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INCLUSIVE NEUTRAL STRANGE PARTICLE PRODUCTION
IN νp INTERACTIONS

Aachen-Bonn-CERN-Munich (MPI)-Oxford Collaboration

H. Grässler, D. Lanske, R. Schulte and H.H. Seyfert
III. Physikalisches Institut der Technischen Hochschule, Aachen

K. Böckmann, C. Geich-Gimbel, B. Nellen, R. Pech and H. Saarikko
Physikalisches Institut der Universität Bonn, Bonn

P.C. Bosetti¹, V.T. Cocconi, A. Grant, P.O. Hulth, H. Klein,
D.R.O. Morrison, L. Pape, P. Schmid, E. Simopoulou² and H. Wachsmuth
CERN, European Organization for Nuclear Research, Geneva

M. Aderholz, N. Schmitz, R. Settles, K.L. Wernhard and W. Wittek
Max Planck Institut für Physik und Astrophysik, Munich

R. Batley, R. Giles, P. Grossmann, G. Myatt, D. Radojicic and B. Saitta
Department of Nuclear Physics, Oxford

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¹ CERN Fellow from III. Physikalisches Institut der Technischen Hochschule, Aachen.

² Now at Democritos, Athens.

ABSTRACT

In a selected sample of 6770 charged current (CC) events of νp interactions with $\langle E_\nu \rangle = 43$ GeV and $\langle W \rangle = 4.6$ GeV, 359 K^0 , 180 Λ and 13 $\bar{\Lambda}$ have been observed, which corresponds to a corrected production rate of at least one neutral strange particle in $(17.4 \pm 0.8)\%$ of the CC events. The ratio of the inclusive Λ to K^0 production cross sections is found to be 0.26 ± 0.03 . The number of CC events containing at least one K^0 increases with increasing E_ν and Q^2 , while the CC events containing at least one Λ remain practically constant. The fraction of the total hadronic energy carried by K^0 and Λ are found to be approximately the same in νp as in $e p$ and μp interactions. In the hadronic c.m.s., the K^0 are produced mostly forwards, the Λ mostly backwards, with asymmetry parameters of $+0.32 \pm 0.02$ and -0.45 ± 0.06 , respectively. The total strange particle production cross section is estimated to be $(25.2 \pm 4.1)\%$ of the cross section for production of CC events with $W > 1.5$ GeV and that for charm production $(10.5 \pm 1.5)\%$ of the CC cross section well above charm threshold ($W > 3$ GeV). The production of the resonances $K^{*+}(890)$ and $\Sigma^+(1385)$ has been observed. The production rate of $K^{*+}(890)$ is comparable to that of $D^{*+}(2009)$, above the corresponding thresholds.

1. INTRODUCTION

This paper reports the results of an investigation of neutral strange particle production in neutrino proton interactions at energies from 5 to 200 GeV, in the Big European Bubble Chamber (BEBC) at CERN.

In 6770 Charged Current (CC) events selected for this work, 359 K^0 , 180 Λ and 13 $\bar{\Lambda}$ decays have been observed.

For νp interactions, the only previous work on this subject is an experiment in the Fermilab 15' bubble chamber [1], based on 2300 CC events, 132 of which contained at least one neutral strange particle. For $\bar{\nu} p$ interactions, results are reported in ref. [2a] for 32 events containing strange particles observed in 432 CC interactions and in ref. [2b] for 124 events observed in 2123 CC events. Large statistics experiments in bubble chambers filled with H_2/Ne mixtures have provided information on strange particle production in νN [3] and $\bar{\nu} N$ [4] interactions. It is to be noted that the results obtained with neutrinos may be different from those with antineutrinos, as the charge of the hadronic system is +2 for ν and 0 for $\bar{\nu}$, and the quarks involved in the interactions are not the same in the two cases.

The investigation of strange particle production in reactions induced by neutrinos is of interest both in itself and because of its connection to charm production. Strange particles, in fact, can be produced either directly or through the decay of charmed hadrons, via one of the following interactions on a valence (V) or sea (S) quark:

$$(1) \nu d_V \rightarrow \mu^- u + s\bar{s}$$

$$(6) \nu d_V \rightarrow \mu^- c \downarrow s$$

$$(2) \nu d_S \rightarrow \mu^- u + s\bar{s}$$

$$(7) \nu d_S \rightarrow \mu^- c \downarrow s$$

$$(3) \nu \bar{u} \rightarrow \mu^- \bar{d} + s\bar{s}$$

$$(8) \nu s (+\bar{s}) \rightarrow \mu^- c (+\bar{s}) \downarrow s$$

$$(4) \nu \bar{u} \rightarrow \mu^- \bar{s}$$

$$(5) \nu s (+\bar{s}) \rightarrow \mu^- u (+\bar{s}).$$

The dominant process (1), along with the rarer reactions (2) and (3), is the usual associated production of two strange particles via an $s\bar{s}$ pair of the sea. Channels (4) and (5) have very small cross sections. Of the charm-producing reactions, processes (6) and (8) are the most probable ones, the former leading in general to a single strange particle, the latter to a pair.

The total production rate of charmed particles in neutrino interactions, as deduced from the di-lepton rate measured in several high energy bubble chamber [3,5] and counter [6] experiments is of the order of 10% of the CC cross section. The direct evidence for charm production, however, is based on only a few events [7-10]. A detailed investigation of inclusive strange particle production may provide additional information. Furthermore, data on strange particle production in neutrino interactions are interesting for comparison with the corresponding results in hadronic and other leptonic interactions, and for tests of the Quark-Parton Model (QPM).

This paper is organized as follows. In sect. 2 information is given on experimental details. Inclusive rates for various final states containing strange particles are presented in sect. 3. The differential distributions in terms of both hadronic and leptonic variables are in sect. 4. In sect. 5 the total strange particle cross section is estimated. In sect. 6 attempts are made to evaluate the amount of strange particles deriving from the decay of charmed hadrons. The total charm particle production is estimated in the framework of the QPM. In sect. 7 the production of the resonances $K^*(890)$ and $\Sigma(1385)$ is discussed. The conclusions are summarised in sect. 8.

2. THE DATA

The data used in this work are charged current (CC) νp interactions observed in BEBC filled with hydrogen (fid. volume 18.9 m³, mass 1.1 tons) and exposed to a two-horn focussed wideband neutrino beam produced by 350 GeV protons from the SPS at CERN.

Muons with momentum greater than 3 GeV/c were identified by a two-plane External Muon Identifier (EMI), with detection efficiency varying from 40% at 3 GeV/c to 98.5% above 10 GeV/c.

Events were accepted as CC interactions if they had an identified single μ^- and total visible energy above 5 GeV. Approximately 7800 events fulfilled these requirements, and the distribution of their total energy, corrected for losses due to undetected neutral particles [11], peaks at 20 GeV and has an average value of 42 GeV.

For the work reported here, the further requirement was set that the effective mass of the hadronic system, W , be larger than 1.5 GeV, so as to be above the strange particle production threshold. Thus the CC sample finally used consisted of 6770 events with $\langle E_v \rangle = 43$ GeV, $\langle W \rangle = 4.6$ GeV and average squared four-momentum transfer $\langle Q^2 \rangle = 7$ GeV². A search was made for neutral strange particles associated with these events.

Neutral strange particles were identified by their characteristic decay. A path of at least 1 cm before decay, a decay point at least 10 cm from the bubble chamber wall and a proper time τ not exceeding 6 mean lifetimes were required. It was checked that 1 cm is enough to avoid losses of V^0 due to overlapping tracks near the vertex.

Mass assignments were done by kinematic fitting. In 50 cases out of the total 552, the V^0 observed fitted both the $\Lambda \rightarrow p\pi^+$ and $K^0 \rightarrow \pi^+\pi^-$ decay hypotheses. The hypothesis with the higher fit probability was chosen. Because of the large γ conversion length in hydrogen, no attempt was made to separate Λ from Σ^0 . In the following, Λ always means $(\Lambda + \Sigma^0)$, while K^0 means $(K^0 + \bar{K}^0)$.

Each V^0 was weighted to account for neutral decay modes (including lost K_L^0), geometrical detection inefficiencies (decays within 1 cm from primary vertex and outside the fiducial volume) and scanning losses. The average combined weights for K^0 , Λ and $\bar{\Lambda}$ are 3.3, 1.7 and 1.7, respectively. Except for the mass distributions in sects 6 and 7, all the plots in the following refer to corrected numbers of V^0 .

3. RATES OF NEUTRAL STRANGE PARTICLE PRODUCTION

In the 6770 CC events investigated, 510 events (i.e. 7.5%) were found where at least one strange particle was seen to decay. In 42 of them the decay of two strange particles was observed. No case of 3 V^0 decays was seen.

The total numbers of K^0 , Λ and $\bar{\Lambda}$ seen are listed in table 1. They include the contributions of the $K^0 K^0$, $K^0 \Lambda$ and $\Lambda \bar{\Lambda}$ pairs observed: (e.g., an event with a $K^0 K^0$ pair is counted twice in the total K^0 count). The corresponding numbers corrected with the weights discussed in sect. 2 are in the second column of the table. From these numbers the inclusive production rates of the various V^0 or $2V^0$ systems can be calculated, relative to the total production rate of CC events (last column of the table). They represent the average multiplicity $\langle n \rangle$ of the strange particle V^0 or of the $2V^0$ system considered.

From the results that $\langle n(K^0) \rangle = 0.175 \pm 0.009$ and $\langle n(\Lambda) \rangle = 0.045 \pm 0.004$ one derives that the ratio of the inclusive cross sections for Λ and K^0 production is

$$\frac{\langle n(\Lambda) \rangle}{\langle n(K^0) \rangle} = \frac{\sigma(\Lambda)}{\sigma(K^0)} = 0.26 \pm 0.03. \quad (9)$$

It is interesting to compare these results with those for strange particle production in hadronic interactions. In a $\pi^+ p$ experiment at 16 GeV/c [12], where the total hadronic charge is +2 as in νp interactions and the c.m. energy is 5.56 GeV, not too different from the $\langle W \rangle = 4.6$ GeV of this experiment, the inclusive K^0 and Λ cross sections were found to be $(15.5 \pm 0.5)\%$ and $(4.4 \pm 0.3)\%$, respectively, of the inelastic cross section, and hence $\langle n(\Lambda) \rangle / \langle n(K^0) \rangle = 0.28 \pm 0.02$, very similar to what is found in this work.

For antineutrinos these quantities have been calculated in the $\bar{\nu} N$ experiment of ref. [4] and found to be

$$\frac{\langle n(\Lambda) \rangle}{\langle n(K^0) \rangle} = \frac{\sigma(\Lambda)}{\sigma(K^0)} = \frac{0.063 \pm 0.004}{0.164 \pm 0.009} = 0.38 \pm 0.03 .$$

As for the production of V^0 pairs, it can be seen in table 1 that the $K^0 K^0$ combination is about twice as frequent as the ΛK^0 combination.

Besides the inclusive rates, a quantity of interest is the fraction F of the CC events with at least one neutral strange particle, irrespective of its nature. The result is

$$F(V^0) = \frac{\# \text{ events with } \geq 1 V^0}{\# \text{ CC events}} = (17.4 \pm 0.8)\%. \quad (10)$$

This is in rough agreement with the value $(14 \pm 2)\%$ reported in the FNAL νp experiment [1] ($E_\nu > 10$ GeV). It is interesting to note that for $\bar{\nu} N$ interactions [4], in principle different from νp interactions, a similar value was obtained, namely $(16 \pm 1)\%$.

In fig. 1 the fractions $F(K^0)$ and $F(\Lambda)$ of the CC events containing at least one K^0 or at least one Λ are shown as functions of the incident neutrino energy E_ν . For the K^0 events, the rate increases strongly with increasing E_ν , while for the Λ events it remains approximately constant from ~ 10 to ~ 130 GeV.

4. DIFFERENTIAL DISTRIBUTIONS

4.1 Leptonic variables

In fig. 2 the fractions $F(K^0)$ and $F(\Lambda)$ of CC events with at least one K^0 or at least one Λ , respectively, are shown as functions of Q^2 . It can be seen that $F(K^0)$ increases smoothly with increasing Q^2 , from ~ 0.1 to ~ 100 (GeV/c) 2 , while $F(\Lambda)$ seems approximately constant. In the Q^2 region below ~ 0.1 (GeV/c) 2 , where one would expect contributions to K^0 and Λ production from the decay of charmed baryons quasi-elastically produced, the experimental points are high, but the errors are too large for this to be statistically significant.

The distributions of the same quantities as functions of W^2 are in fig. 3(a). The rates increase rapidly with W^2 , at least up to ~ 50 GeV 2 .

In fig. 3(b) the fraction $F(K^0)$ is plotted as a function of W^2 separately for the K^0 going forwards and backwards in the hadronic c.m.s. The two distributions are similar, but above $\sim 20 \text{ GeV}^2$ there are about twice as many K^0 produced forwards as backwards, for the same W^2 .

The Q^2 and W^2 dependence of V^0 production has been studied for $\bar{\nu}N$ interactions in ref. [4]. The quantities plotted there are not $F(V^0)$ but the average V^0 multiplicities, $\langle n(V^0) \rangle$, i.e. the ratio of the V^0 inclusive cross section to the CC cross section. We have verified on our data that plotting $\langle n(V^0) \rangle$ instead of the $F(V^0)$ presented in figs 2 and 3 does not change the trend of the distributions. The Q^2 dependence found in ref. [4] is similar to that observed here. For the W^2 dependence, a continuous growth is reported for $\bar{\nu}N$.

$F(K^0)$ and $F(\Lambda)$ are shown in figs 4(a) and 4(b) as functions of the Bjorken scaling variable $x_B = Q^2/2M\nu$, where ν is the energy transfer from the leptonic to the hadronic vertex and M is the proton mass. A clear decrease with increasing x_B is seen for K^0 , and the Λ points are consistent with a similar behaviour. This reflects the fact that sea-quark scattering is relatively more important for the events containing strange particles than for all CC events.

4.2 Hadronic variables

The distributions of all the K^0 and Λ produced is shown in fig. 5 in terms of the Feynman variable $x_F = 2p_L/W$ in the hadronic c.m.s. About twice as many K^0 are produced forwards as backwards, while the majority (over 70%) of the Λ are in the backward hemisphere. The asymmetry parameters $A = (N_F - N_B)/(N_F + N_B)$ are $+0.32 \pm 0.02$ for K^0 and -0.45 ± 0.06 for Λ . Once more the comparison with the π^+p results [12] is interesting. The values reported for that experiment are $+0.32 \pm 0.02$ and -0.56 ± 0.02 for K^0 and Λ , respectively, close to our results.

The squared transverse momentum distributions are shown in fig. 6 (the transverse momentum is relative to the axis of the hadronic shower). For both K^0 and Λ , they have been fitted with an exponential function

$\Lambda \exp(-B p_T^2)$. In the p_T^2 interval $0 - 0.5 \text{ (GeV/c)}^2$, the values of B are $5.3 \pm 0.5 \text{ (GeV/c)}^{-2}$ for K^0 and $(3.5 \pm 0.6) \text{ (GeV/c)}^{-2}$ for Λ . These values are essentially the same as reported for K^0 and Λ in $16 \text{ GeV/c } \pi^+ p$ interactions [12], namely $B(K^0) = 5.60 \pm 0.08$ and $B(\Lambda) = 3.48 \pm 0.09 \text{ (GeV/c)}^{-2}$, respectively, in the same p_T^2 interval.

The values of $\langle p_T \rangle$ and $\langle p_T^2 \rangle$ (over the whole p_T range) are $0.412 \pm 0.022 \text{ GeV/c}$ and $0.226 \pm 0.012 \text{ (GeV/c)}^2$, respectively, for K^0 , and $0.430 \pm 0.033 \text{ GeV/c}$ and $0.238 \pm 0.018 \text{ (GeV/c)}^2$ for Λ . These values are higher than those for non-strange charged hadrons, mostly pions, in the same vp interactions, $\langle p_T \rangle = 0.325 \text{ GeV/c}$ and $\langle p_T^2 \rangle = 0.155 \text{ (GeV/c)}^2$.

In table 2 the values of $\langle p_T^2 \rangle$ are listed for various intervals of W^2 , separately for forward and backward-going K^0 . An increase of $\langle p_T^2 \rangle$ with W^2 is observed for the forward-going K^0 , while there is no significant variation for the backwards ones. A similar effect was seen for pions in this vp experiment [13].

4.3 Energy distributions

The distribution in energy of the strange particles is studied in terms of the variable $z = E(V^0)/E(\text{HAD})$, i.e. of the ratio of the energy $E(V^0)$ carried by the V^0 considered, relative to the total hadronic energy $E(\text{HAD})$, in the lab. system.

Fig. 7 shows the distribution $dN(V^0)/dz$, for K^0 and Λ . On average, a K^0 carries $\sim 1/5$ and a Λ about $1/4$ of the total hadronic energy. The z -distribution of the positive and of the negative pions produced in the same events is shown for comparison. In these events, the pion carries, on average, $\sim 1/6$ of the total energy.

In fig. 8(a) the z distribution of the K^0 mesons normalized to the total number N of CC events, $1/N dN(K^0)/dz$, is compared with the corresponding results obtained in ep [14] and μp [15] interactions. The results of the νN experiment of ref. [3] are also plotted. Fig. 8(b)

shows the z distribution for the Λ , $1/N \, dN(\Lambda)/dz$, compared with μp results [15]. Notwithstanding the fact that the definition of the variable z is often different in different experiments, the comparison is meaningful, as we have verified that the distributions of our νp data do not change appreciably when the other definitions of z are used, except for very small z values. One can thus conclude that at least for $z > 0.2$ the distributions of the fractional energy carried by the K^0 and by the Λ are very similar in all leptonic interactions.

For $z > 0.2$, the function plotted in fig. 8 for the K^0 , can be interpreted as the fragmentation function $D_u^{K^0}(z)$ of the scattered u quark into a K^0 meson. Thus the fragmentation into K^0 seems independent, in first approximation at least, of the nature of the incoming lepton. As the W -range covered is not the same in the various experiments, the fragmentation function appears to depend only weakly on W .

5. ESTIMATION OF THE TOTAL STRANGE PARTICLE CROSS SECTION

An estimation of the total cross section for events with at least one strange particle, $\sigma(\text{SP})$, has been made starting from the assumptions that at these energies the production of more than two strange particles in one event, and of strange particles with $|S| > 1$ are negligible. As charged strange particles are in general not identified in this experiment, the following equalities are assumed to hold:

- (a) $\sigma(\Lambda) = \sigma(\Sigma^+) + \sigma(\Sigma^-)$
- (b) $\sigma(K_{\text{single}}^+) + \sigma(K_{\text{single}}^-) = \sigma(K_{\text{single}}^0)$
- (c) $\sigma(K^+ K^-) = \sigma(K^0 \bar{K}^0)$
- (d) $\sigma(K^0 K^-) + \sigma(\bar{K}^0 K^+) = \sigma(K^+ K^-) + \sigma(K^0 \bar{K}^0),$

where the σ 's are the inclusive cross sections for the indicated particles and the subscript "single" means that the corresponding particle is the only strange hadron produced. It must be remembered that, as stated in sect. 2, $\sigma(\Lambda)$ always means $\sigma(\Lambda) + \sigma(\Sigma^0)$, and $\sigma(K^0)$ means $\sigma(K^0) + \sigma(\bar{K}^0)$. The assumptions (a), (c) and (d) are borne out by the results obtained for strange particle production in 16 GeV/c $\pi^+ p$ interactions [12].

The total cross section $\sigma(\text{SP})$ can be written as

$$\sigma(\text{SP}) = \sigma(K_{\text{single}}) + \sigma(Y_{\text{single}}) + \sigma(K\bar{K}) + \sigma(KY) + \sigma(Y\bar{Y}). \quad (11)$$

($\sigma(K\bar{A})$ is taken as negligible).

From assumption (a) one deduces $\sigma(K^0 Y) = 2\sigma(K^0 \Lambda)$ and $\sigma(Y_{\text{single}}) = 2\sigma(\Lambda_{\text{single}})$, which gives

$$\sigma(Y) = 2\sigma(\Lambda) = \sigma(Y_{\text{single}}) + \sigma(KY) + \sigma(Y\bar{Y}). \quad (12)$$

The cross section for $K\bar{K}$ production can be expressed as

$$\sigma(K\bar{K}) = \sigma(K^0) - \sigma(K^0 Y) - \sigma(K_{\text{single}}^0) \quad (13)$$

and from assumptions (b) to (d) it follows

$$\sigma(K_{\text{single}}) = 2\sigma(K_{\text{single}}^0) = 2[\sigma(K^0) - \sigma(K^0 Y) - 4\sigma(K^0 \bar{K}^0)]. \quad (14)$$

With eqs (12) to (14), eq. (11) becomes

$$\sigma(\text{SP}) = 2[\sigma(\Lambda) + \sigma(K^0)] - 4[\sigma(K^0 \Lambda) + \sigma(K^0 \bar{K}^0)]. \quad (15)$$

Inserting the values given in table 1 for the ratios of these cross sections to $\sigma(\text{CC})$, one obtains

$$\sigma(\text{SP})/\sigma(\text{CC}) = 0.252 \pm 0.041. \quad (16)$$

Thus, the total strange particle cross section is approximately $\frac{1}{4}$ of the cross section for production of CC events, above the strange particle threshold.

6. CHARMED PARTICLE PRODUCTION

Of the processes (1) to (8) leading to strange particle production (see the introduction and the first column of table 3), the channels (6) to (8) involve the production and subsequent decay of a charmed hadron. Several attempts were made to find direct evidence for, and evaluate the importance of, these latter processes.

(a) The sample of CC events with 3-constraint kinematic fits was searched for unambiguous examples of charmed hadron production. Two cases of $D^*(2010)$ mesons and two of $\Lambda_c(2285)$ baryons were found and are reported in the literature [7,10]. In all four cases the charmed hadrons decayed into a K^- , not into a neutral strange particle.

(b) A search was made for events where the only strange particle produced was a Λ . Only the charm producing channels (6) and (7) can, in fact, lead to the production of a single baryon of strangeness -1 . No such event was found in the sample of events with a 3-C fit. An attempt was then made to search for these processes inclusively. In order to estimate the number of events where a Λ is the only strange particle produced, starting from the $1V^0$ and $2V^0$ inclusive rates, one has to know the ΛK^0 , $\Lambda \bar{\Lambda}$ and ΛK^+ rates. The first two, relative to the total CC cross section, are experimentally known (see table 1). For ΛK^+ , it was assumed that $\sigma(\Lambda K^+) = 1.4 \sigma(\Lambda K^0)$, on the basis of 16 GeV/c $\pi^+ p$ results [12]. The corrected number of single Λ events was then calculated to be 37 ± 54 . Because of the large error, which derives from the small number of $2V^0$ events observed, this result is consistent with, but provides no quantitative information for, charmed baryon production on a d_V or d_S quark.

(c) The invariant mass distributions of the $(K^0 \pi^+)$ and $(K^0 \pi^+ \pi^-)$ systems of all fitted and unfitted events were inspected for enhancements at the $D(1868)$ mass. No signals were seen (see fig. 9). Using a polynomial for the background, the upper limits for the D^0 and D^+ production rates (above the D threshold) are

$$\frac{\sigma(\nu p \rightarrow \mu^- (D^+ + K^0 \pi^+) + X)}{\sigma(\nu p \rightarrow \mu^- + X)_{W > 2.8 \text{ GeV}}} < 0.19\% \quad (95\% \text{ C.L.})$$

and

$$\frac{\sigma(\nu p \rightarrow \mu^- (D^0 + K^0 \pi^+ \pi^-) + X)}{\sigma(\nu p \rightarrow \mu^- + X)_{W > 2.8 \text{ GeV}}} < 1.2\% \quad (95\% \text{ C.L.})$$

Using the $(K^0\pi^+)$ and $(K^0\pi^+\pi^-)$ branching ratios for D meson decay reported in the PDG tables [16], the upper limits for the D^+ and D^0 production rates are 13% and 26%, respectively, of the total CC cross section, above D-threshold.

(d) The $(\Lambda\pi^+)$ mass spectrum presents a slight enhancement in the $\Lambda_c(2285)$ region, but statistically not significant (see fig. 10). As discussed elsewhere [10] these combinations show a kinematic behaviour different from pure phase space, which could be attributed to Λ_c production. No signal for charmed baryon production was observed in the $(\Lambda\pi^+\pi^-)$ and $(\Lambda\pi^+\pi^+\pi^-)$ mass spectra.

(e) If the total strange particle cross section, $\sigma(\text{SP})$, is determined and the relative importance of the eight channels (1) to (8) of strange particle production is known, then an estimation can be made of the total charmed particle cross section.

In sect. 5, $\sigma(\text{SP})$ has been estimated to be $(25.2 \pm 4.1)\%$ of the CC cross section above the strange particle threshold ($W > 1.5$ GeV). With the same procedure $\sigma(\text{SP})$ is found to be $(30.4 \pm 4.6)\%$ of $\sigma(\text{CC})$ for the events with $W > 3$ GeV, i.e. above charm threshold.

The relative importance of the eight channels of strange particle production can be calculated in the framework of the QPM. In table 3 the eight channels are listed with their weights that take into account the helicity factor, the Cabibbo suppression factors at production and decay, and the relative quark abundance in the proton target. For the channels (1) to (3) an additional factor $N_{s\bar{s}}$ is needed to describe the probability, per event, for associated production of two strange particles. The per cent contributions of the eight channels, listed in the last column of table 3, are calculated with the following assumptions:

(i) $\sin^2\theta = 0.05$.

(ii) The ratios between the quantities D_V , D_S , $\bar{U}$ and S , which represent the fractions of the proton momentum (integrated over x_B) carried by the corresponding valence (V) and sea (S) quarks have been taken to be

$$D_S/D_V = \bar{U}/D_V = AS/D_V = 0.26.$$

This value derives from the results of experiments on ν -interactions on isoscalar targets [17] which have determined the quantities

$$A = S/D_S = S/\bar{U}$$

$$B = Q + \bar{Q} = 3D_V + (A + 2A)D_S,$$

$$C = 2\bar{Q} = (4 + 2A)D_S$$

and is calculated taking $A = 1/3$, $B = 0.45$ and $C = 0.13$.

(iii) $N_{s\bar{s}}$ was taken to be 0.2, from the ratio $\sigma(SP)/\sigma_{inel}$ in π^+p interactions at 16 GeV/c ($W = 5.56$ GeV, to be compared with $\langle W \rangle = 5.55$ GeV for the CC sample used here, with $W > 3$ GeV).

The per cent contributions listed in table 3 are apparatus independent and are also independent of the nature of the strange or charmed particle produced.

Thus, the QPM, with the assumptions indicated, predicts that $\sim 34\%$ (the sum of channels (6) to (8) of the total strange particle cross section (at W -values large enough for charm threshold effects to be negligible) is due to processes involving the production of charmed hadrons and their decay into strange particles.

From the value of $\sigma(SP)/\sigma(CC)_{W > 3 \text{ GeV}}$ and the 34% contribution of the charm producing channel, one deduces the total charm production cross section, $\sigma(CP)$, relative to $\sigma(CC)$, to be

$$\sigma(CP)/\sigma(CC)_{W > 3 \text{ GeV}} = (0.105 \pm 0.015).$$

This is in agreement with the expectation based on the di-lepton rates [3,5,6]. It should be noted that our determination does not involve any assumption on the relative production rate of charmed mesons and baryons, and is independent of the values of the leptonic branching ratio of the various charmed hadrons.

The error given here is only that pertaining to the determination of $\sigma(\text{SP})$. The main uncertainty in the QPM calculation of the relative contributions of the various channels of strange particle production derives from the value chosen for $N_{s\bar{s}}$. However, the final result is not very sensitive to the $N_{s\bar{s}}$ value. In fact, varying $N_{s\bar{s}}$ by 30% changes the result for $\sigma(\text{CP})/\sigma(\text{CC})$ by less than one standard deviation of the quoted error.

7. RESONANCE PRODUCTION

Finally, we turn to the production of resonances with non-zero strangeness in νp interactions.

In fig. 9 the $(K^0\pi^+)$ and $(K^0\pi^+\pi^-)$ invariant mass distributions are shown. A clear $K^{*+}(890)$ signal is seen in the $(K^0\pi^+)$ mass distributions. A fit with a Breit-Wigner function for the resonance and a polynomial background attributes 72 ± 28 combinations to the $K^{*+}(890)$ resonance. This corresponds to a cross section ratio above the $K^{*+}(890)$ threshold (corrected for the K^0 weight and the $(K^+\pi^0)$ decay mode) of

$$\frac{\sigma(\nu p \rightarrow \mu^- K^{*+}(890) + X)}{\sigma(\nu p \rightarrow \mu^- + \bar{X})_{W > 1.8 \text{ GeV}}} = (5.5 \pm 2.0)\% .$$

It is interesting to note that this ratio is comparable with the value of $(4.1 \pm 2.7)\%$ obtained for the inclusive D^{*+} production above its threshold in this same νp experiment [7].

Performing a fit to the $(K^0\pi^+)$ mass spectrum separately for combinations going forward and backward in the hadronic c.m.s., we find $(58 \pm 19)\%$ and $(42 \pm 22)\%$ of the $K^{*+}(890)$ produced with $x_F > 0$ and $x_F < 0$, respectively.

The $(K^0\pi^-)$ mass spectrum presents no evidence for $K^{*-}(890)$ production. In $\bar{\nu}p$ interaction the opposite is found, namely evidence for $K^{*-}(890)$ and absence of $K^{*+}(890)$ [2].

In fig. 10 are shown the $(\Lambda\pi^+)$ and $(\Lambda\pi^+\pi^+\pi^-)$ invariant mass distributions. A clear $\Sigma^+(1385)$ signal is observed in the $(\Lambda\pi^+)$ distribution. A Breit-Wigner fit to the resonance, again with a polynomial background, yields 49 ± 12 events in the resonance region. This corresponds to a rate (corrected for the Λ weight and the other Σ^+ decay modes) of

$$\frac{\sigma(\nu p \rightarrow \mu^- \Sigma^+(1385) + X)}{\sigma(\nu p \rightarrow \mu^- + X)_{W > 1.5 \text{ GeV}}} = (1.4 \pm 0.4)\% .$$

8. CONCLUSIONS

From the study of neutral strange particle production in 6770 charged current νp interactions with $\langle E_\nu \rangle = 43 \text{ GeV}$ and $\langle W \rangle = 4.6 \text{ GeV}$, the following main conclusions can be drawn:

- (a) The production of at least one neutral strange particle occurs in $(17.4 \pm 0.8)\%$ of the cases.
- (b) The inclusive K^0 and Λ production cross sections are $(17.5 \pm 0.9)\%$ and $(4.5 \pm 0.4)\%$ of the total CC cross section. The ratio of Λ to K^0 production, is thus 0.26 ± 0.03 .
- (c) In the cases where 2 V^0 are produced, the $K^0\bar{K}^0$ combination is about twice as probable as the ΛK^0 combination.

- (d) The K^0 are produced mostly forwards, the Λ mostly backwards, in the hadronic c.m.s., with asymmetry parameters of $A(K^0) = + 0.32 \pm 0.02$ and $A(\Lambda) = - 0.45 \pm 0.06$.
- (e) The p_T^2 distributions for K^0 and Λ fitted with $\exp(-Bp_T^2)$ up to 0.5 (GeV/c)^2 yield $B(K^0) = 5.3 \pm 0.5 \text{ (GeV/c)}^{-2}$.
 $B(\Lambda) = 3.5 \pm 0.6 \text{ (GeV/c)}^{-2}$.
- (f) The results (a) to (e) are very similar to those obtained in a $16 \text{ GeV/c } \pi^+p$ experiment ($W = 5.6 \text{ GeV}$), which indicates that strange particle production in νp interactions has general characteristics similar, at least in first approximation, to those in the interactions of hadrons.
- (g) The fraction $F(K^0)$ of CC events containing at least one K^0 increases with increasing E_ν , Q^2 and W^2 (at least up to $W^2 \approx 50 \text{ GeV}^2$). For the fraction of Λ events, $F(\Lambda)$, no strong variation with E_ν , Q^2 and W^2 is observed.
- (h) The z distributions for K^0 and Λ , where z is the fraction of the total hadronic energy they carry, are very similar to those obtained in other lepton-hadron interactions, at least for $z > 0.2 \text{ GeV}$.
- (i) The total strange particle production cross section is estimated to be $(25.2 \pm 4.1)\%$ of the cross section for production of CC events with $W > 1.5 \text{ GeV}$.
- (j) Using the result that the total strange particle cross section is $(30.4 \pm 4.6)\%$ of the cross section for CC events with $W > 3 \text{ GeV}$ and the prediction of the QPM that $\sim 34\%$ of the events with strange particles in the final state derive from charm producing processes, the total charm particle production cross section is estimated to be $(10.5 \pm 1.5)\%$ of the CC cross section, above charm threshold.

- (k) Evidence is found for the production of $K^{*+}(890)$ with a rate comparable to $D^{*+}(2009)$ production, above the corresponding production thresholds. The production of $\Sigma^+(1385)$ is also clearly observed.

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TABLE CAPTIONS

- Table 1 Raw and corrected inclusive rates for K^0 , Λ and $\bar{\Lambda}$ production in CC events with $\langle E_\nu \rangle = 43$ GeV and $\langle W \rangle = 4.6$ GeV.
- Table 2 Values of $\langle p_T^2 \rangle$ for K^0 produced forward and backwards in the hadronic c.m.s., in various intervals of W^2 .
- Table 3 Weighting factors and per cent contributions of the eight channels of νp interaction to the total strange particle cross section.

TABLE 1

Particle	Observed number	Corrected number	$\langle n \rangle = \frac{\sigma(V^0)}{\sigma(CC)}$
K^0	359	1185.7	0.175 ± 0.009
Λ	180	305.5	0.045 ± 0.004
$\bar{\Lambda}$	13	22.1	0.003 ± 0.001
Particle combinations	Observed number	Corrected number	$\langle n \rangle = \frac{\sigma(2V^0)}{\sigma(CC)}$
$K^0 \bar{K}^0$	20	217.8	0.032 ± 0.007
ΛK^0	18	102.7	0.015 ± 0.004
$\bar{\Lambda} \bar{K}^0$	4	11.6	0.002 ± 0.001

TABLE 2

W^2 (GeV ²)	$\langle p_T^2 \rangle$ for K^0 forward (GeV/c) ²	$\langle p_T^2 \rangle$ for K^0 backward (GeV/c) ²
2.25 - 25	0.171 ± 0.09	0.205 ± 0.031
25 - 80	0.224 ± 0.020	0.237 ± 0.033
> 80	0.343 ± 0.059	0.234 ± 0.051
all	0.226 ± 0.015	0.224 ± 0.021

TABLE 3

Channel	Weighting factors	Per cent contributions to strange particle cross section
(1) $\nu d_V + \mu^- u + s\bar{s}$	$D_V \cdot \cos^2 \theta \quad .N_{ss}$	47.1
(2) $\nu d_S + \mu^- u + s\bar{s}$	$D_S \cdot \cos^2 \theta \quad .N_{ss}$	12.3
(3) $\nu \bar{u} + \mu^- \bar{d} + s\bar{s}$	$\frac{1}{3} \bar{U} \cdot \cos^2 \theta \quad .N_{ss}$	4.2
(4) $\nu \bar{u} + \mu^- \bar{s}$	$\frac{1}{3} \bar{U} \cdot \sin^2 \theta$	1.1
(5) $\nu s(+\bar{s}) + \mu^- u(+\bar{s})$	$S \cdot \sin^2 \theta$	1.1
(6) $\nu d_V + \mu^- c \downarrow s$	$D_V \cdot \sin^2 \theta \cdot \cos^2 \theta$	11.8
(7) $\nu d_S + \mu^- c \downarrow s$	$D_S \cdot \sin^2 \theta \cdot \cos^2 \theta$	3.1
(8) $\nu s(+\bar{s}) + \mu^- c(+\bar{s}) \downarrow s$	$S \cdot \cos^2 \theta \cdot \cos^2 \theta$	19.5

} 34.4%

FIGURE CAPTIONS

- Fig. 1 Fractions of the CC events with at least one K^0 , $F(K^0)$, or at least one Λ , $F(\Lambda)$, in the final state as functions of the incident neutrino energy E_ν .
- Fig. 2 Fractions of the CC events with at least one K^0 or at least one Λ as functions of the squared four-momentum transfer Q^2 .
- Fig. 3 (a) Fractions of the CC events with at least one K^0 or at least one Λ as functions of the hadronic effective mass squared, W^2 .

(b) Fraction $F(K^0)$ as a function of W^2 plotted separately for K^0 going forwards and backwards in the hadronic c.m.s.
- Fig. 4 (a) Fraction of CC events with at least one K^0 in the final state, $F(K^0)$, as a function of the Bjorken variable $x_B = Q^2/2 M\nu$.

(b) x_B dependence of the fraction of CC events with at least one Λ , $F(\Lambda)$.
- Fig. 5 Distribution in the Feynmann variable x_F of the K^0 (solid line) and of the Λ (dashed line), normalised to the total number N of CC events.
- Fig. 6 p_T^2 -distributions of the K^0 and of the Λ , normalised to the total number N of CC events. The curves are fits with the function $A \exp(-B p_T^2)$ over the range of $p_T^2 = 0$ to 0.5 $(\text{GeV}/c)^2$.

FIGURE CAPTIONS (Cont'd)

Fig. 7 Numbers of K^0 or of Λ normalised to the total number N of CC events, as functions of $z = E(V^0)/E(\text{HAD})$, where $E(V^0)$ is the lab energy carried by the strange particle V^0 considered and $E(\text{HAD})$ is the total lab energy of the hadronic system (corrected). The z distribution of the pions produced in the same events is shown for comparison (dashed). The curves are drawn to guide the eye.

Fig. 8 (a) z distribution of the K^0 , normalised to the total number N of CC events, for νp interactions, compared with the results obtained in νN , $e p$ and μp interactions.

(b) z distribution of the Λ , normalized to the total number N of CC events, for νp interactions, compared with the results obtained in μp interactions.

Fig. 9 Invariant mass distributions of the $(K^0 \pi^+)$ and $(K^0 \pi^+ \pi^-)$ systems. The solid lines are fits with a Breit-Wigner function and the background shown (dashed lines).

Fig. 10 Invariant mass distributions of the $(\Lambda \pi^+)$ and $(\Lambda \pi^+ \pi^+ \pi^-)$ systems.

Fig. 1

Fig. 2

Fig. 3

Fig.4

Fig. 5

Fig.6

Fig. 7

Fig. 8

Fig. 9

Fig. 10