efficiency was determined from the effective mean free path, using the distribution in track lengths of interacting particles and the distribution of potential track lengths of leaving (non-interacting) particles, which were not detected by the EMI. For muons above 5 GeV/c momentum the combined detection and operation inefficiencies were found to be (4.8 ± 0.6)% in neutrino and (4.6 ± 1)% in antineutrino events. Mean measurement errors for the muon momentum are 3.3% below and 4.2% above 100 GeV/c.

The hadron energy, E_H, was obtained by summing over the energies of all charged hadrons, primary gammas and secondaries of interactions of primary neutral particles. Some hadron energy is lost in unobserved neutral particles, through measurement errors and from unmeasurable tracks in confused events. The amount of the loss and its spread has been determined from the measurement of 40, 70 and 110 GeV π^- interactions in the same Ne/H_2 mixture to be (9 ±21), (17 ± 23), (25 ± 27)%, respectively. The results of these measurements agree with those from missing transverse momentum studies in neutrino interactions. A global correction factor of 1.13 has been applied to the visible hadron energy of each event. The measured resolution function was used to correct the energy distribution of the events. The track configuration in about 5% of the events is too complicated to allow measurement of all tracks. The total energy of such incomplete events has been taken to be the mean energy at the radial position of the event, calculated from the beam parameters.

Table 1 shows the event numbers as a function of energy before and after corrections. Some comments on the various corrections and their uncertainties are:

(a) The uncertainty in the correction for energy resolution is due to model assumptions.

(b) The contamination of events due to neutrinos originating from parent decays upstream of the decay tunnel (the so-called wideband background flux) has been determined from the rate of events with wrong sign muons. It decreases rapidly with energy and amounts to about 1.5% of the events above 20 GeV. The error comes mainly from the low statistics of wrong-sign muon events.

(c) The p_μ-cut correction is based on y-distributions with B = 0.8, where $y = E_H/E$ and B is the ratio $\int xF_3dx/\int F_2dx$ of structure functions defined in the exact scaling formula [10]. A 10% error allows for model uncertainties.

(d) In the analysis, elastic events were not included, and an allowance must be made for them in computing the total cross section. The expected number of elastic events above 20 GeV energy is about 18 for both the neutrino and the antineutrino samples. They are shown in Table 1 assuming a 20% error in the elastic cross section.

(e) In order to obtain the total cross section for an isoscalar target nucleus the data are corrected for the 7.4% proton excess in the Ne/H_2 mixture, assuming $\sigma^{\nu n}/\sigma^{\nu p} = \sigma^{\bar{\nu}p}/\sigma^{\bar{\nu}n} = 2$.

Also shown in table 1 are the event rates in the fiducial volume of BEBC calculated from the measured muon fluxes assuming a cross section such that $\sigma/E = 1.0 \cdot 10^{-38}\ cm^2(GeV \cdot nucleon)^{-1}$. The uncertainty of these numbers is given by the 4% error in the neutrino flux (4.5% above 100 GeV due to the K/π ratio error). The measured values of σ/E (also shown in fig. 3) are obtained by dividing the observed event rates by the calculated ones. The first errors quoted in table 1 are statistical. The systematic errors of the σ/E values are computed from the uncertainties in the flux and the combined uncertainties in the corrections. The error of the flux drops out if one is considering only the cross section ratio.

In the quark parton model, the sum of the total cross sections can be interpreted in terms of the fractional momentum carried by quarks and antiquarks in the nucleon, assuming the validity of the Callan-Gross relation [11] and equality of the structure functions in neutrino-nucleon and antineutrino-nucleon interactions. It is found to be

$$(3\pi/4G^2ME)(\sigma^{\nu} + \sigma^{\bar{\nu}}) = .461 \pm .007\ (stat.) + .010\ (syst.)$$

The σ/E values do not show a significant variation with energy. Another quantity that can be used to study energy dependence is the scaling variable $q^2/E = 2\,E_\mu(1 - \cos\theta_\mu)$. This variable has the important advantage that it is determined completely by muon track measurements and hence free from systematic errors associated with uncertainties in the determination of hadron energy. The mean values determined from the present data and corrected for the muon momentum cut for energies below and above 100 GeV are given in table 2. It may be seen that there is a significant energy dependence with $\langle q^2/E \rangle$ decreasing for both neutrino and antineutrino interactions.

In conclusion, total cross sections for charged current interactions of neutrinos and antineutrinos with an isoscalar target nucleus have been measured from 20 to 200 GeV neutrino energy, i.e. at a mean neutrino (antineutrino) energy of 76.6 (62.6) GeV. No deviation from a linear rise of the cross section with energy is observed. The scaling variable q^2/E shows a significant drop with energy.

It is a pleasure to acknowledge the work of the scanning and measuring teams at the laboratories of the collaboration, and the staff at CERN for the efficient operation of accelerator, beam, bubble chamber, and associated equipment.

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TABLE CAPTIONS

Table 1 Summary of event rates and cross sections, corrections and backgrounds versus energy.

Table 2 Mean values of q^2/E.

TABLE 1

	E[GeV]	20-40	40-60	60-80	80-120	120-160	> 160	Total
	Observed event numbers	242 ± 15.6	476 ± 21.8	638 ± 24.3	534 ± 23.1	536 ± 23.2	629 ± 25.1	3055 ± 55.3
	Correction for							
	- energy resolution	- 14.0 ± 8.5	- 24.0 ± 21.4	44.0 ± 17.3	- 143. ± 24.5	- 2.9 ± 18.0	+ 139.5 ± 25.8	+ 2.0 ± 4.4
	- wide band backgr.	- 25.5 ± 15.3	- 13.0 ± 7.8	- 3.1 ± 1.9	- 0.9 ± 0.5	- 0.5 ± 0.3	- 0.1 ± 0.1	- 43.0 ± 25.8
	- EMI inefficiency	+ 12.3 ± 1.5	+ 24.6 ± 3.1	+ 36.9 ± 4.6	+ 20.7 ± 2.6	+ 27.9 ± 3.5	+ 39.9 ± 5.0	+ 162.3 ± 20.3
	- 5 GeV p_μ cut	+ 41.3 ± 4.1	+ 49.2 ± 5.0	+ 53.1 ± 5.3	+ 20.7 ± 2.1	+ 19.7 ± 2.0	+ 23.3 ± 2.3	+ 207.0 ± 21.0
ν	- Elastic events	+ 3.8 ± 0.8	+ 4.3 ± 0.9	+ 4.6 ± 0.9	+ 2.1 ± 0.4	+ 1.9 ± 0.4	+ 2.0 ± 0.4	+ 18.7 ± 3.7
	- Isoscalar target	+ 3.2	+ 6.2	+ 9.2	+ 5.2	+ 6.9	+ 10.	+ 40.8
	Corrected event numbers	263.0±16.0±18.0	522.8±22.0±23.5	782.0±24.0±18.8	438.4±23.0±25.0	588.5±23.0±18.5	842.8±25.0±26.0	3443.0±55.0±39.2
	Calculated (see text)	459.0 ± 18.4	789.2 ± 31.6	1142.9 ± 45.6	693.1 ± 29.0	928.8 ± 41.5	1224.4 ± 54.8	5237.5 ± 209.5
	$\sigma/E[10^{-38}$ cm^2 (GeV-nucleon)$^{-1}$]	0.573±0.034±0.046	0.662±0.028±0.040	0.685±0.022±0.032	0.633±0.033±0.045	0.634±0.025±0.035	0.688±0.020±0.038	0.657±0.012±0.027
	Observed event numbers	129 ± 11.4	244 ± 15.6	317 ± 17.8	193 ± 13.9	101 ± 10.1	104 ± 10.2	1088 ± 33.0
	Correction for							
	- energy resolution	+ 0.8 ± 2.6	+ 0.2 ± 0.2	+ 24.5 ± 3.5	- 31.7 ± 3.9	- 3.0 ± 0.3	+ 10.9 ± 1.9	+ 1.7 ± 2.0
	- wide band backgr.	- 11.3 ± 2.2	- 3.5 ± 0.7	- 0.8 ± 0.2	- 0.3 ± 0.1			- 16. ± 3.0
	- EMI inefficiency	+ 6.0 ± 1.3	+ 11.9 ± 2.6	+ 16.7 ± 3.7	+ 7.9 ± 1.7	+ 4.8 ± 1.0	+ 5.6 ± 1.2	+ 52.9 ± 12.0
	- 5 GeV p_μ cut	+ 5.9 ± 0.6	+ 6.5 ± 0.7	+ 6.6 ± 0.7	+ 2.2 ± 0.2	1.0 ± 0.1	0.8 ± 0.1	+ 23.0 ± 3.0
$\bar{\nu}$	- Elastic events	+ 4.8 ± 1.0	+ 4.9 ± 1.0	+ 5.0 ± 1.0	+ 1.6 ± 0.3	1.0 ± 0.2	0.7 ± 0.2	+ 18.0 ± 2.0
	- Isoscalar target	- 1.6	- 3.2	- 4.4	- 2.1	- 1.2	- 1.3	- 14.0
	Corrected event numbers	133.6±11.0±4.0	260.8±16.0±3.0	364.6±18.0±6.0	170.6±14.0±5.0	103.6±10.0±1.1	120.7±10.0±3.0	1153.6±33.0±13.0
	Calculated (see text)	482.0 ± 19.3	823.8 ± 33.0	1176.9 ± 47.0	502.6 ± 21.0	336.3 ± 15.0	414.3 ± 19.0	3736. ± 149.4
	$\sigma/E[10^{-38}$ cm^2 (GeV-nucleon)$^{-1}$]	0.277±0.024±0.014	0.317±0.019±0.014	0.310±0.015±0.013	0.339±0.028±0.017	0.308±0.030±0.014	0.291±0.025±0.015	0.309±0.009±0.013
	$\sigma^{\bar{\nu}}/\sigma^{\nu}$	0.483±0.051±0.036	0.479±0.035±0.022	0.453±0.026±0.013	0.536±0.050±0.034	0.486±0.051±0.016	0.423±0.038±0.017	0.470±0.015±0.008

TABLE 2

<E> [GeV]	$\langle q^2/E \rangle$ [GeV]	
	Neutrino	Antineutrino
53	0.215 ± 0.005	0.119 ± 0.004
159	0.187 ± 0.005	0.095 ± 0.007

FIGURE CAPTIONS

Fig. 1 Layout for narrowband neutrino beam experiments at the CERN SPS.

Fig. 2 (a) Vertical muon flux distribution - measured and calculated - after 30, 50, 70 and 94 m of steel. For multiple scattering the constant energy loss (1.4 GeV/m) solution of Fermi's diffusion equation has been assumed [4]. Deviations at larger radii are due to the difference in the radial distributions of muon flux and delta ray flux [5].

(b) Angular distribution of 2754 tracks in five nuclear emulsions exposed at 30 m shielding depth at a radius of 15 cm. The solid curve shows the calculated angular distribution as a sum of the distribution of multiple scattering angles of muons (curve 1, allowing for a 4 mr track measurement error) and the distribution of delta ray angles (curve 2) [6].

Fig. 3 Neutrino and antineutrino cross sections divided by energy and converted to values for an isoscalar target assuming $\sigma^{\nu n}/\sigma^{\nu p} = \sigma^{\bar{\nu} p}/\sigma^{\bar{\nu} n} = 2$. Errors shown are statistical (solid) and systematic (dotted).

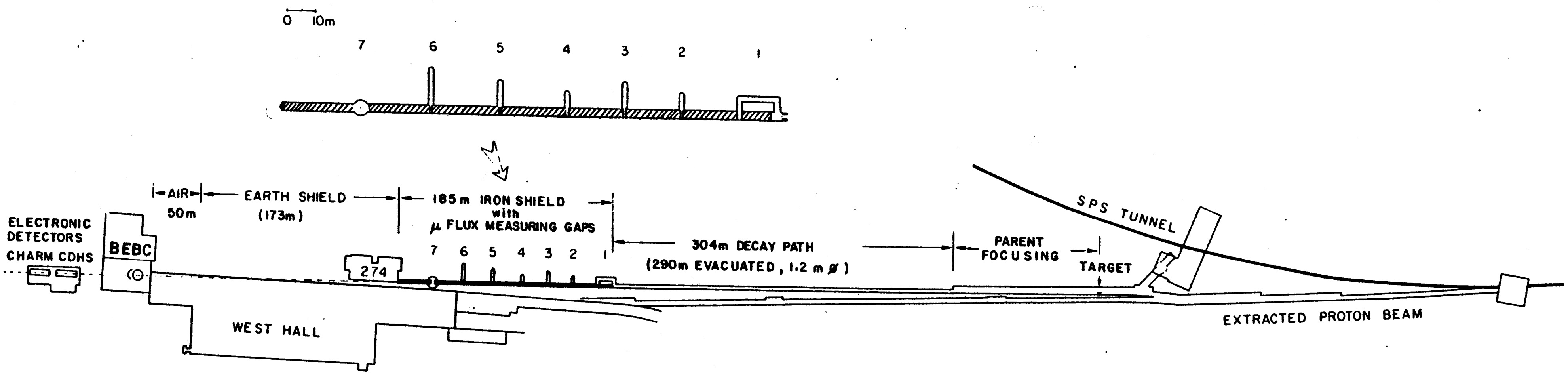

0 10m
7 6 5 4 3 2 1
AIR
50m
EARTH SHIELD
(173m)
185m IRON SHIELD
with
μ FLUX MEASURING GAPS
ELECTRONIC
DETECTORS
CHARM CDHS
BEBC
274
7 6 5 4 3 2 1
304m DECAY PATH
(290m EVACUATED, 1.2 m ø)
PARENT
FOCUSING
TARGET
SPS TUNNEL
WEST HALL
EXTRACTED PROTON BEAM

Fig. 1

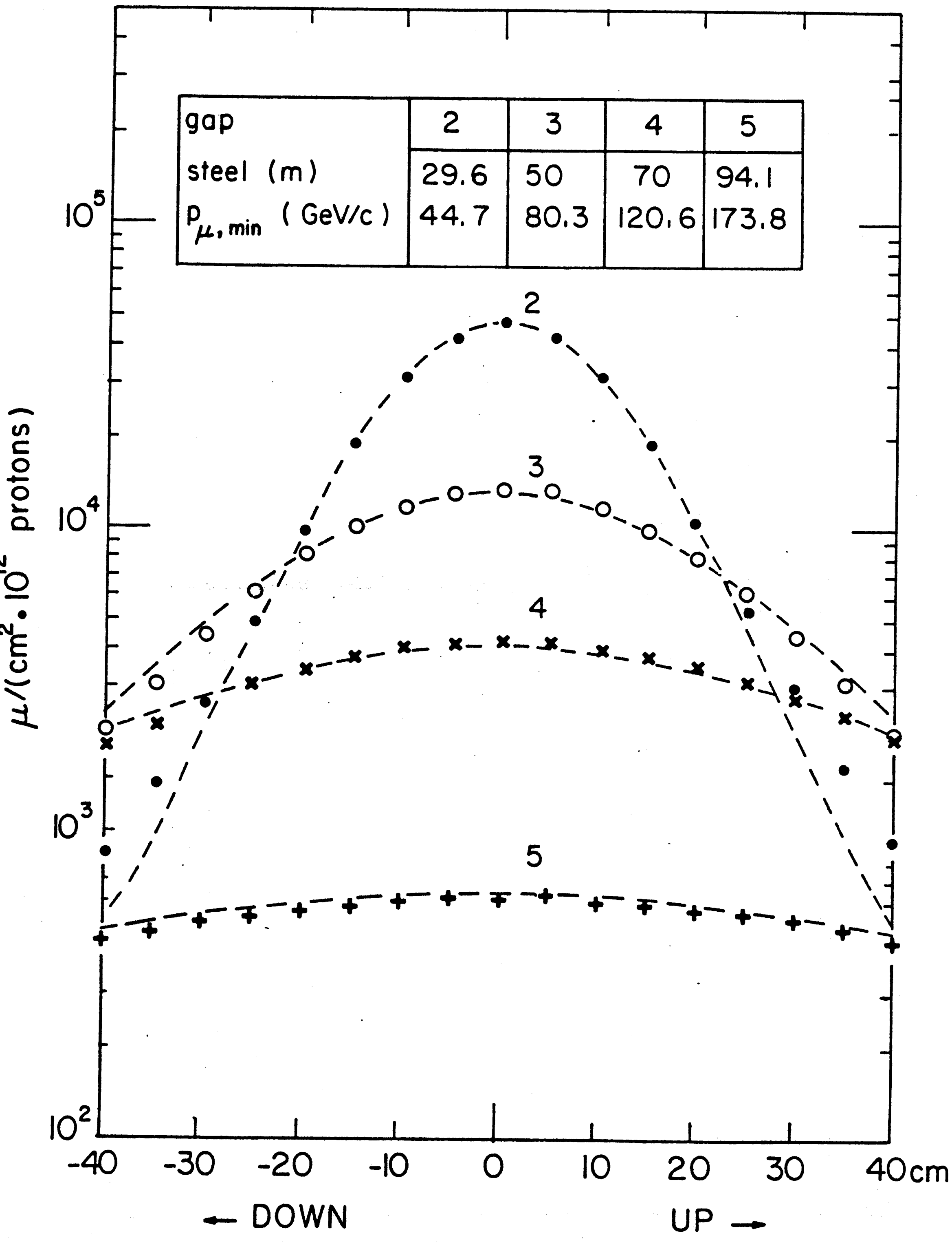
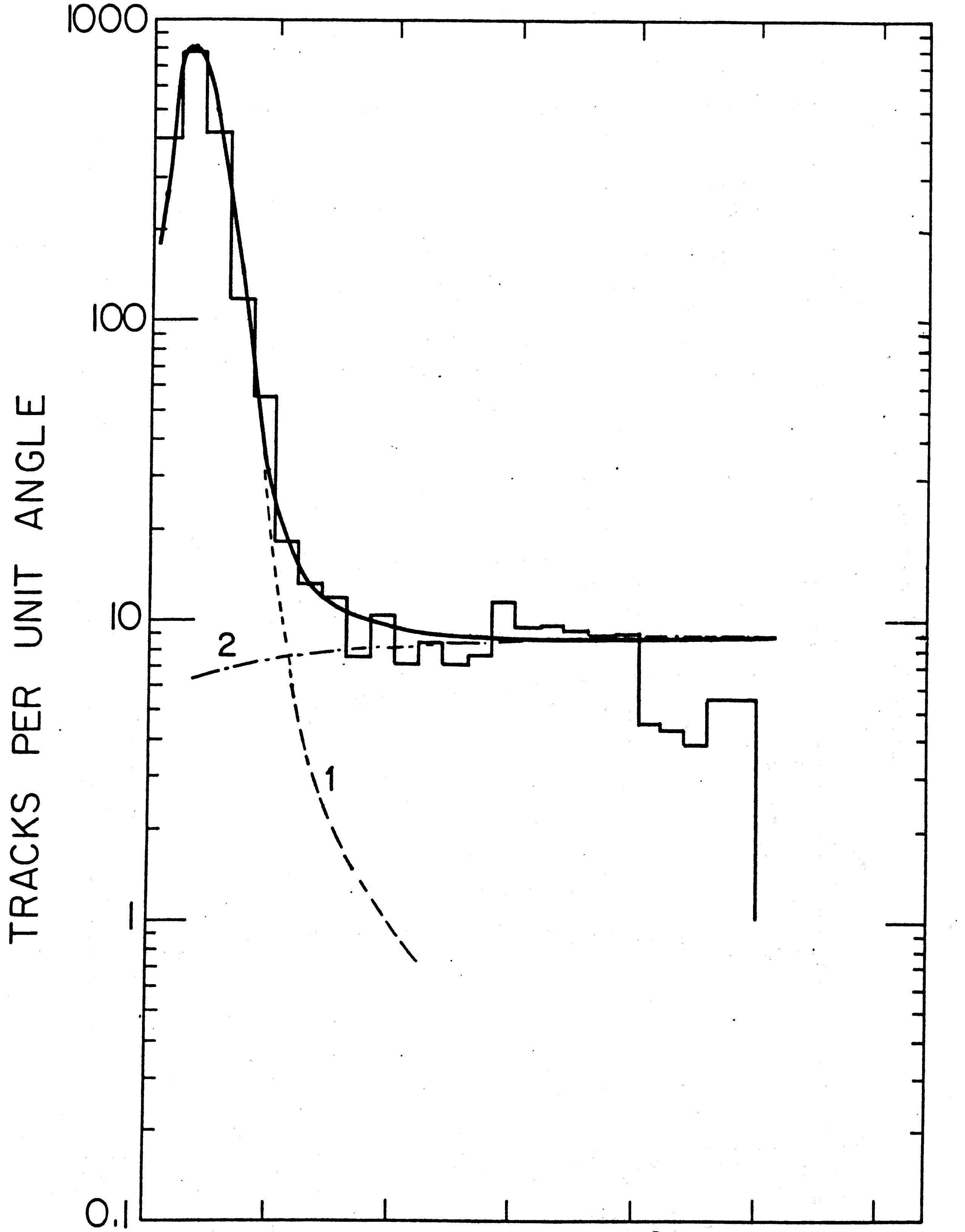
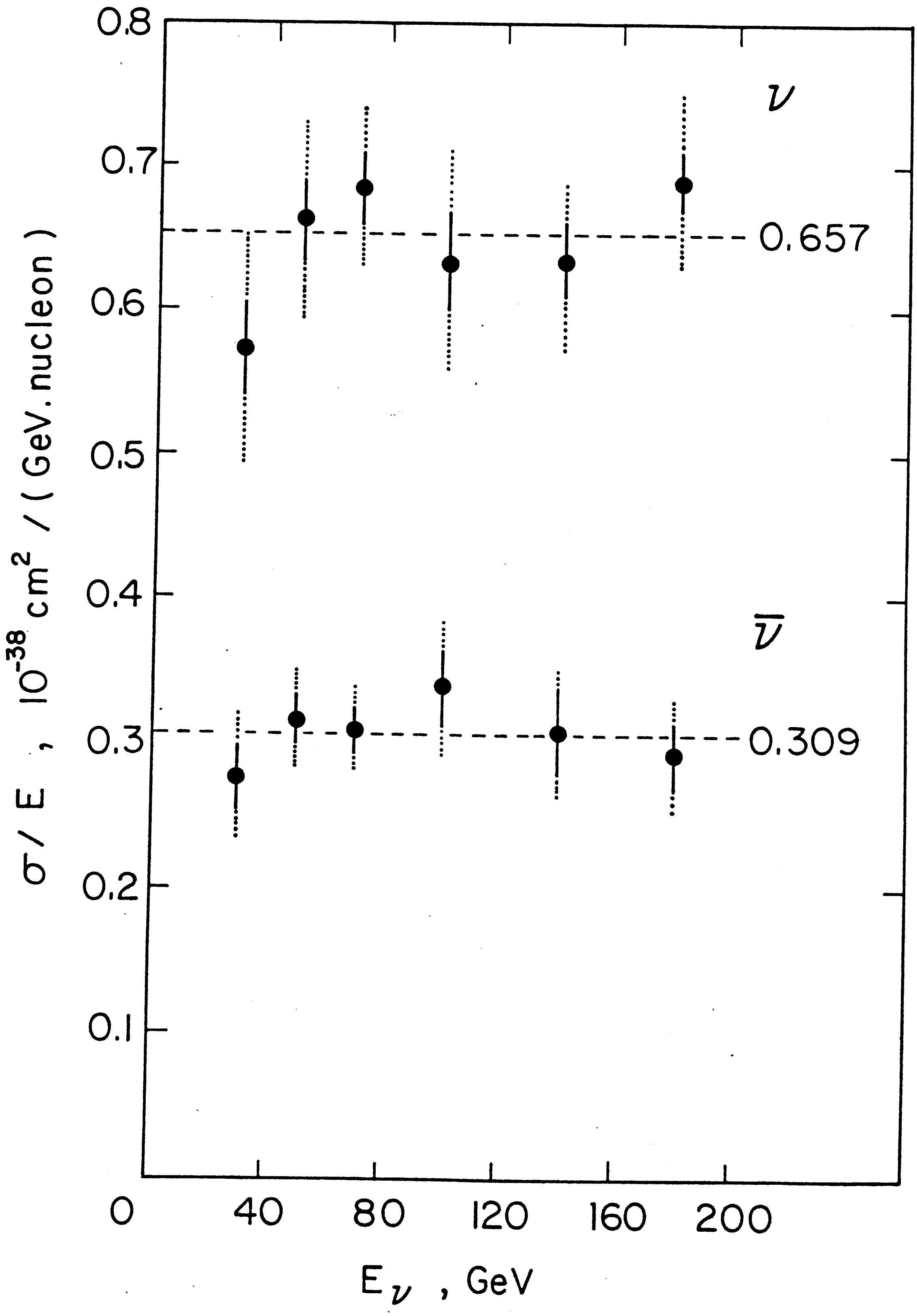

gap 2 3 4 5
steel (m) 29.6 50 70 94.1
$p_{\mu, min}$ (GeV/c) 44.7 80.3 120.6 173.8
2
3
4
5
10^5
10^4
10^3
10^2
$\mu/(cm^2 \cdot 10^{12}$ protons)
-40 -30 -20 -10 0 10 20 30 40cm
← DOWN
UP →

Fig. 2(a)



Fig, 2(b)



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
σ / E , 10⁻³⁸ cm² / (GeV. nucleon)
ν
0.657
ν̄
0.309
0
40
80
120
160
200
E_ν , GeV

Fig. 3