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Neutral Strange Particle Production in Neutrino and Antineutrino Charged Current Interactions on Protons

Birmingham-CERN-Imperial College-München (MPI)-Oxford-
University College London Collaboration (WA21)

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Abstract. The production of the neutral strange particles K^0 , Λ and $\bar{\Lambda}$ in νp and $\bar{\nu} p$ charged current interactions is studied in an experiment with the Big European Bubble Chamber. Mean multiplicities are measured as a function of the event variables E_ν , W^2 and Q^2 and of the hadron variables x_F , z and p_T^2 . $K^{*\pm}(892)$ and $\Sigma^{*\pm}(1385)$ signals are observed, whereas there is no evidence for $\Sigma^{*-}(1385)$ production in νp scattering. Forward, backward and total mean multiplicities are found to compare well with the predictions of an empirical model for deep-inelastic reactions in the case of the strange mesons K^0 and $K^{*\pm}(892)$ but less so for the strange baryons Λ , $\bar{\Lambda}$ and $\Sigma^{*\pm}(1385)$. The strange baryon multiplicities are used to obtain the decuplet to octet baryon production ratio and to assess the probabilities of a uu or ud system to break up.

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1. Introduction

The production of neutral strange particles is of interest for several reasons. They are the only class of hadrons which can be well identified over a broad kinematic range in a hydrogen bubble chamber, and as such yield comparatively unbiased information. Some of the features of the data may be explained in terms of the quark-parton model. For both νp and $\bar{\nu} p$ interactions, the most important strangeness production mechanism is believed to be the associated production of $s\bar{s}$ quark pairs in the fragmentation process. Strange particles can also be produced through Cabibbo-suppressed flavour-changing interactions, both directly and *via* charm decay, and by interactions with the strange sea. A summary of channels for strangeness production and expected relative rates is given in table 1. The symbols U, D and S represent the proton momentum fractions (integrated over Bjorken- x) carried by u , d and s quarks, $N_{s\bar{s}}$ is the probability per event of producing an $s\bar{s}$ quark pair, and the subscripts v and s denote valence and sea quark quantities.

There has also been considerable interest in the fragmentation of the target remnant consisting of two or four quarks, which in terms of QCD represents a coloured, spatially extended object [1]. This has different flavour properties in νp and $\bar{\nu} p$ reactions which manifest themselves in different properties of the backward going hadron system, and particularly of baryon production. The production of various baryons that yield neutral strange particles among their decay products may be studied using our data, where the beam used selects the valence quark composition of the target remnant system.

There have been several previous studies of neutral strange particle production using ν and $\bar{\nu}$ beams [2–29], including one by this collaboration [12], which used a subset of the ν data. The present study is based on the highest statistics data yet reported for neutral strange particle production in νp and $\bar{\nu} p$ charged current (CC) interactions. The experiment, WA21, was performed with the bubble chamber BEBC filled with hydrogen. In the 16896 (9764) $\nu(\bar{\nu})$ CC events selected, 831 (401) K^0 , 491 (344) Λ and 27 (9) $\bar{\Lambda}$ particles have been observed. This allows strange baryon resonances to be studied.

2. Experimental Procedure

The data come from several exposures of the Big European Bubble Chamber (BEBC) to the horn-focussed CERN SPS wide band ν and $\bar{\nu}$ beams, derived from both 350 and 400 GeV protons incident on a beryllium target. BEBC was filled with liquid H_2 , giving a fiducial mass of 1.1 t in a fiducial volume of 18.1 m³.

The identification of CC events is based on the two downstream planes of the BEBC External Muon Identifier (EMI) system [30–32]. For later runs this was supplemented by a single downstream plane of the Internal Picket Fence (IPF) [33–35]. The association of hit patterns in several of the detector planes with the extrapolations of measured tracks which leave the bubble chamber identifies muons, thus flagging CC events.

For the purposes of this analysis, a CC event must satisfy the following criteria :

1. There must be at least one EMI/IPF identified muon with momentum $p_\mu > 3$ GeV; if there is more than one muon, that with the highest transverse momentum with respect to the incident $\nu(\bar{\nu})$ direction is selected, other muon candidates being relabelled as pions.
2. The selected muon must have the correct charge (positive in $\bar{\nu}p$, negative in νp reactions).
3. The event must have at least 3 charged particles (including the muon). In the $\bar{\nu}p$ reaction there are events with no charged particle besides the muon ('one-prong' events). These events are excluded from the main sample as the scanning efficiency for such events is low, and the event energy may not reliably be estimated.
4. The event must have a visible energy (muon plus hadronic) greater than 5 GeV.
5. The vertex of the event must lie within a reduced fiducial volume, the boundaries of which were at closest 15 cm from the chamber walls.

The sample passing these cuts has overall scanning, electronic and geometrical efficiencies each of which are found to be better than 95%.

Transverse momentum balance is used to estimate the true event energy, correcting for missing neutral hadrons [36]. A further cut is then made to select events with a total hadronic mass W greater than 1.5 GeV; this ensures that all events considered are above the kinematic threshold for neutral strange particle production.

The properties of the resulting sample of 16896 (9764) νp ($\bar{\nu}p$) CC events are summarized in table 2. E_ν is the laboratory energy of the incident (anti)neutrino, W is the effective mass of the total hadronic system and Q^2 is the negative square of the 4-momentum transfer between the (anti)neutrino and the target proton.

Measurement errors, particle misidentification and the estimation of the (anti)-neutrino energy may give rise to smearing effects in the variables E_ν , W , Q^2 , x_F , z and p_T . In the present analysis however these effects were found to be small and no corrections were applied for them.

3. Identification of neutral strange particles

The two-body decays of neutral strange particles ($K^0 \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$, $\bar{\Lambda} \rightarrow \bar{p}\pi^+$) give characteristic ‘vee’-shaped pairs of tracks (V^0) in the bubble chamber, as do the conversions of photons (γ) into e^+e^- -pairs. The kinematics program attempts to fit in turn the K^0 , Λ , $\bar{\Lambda}$ and γ hypotheses to the observed V^0 s, unless one of the V^0 tracks has been clearly identified so as to exclude the particular hypothesis. The resulting incident V^0 trajectory is extrapolated backwards to see if it is consistent with an origin at a measured vertex.

After this procedure most V^0 s are uniquely identified, but there remains a small number where there is some ambiguity as to the correct mass hypothesis. This is due in part to the overlap of the kinematic regions for the different decays, and also to the effective broadening of these regions by measurement errors.

Decays ambiguous with the γ hypothesis have a characteristic small transverse momentum of the decay products with respect to the V^0 line of flight. They were all assigned to the γ category. Decays ambiguous between the K^0 and Λ hypotheses are determined to be mainly ($\sim 75\%$) Λ s, on the basis of the distribution of Θ , where Θ is the angle in the V^0 rest frame between the positive decay particle and the V^0 boost direction from the laboratory system. The decays are assigned to the Λ category and a correction is applied for the fraction ($\sim 25\%$) of ambiguous decays that are K^0 s.

To select the final sample of V^0 s a fiducial volume is defined (which is larger than that used for CC event vertices), the decay lengths are required to be greater than 1 cm and the proper decay time to be less than six mean lifetimes.

The V^0 production rates given in the subsequent sections have been corrected for scanning losses, for the cuts applied in the decay length and the lifetime, and for neutral decay modes, by applying appropriate weights to each V^0 . The inverse average weights for K^0 , Λ and $\bar{\Lambda}$ are 0.26 (0.26), 0.56 (0.62) and 0.47 (0.58) for ν ($\bar{\nu}$) scattering respectively. The uniquely selected K^0 s and Λ s give measured lifetimes (not shown) which agree within 1σ with the Particle Data Group values [37].

4. Global Production Rates

In table 3 the mean multiplicity $\langle n(V^0) \rangle$ for each V^0 type is given, where :

$$\langle n(V^0) \rangle = \frac{\text{Weighted number of } V^0\text{s of given type}}{\text{Number of CC events}}.$$

From the discussion in section 5 it will become clear that the differences between νp and $\bar{\nu} p$ scattering in the mean K^0 and $\bar{\Lambda}$ multiplicities are due to the different mean W of the νp and $\bar{\nu} p$ samples, while the mean Λ multiplicity at fixed W is in fact larger in $\bar{\nu} p$ than in νp scattering. Table 4 gives the number of events ($N_{obs}(V_i)$) with a given combination of seen V^0 decays. Given the average weight of a V^0 (and thus the probability to observe its decay), $N_{obs}(V_i)$ may be expressed as a linear combination of the number of events $N_{cor}(V_j)$ with a given combination of V^0 s (seen or unseen). Solving this set of equations yields $N_{cor}(V_j)$. The fraction of CC events with a given combination of V^0 s is :

$$F(V_i X) = \frac{N_{cor}(V_i)}{\text{Number of CC events}}$$

where V_i denotes the V^0 combination and X the non- V^0 hadrons. The fractions $F(V_i X)$ are given in table 5.

The mean multiplicities of K^0 , Λ and $\bar{\Lambda}$ are given in table 6 for this and other experiments. As some of the production rates seem to depend strongly on E_ν (see the next section) the mean E_ν is given in each case. All the multiplicities are in reasonable agreement with previously published values for experiments conducted with comparable mean E_ν .

In the following the measured strange particle rates will also be compared with the predictions of a semi-empirical quark model of hadronization [38] denoted hereafter as ‘the Wells model’. This model gives absolute predictions for particle and resonance multiplicities, including those for tensor mesons. In the model the hadronic system produced in deep-inelastic reactions is divided into a ‘beam residue’, a ‘central component’ and a ‘target residue’, where in (anti)neutrino-induced reactions the beam residue is defined as the meson (or its decay products) containing the struck quark. The central component is a function of W only, whereas the beam and target residues are independent of W but do depend on the beam and target quark contents. Besides the mesons of the $J^P = 0^-$ and 1^- multiplets ($l = 0$), the model includes the production of mesons of the $J^P = 0^+, 1_{a_1}^+, 2^+, 1_{b_1}^+$ multiplets, for which the orbital angular momentum (l) between the quark and the antiquark forming the meson is 1. The parameters of the model are a strangeness suppression factor (λ) in meson production, the coefficients a and b in the central component

expression $\langle \text{primordial multiplicity} \rangle = a \cdot \ln(W/b)$ and a high- l meson excitation cut-off l_{max} . The parameters ($\lambda_{meson} \simeq 0.3, \lambda_{baryon} \simeq 0.1, a = 1.34, b = 4.0$ GeV and $l_{max} = 1$) were determined from hadron interaction data. The model has neither a free pseudoscalar/vector (P/V) ratio nor a free η/π ratio. They are set to 1/3 and 1/1 respectively, as expected from spin-statistics.

In table 7 the forward, backward and total V^0 multiplicities are compared with the predictions of the Wells model (the forward hemisphere is defined by the direction of the virtual W -boson in the overall hadronic system). The agreement is good for total multiplicities, however the model overestimates the forward K^0 rates and underestimates the backward K^0 and forward Λ rates, both in νp and in $\bar{\nu} p$ scattering. However, one should note that there is an additional systematic error of the mean forward and backward multiplicities due to experimental smearing.

Further comparisons with the Wells model are made in section 7 for the $K^{*\pm}(892)$ and $\Sigma^{*\pm}(1385)$ resonances.

5. Dependence of the Mean Multiplicities on E_ν, W^2, Q^2 and x_B

A strong increase of the mean K^0 multiplicity with E_ν, W^2 and Q^2 in both the νp and the $\bar{\nu} p$ reaction is observed (Figs. 1–3). As can be seen from Fig. 4 the K^0 s are predominantly produced in the forward region for $W \gtrsim 2.5$ GeV. The mean Λ multiplicity on the other hand shows a weak increase with E_ν, W^2 and Q^2 in νp (Figs. 1a, 2a, 3a) and a stronger increase in $\bar{\nu} p$ scattering (Figs. 1b, 2b, 3b).

The mean K^0 multiplicity decreases strongly with increasing x_B , both in νp and $\bar{\nu} p$ scattering (Fig. 5). (x_B is defined as $Q^2/(2M_p\nu)$, where M_p is the proton mass and ν is the leptonic energy transfer in the laboratory system). The mean Λ multiplicity is independent of x_B in the νp sample, whereas it is decreasing with x_B in the $\bar{\nu} p$ sample. The latter observation is interpreted as a contribution to Λ production from scattering off the sea.

Since the variables E_ν, W, Q^2 and x_B are not independent ($W^2 - M_p^2 = Q^2(\frac{1}{x_B} - 1)$), there are correlations between the dependences on the variables. From Figs. 1–5 it is evident that the strongest dependence is on W^2 .

The results on mean multiplicities are essentially unchanged if fractions instead of multiplicities are used, and they are insensitive to a reclassification of the ambiguous K^0/Λ candidates as K^0 .

The experimental dependences obtained are compared with the predictions of the LUND Monte Carlo (LEPTO 4.5, JETSET 6.3 [39]). The default values were used for all parameters except the s/u ratio, which was changed to 0.15. This reproduced best the observed K^0 multiplicity, and has previously been found to describe adequately the V^0 production in νD and $\bar{\nu} D$ interactions [20]. In all the cases considered in Figs. 1–5 the LUND Monte Carlo reproduces the experimental behaviour qualitatively.

6. Single Particle Distributions

Examination of the single particle distributions of neutral strange particles allows an investigation of the dynamics of fragmentation. It also reveals the details of V^0 production, and in particular may give evidence as to the fragmentation region (target, central or current) in which this production occurs.

6.1 p_T^2 Distributions

The distributions of p_T^2 with respect to the current (virtual boson) axis for both K^0 s and Λ s are shown in Fig. 6. An approximately exponential fall is evident in both cases. This is in agreement with the LUND model predictions and the observations for hadroproduction in general. Fits of the form $a \exp(bp_T^2)$ to the experimental distributions in the region $p_T^2 < 0.5 \text{ GeV}^2$ yield the values of b given in table 8. There is no strong evidence of the high- p_T^2 tail reported in [19]. There is apparently some deviation from the exponential fall in the K^0 distributions, especially in the νp case at $p_T \approx 0.75 \text{ GeV}$. This is possibly an indication of charm production.

6.2 Feynman- x (x_F) Distributions

The x_F distributions for K^0 s and Λ s are shown in Fig. 7. (Feynman- x_F is the longitudinal momentum fraction $2p_L^*/W$ in the hadronic cms). The K^0 s are clearly peaked at x_F slightly greater than zero ($\langle x_F^{\nu p} \rangle = 0.093 \pm 0.007$, $\langle x_F^{\bar{\nu} p} \rangle = 0.149 \pm 0.011$) and favour the (forward) current region, though extending into the target region for both νp and $\bar{\nu} p$ scattering. The Λ s are more broadly distributed in x_F , but are clearly at lower mean x_F ($\langle x_F^{\nu p} \rangle = -0.17 \pm 0.02$, $\langle x_F^{\bar{\nu} p} \rangle = -0.26 \pm 0.02$) than the K^0 s. The $\bar{\Lambda}$ s (not shown) seem very centrally produced for both beam types

($\langle x_F^{\nu p} \rangle = 0.08 \pm 0.04$, $\langle x_F^{\bar{\nu} p} \rangle = 0.07 \pm 0.07$). A point-by-point comparison between the νp and $\bar{\nu} p$ distributions indicates that the Λ s are more backwards and the K^0 s slightly more forwards in $\bar{\nu} p$ than in νp scattering.

There is agreement on the broad features of the K^0 and Λ x_F distributions between this and previous studies. For the $\bar{\Lambda}$ s similar results to those of the present study have been found in a ν Ne experiment [19].

The LUND model reproduces the observed x_F distributions for K^0 s and Λ s in the ν sample. In the $\bar{\nu} p$ reaction, however, the K^0 s seem more forwards in the data than in the LUND model. The observed Λ distribution seems slightly more backward than the LUND prediction. Similar observations have been made in the study of νD and $\bar{\nu} D$ reactions [20].

6.3 z Distributions

The distributions of the energy fraction $z = E_{lab}(V^0)/E_{lab}(\text{all hadrons})$ are shown in Fig. 8. The features seen in the x_F plots are again observed, though less clearly: the K^0 s in the $\bar{\nu} p$ data are more forward (higher z) than in the νp data. Conversely, the Λ s in the νp data favour higher z values than in $\bar{\nu} p$ scattering.

These z distributions are in agreement with those reported in previous experiments. As with the x_F distributions, the LUND Monte Carlo reproduces the K^0 and Λ distributions in νp and the Λ distribution in $\bar{\nu} p$ scattering, while the K^0 distribution in $\bar{\nu} p$ scattering is more forward than the Monte Carlo prediction.

7. Resonance Production

7.1 Extraction of $\Sigma^{*\pm}(1385)$ and $K^{*\pm}(892)$ Signals

Fits have been made to the distributions dN/dm of the $\Lambda\pi^\pm$ and $K^0\pi^\pm$ invariant mass m using the MINUIT [40] function minimization package :

$$\frac{dN}{dm} = BG \cdot (1 + \varepsilon \cdot R). \quad (1)$$

The background BG is parameterized as :

$$BG = \alpha(m - m_{th})^\beta \exp [-(\gamma m + \delta m^2)] \quad (2)$$

with the threshold mass $m_{th} = m_\pi + m_\Lambda$ and $m_{th} = m_\pi + m_{K^0}$ respectively. The resonance term R has the standard relativistic Breit-Wigner form [41] :

$$R = \frac{\Gamma}{(m^2 - m_0^2)^2 + m_0^2 \Gamma^2} \left(\frac{m}{q} \right) \quad (3)$$

with

$$\Gamma = \Gamma_0 \left(\frac{q}{q_0} \right) \frac{m_0}{m} , \quad (4)$$

where q is the decay momentum in the rest frame of the two-particle system of mass m (q_0 corresponding to m_0) and $\alpha, \beta, \gamma, \delta$ and ε are the free parameters to be determined in the fit.

The $\Sigma^{*\pm}(1385)$ mass m_0 and width Γ_0 were taken as 1382 MeV and 36 MeV respectively; the $K^{*\pm}(892)$ values are 892 MeV and 51 MeV. (The experimental mass resolution is ≈ 5 MeV and so may be neglected.)

7.2 Production of $\Sigma^{*\pm}(1385)$

The $\Lambda\pi^+$ and $\Lambda\pi^-$ invariant mass plots are given in Figs. 9 and 10; the $\Sigma^*(1385)$ signals resulting from the corresponding fits are summarized in table 9. Since the mass fits were performed for the total sample and for the forward and backward hemispheres independently, the mean forward and backward multiplicities do not exactly add up to the total mean multiplicity. The numbers of resonance decays are corrected for the geometrical efficiency for detecting the Λ and the branching ratios of $(88 \pm 2)\%$ for $\Sigma^{*\pm}(1385) \rightarrow \Lambda\pi^\pm$ and of $(64.1 \pm 0.5)\%$ for $\Lambda \rightarrow p\pi^-$. The upper limits quoted are at the 2σ (95.6%) level. The mean Σ^* multiplicities were calculated using the numbers of CC events with $W > 1.8$ GeV, the approximate threshold for Σ^* production. These numbers are 16310 and 9074 for νp and $\bar{\nu} p$ scattering without an x_B cut, and 7623 and 4528 with $x_B > 0.2$, respectively.

There is clear evidence for $\Sigma^{*+}(1385)$ production both in νp and $\bar{\nu} p$ scattering; backwards production is favoured over forwards production, especially in the νp reaction. For $\Sigma^{*-}(1385)$ a weak signal is seen in the $\bar{\nu} p$ reaction, but there is no evidence for $\Sigma^{*-}(1385)$ production in νp scattering.

In table 10 the extracted multiplicities are compared with the predictions of the Wells model [38]. In the νp sample, the predictions are only in rough agreement with the observations, the observed $\Sigma^{*+}(1385)$ signal being about half that predicted. The non-observation of the $\Sigma^{*-}(1385)$ is as predicted; this implies that central production of baryons is not significant, and should be even less important in the $\bar{\nu} p$ sample where the mean W is lower. In the $\bar{\nu} p$ case the predictions are significantly smaller than the observations.

7.3 Production of $K^{*\pm}(892)$

The $K^0\pi^+$ and $K^0\pi^-$ invariant mass plots are shown in Figs. 11 and 12; the $K^*(892)$ -signals resulting from the corresponding fits are summarized in table 11. Again, since the mass fits were performed for the total sample and for the forward and backward hemispheres independently, the mean forward and backward multiplicities do not exactly add up the total mean multiplicity. The corrected multiplicities take into account the branching ratios for $K^{*\pm}(892) \rightarrow K^0\pi^\pm$ (67%) and $K^0 \rightarrow \pi^+\pi^-$ ($(34.3 \pm 0.2)\%$), and also the geometrical losses. Clear $K^{*+}(892)$ signals are seen in both νp and $\bar{\nu} p$ scattering (see Fig. 11). There is also a significant $K^{*-}(892)$ signal in $\bar{\nu} p$, but not in νp scattering (Fig. 12).

The $K^{*\pm}$ production is predominantly forward in both νp and $\bar{\nu} p$ scattering (table 11). The experimental smearing and model uncertainties mean that the measurements and predictions of the forward and backward multiplicities must be treated with some caution. The measured forward-backward asymmetries $A = \frac{F-B}{F+B}$ are given in table 12. The K^{*+} is the more forward in the νp reaction, while in $\bar{\nu} p$ it is the K^{*-} . This is the situation expected, as the K^{*+} (a $u\bar{s}$ system) may contain the leading quark in νp , while the same is true for the K^{*-} ($\bar{u}s$) in $\bar{\nu} p$ scattering (see table 1). The asymmetry found for K^0 s lies between the values found for K^{*+} and K^{*-} in both νp and $\bar{\nu} p$ scattering.

The mean $K^{*\pm}$ multiplicities are compared with the predictions of the Wells model [38] in table 13. There is quite good agreement with the predictions for the total mean multiplicities of $K^{*\pm}(892)$ in νp scattering, while in $\bar{\nu} p$ scattering the predictions are only reasonable, although the experimental errors are quite large.

8. Diquark Break-up

When the ν or $\bar{\nu}$ interacts with a valence quark, it leaves two valence quarks in the target (target remnant). It is not known if these can form bound or quasi-bound states (often referred to as diquarks); it is thought that for such coloured, spatially extended objects the colour-magnetic force may be attractive [1]. Such a force may make the two quarks more likely to end up in the same hadron. Here we use the term “diquark” only for the target remnant in case of scattering on a valence quark without addressing the question of a colour force between the two quarks.

The $\Sigma^{*+}(1385)$ is a uus quark system, the $\Sigma^{*-}(1385)$ a dds system. In νp valence interactions the target remnant is a uu diquark. Thus, in the simplest case, it need only acquire an s quark to form a $\Sigma^{*+}(1385)$ (no diquark break-up, see Fig. 13a)

while to form a $\Sigma^{*-}(1385)$ neither quark from the diquark can be used; we call this case “diquark exclusion” (see Fig. 13c). If the ν scattering is off a sea quark then the target remnant will contain all three valence quarks and a $\Sigma^{*+}(1385)$ or a $\Sigma^{*-}(1385)$ may be produced which contains respectively the uu diquark or a d quark from the target remnant.

In $\bar{\nu}p$ valence interactions the target remnant is a ud diquark system. To produce either charged $\Sigma^{*}(1385)$ state only one quark from the diquark can be used; there must be a ud break-up (see Fig. 13b,d). As with the νp case, $\bar{\nu}$ scattering off sea quarks can also give rise to both charged $\Sigma^{*}(1385)$ states from the uud part of the target remnant, but with $\Sigma^{*+}(1385)$ favoured over $\Sigma^{*-}(1385)$ (see table 14).

In table 14 the Λ , Σ^0 , $\Sigma^{*0}(1385)$, $\Sigma^{*+}(1385)$, and $\Sigma^{*-}(1385)$ baryons are classified as to how many valence quarks from the target remnant may at most be used for their formation in ν and $\bar{\nu}$ interactions on valence and sea quarks (see also [42, 14, 15]).

The absence of a $\Sigma^{*-}(1385)$ signal in the νp sample (see table 9) indicates that contributions to $\Sigma^{*\pm}(1385)$ production from the exclusion of the spectator diquark, from scattering off sea quarks and from baryon-antibaryon production are all negligible (see table 14).

The measured rates in $\bar{\nu}p$ scattering (see table 9) have quite large relative errors; however, the uncut (all x_B) $\Sigma^{*+}(1385)$ rate seems somewhat larger than that for $\Sigma^{*-}(1385)$, while the rates for $x_B > 0.2$ (where the sea interactions will be largely excluded) are approximately equal. Thus, there is some indication of sea quark interactions contributing. The presence of a signal for $\Sigma^{*\pm}(1385)$ production in $\bar{\nu}p$ scattering for $x_B > 0.2$ suggests the need for diquark break-up (see table 14) — the creation of baryons containing only one quark of the spectator diquark — and that the effect is not due only to sea interactions.

Furthermore, the predictions of the Wells model [38] for the contributions from ‘central’ production (baryon-antibaryon production in this case) are factors of $\gtrsim 2.5$ smaller than the observed rates, despite good agreement for other rates, in νp , $\bar{\nu}p$ scattering and other processes. Thus, it would seem that diquark break-up is required to account for the observations.

8.1 Extraction of Diquark Break-up Probabilities

The Λ , $\bar{\Lambda}$ and $\Sigma^{*\pm}(1385)$ rates may be used to investigate the probabilities that the uu and ud diquark systems break up. It has been predicted [1] that the ud system may have a lower break-up probability than the uu (or dd) system because of an attractive colour-magnetic force.

The same analysis also determines the ratio R_D of decuplet (spin- $\frac{3}{2}$) to octet (spin- $\frac{1}{2}$) baryon production. The asymptotic $SU(6)$ value for this ratio is 2 which

comes from counting the possible spin states. It is expected that this ratio will be the same in νp and $\bar{\nu} p$ interactions.

Defining :

$$\begin{aligned}\gamma_q &= \text{probability of creating a } q\bar{q} \text{ pair from the sea, with} \\ \gamma_u &= \gamma_d \text{ and } \gamma_u + \gamma_d + \gamma_s = 1\end{aligned}\tag{5}$$

where the WA21 published s/u ratio [43] $\gamma_s/\gamma_u = 0.203 \pm 0.014$ has been used to derive the probabilities γ_s and γ_u , and

B_{qq} = break-up probability of the qq system

R = probability that a baryon (formed after diquark break-up) has spin $\frac{3}{2}$

where $R = \frac{R_D}{(1+R_D)}$, then the production rates for Λ s and charged Σ^* s may be constructed. Sea quark scattering and contributions from diquark exclusion will be neglected, as well as $\Sigma^{*\pm}$ production due to baryon-antibaryon production. The two latter assumptions are suggested by the absence of $\Sigma^{*-}(1385)$ in νp scattering. In the following, the particle names will be used to represent the mean particle multiplicity. In νp interactions the $\Sigma^{*\pm}$ and Λ rates are :

$$\Sigma^{*+} = B_{uu}(2\gamma_u\gamma_s)R + (1 - B_{uu})\gamma_s R,\tag{6}$$

$$\Sigma^{*-} = 0$$

$$\Lambda = P\Sigma^{*+} + B_{uu}(2\gamma_s\gamma_u) + \bar{\Lambda}.\tag{7}$$

Eq. (6) is the sum of two contributions: the first term represents the probability of the uu diquark system breaking up, acquiring an s and a u quark from the fragmentation, and forming a spin- $\frac{3}{2}$ baryon; the second, of the uu diquark remaining intact, acquiring an s quark, and again forming a spin- $\frac{3}{2}$ baryon. The probability of forming a spin- $\frac{3}{2}$ baryon has been assumed to be the same ($= R$) in both terms. It should be noted however, that this need not necessarily be the case, as the uu diquark (without break-up) may be in a different spin state than the uu system formed after uu diquark break-up and recombination with a u from the fragmentation. With various assumptions about these spin states it is found that the result for R (Table 15) decreases by less than 20%, which implies an increase of B_{ud} by less than 20%.

The first term in eq. (7) represents the probability of a Λ originating from the decay of a Σ^{*+} where $P = (94 \pm 2)\%$ [37] is the combined branching ratio for $\Sigma^{*+} \rightarrow \Lambda\pi^+$ ($(88 \pm 2)\%$) and $\Sigma^{*+} \rightarrow \Sigma^0\pi^+ \rightarrow \Lambda\gamma\pi^+$ (6%); the second term represents the probability of the uu diquark breaking up, picking up an s and a d quark (essentially all such uds systems (Λ , Σ^0 , $\Sigma^{*0}(1385)$) create, or decay to yield a Λ); the last term represents the probability of Λ production *via* baryon-antibaryon production, which is assumed to be equal to $\bar{\Lambda}$ production.

Combining eqs. (6) and (7), and using eq. (5) gives :

$$\begin{aligned} B_{uu} &= \frac{\Lambda - P\Sigma^{*+} - \bar{\Lambda}}{2\gamma_s\gamma_u} \\ R &= \frac{\Sigma^{*+}}{\gamma_s(1 - B_{uu}\gamma_s)}. \end{aligned} \quad (8)$$

Similar relations hold for the production rates in $\bar{\nu}p$ interactions :

$$\begin{aligned} \Sigma^{*+} &= \Sigma^{*-} = B_{ud}(2\gamma_u\gamma_s)R \\ \Lambda &= P(\Sigma^{*+} + \Sigma^{*-}) + B_{ud}(2\gamma_u\gamma_s) + (1 - B_{ud})\gamma_s + \bar{\Lambda} \end{aligned} \quad (9)$$

and consequently :

$$\begin{aligned} B_{ud} &= \frac{\gamma_s - \Lambda + P(\Sigma^{*+} + \Sigma^{*-}) + \bar{\Lambda}}{\gamma_s^2} \\ R &= \frac{\Sigma^{*+}}{B_{ud}(2\gamma_u\gamma_s)} \end{aligned} \quad (10)$$

Unfortunately, the expression for the break-up probability B_{ud} involves the difference of small numbers with large errors, and consequently B and R are not well determined in the $\bar{\nu}p$ case. However, their product $B_{ud}R$ may be determined and B_{ud} inferred assuming that R is the same in νp and $\bar{\nu}p$ interactions.

The results obtained using the mean $\Lambda, \bar{\Lambda}$ and $\Sigma^{\pm}(1385)$ multiplicities in tables 15 and 9 respectively are shown in table 16, with and without a cut in x_B . Since in the model interactions with sea quarks are ignored the relevant sample is the one with the x_B cut.

The extracted values for the decuplet to octet baryon ratio R_D are considerably smaller than the SU(6) prediction of 2. The extracted break-up probability B_{qq} is greater for the ud case than for the uu case which is contrary to some predictions [1].

Performing the same analysis using the measured values of the $\Sigma^{\pm}(1385)$, Λ and $\bar{\Lambda}$ rates from other experiments, the values in table 17 are obtained. The extracted R values compare well with the results from the current study. The weighted mean is 0.14 ± 0.01 for uncut results and 0.24 ± 0.03 for those where an x_B cut is applied. There is more of a spread in the values for the uu system break-up probability. The weighted mean for B_{uu} is 0.48 ± 0.04 for the uncut results and 0.38 ± 0.05 for those with an x_B cut applied.

9. Conclusions

In this paper the production of neutral strange particles ($K^0, \Lambda, \bar{\Lambda}$) in νp and $\bar{\nu} p$ charged current interactions is studied. K^0 s are more copiously produced than Λ s, with a ratio of about 3:1. $\bar{\Lambda}$ production is lower still. These findings are all in accordance with the expectations from the quark-parton model.

The production of K^0 s rises with E_ν, W^2 and Q^2 and falls with increasing x_B in both νp and $\bar{\nu} p$ scattering. In the νp sample the Λ rate is independent of x_B , while in the $\bar{\nu} p$ sample the Λ s favour lower values of x_B , which is interpreted as a contribution from scattering off the sea. This is the first clear observation of this effect.

The x_F distributions of V^0 s reveal that the K^0 s favour the forward ($x_F > 0$) region, Λ s the backward region ($x_F < 0$) and $\bar{\Lambda}$ s are produced at low values of $|x_F|$. This is consistent with the K^0 s being mainly current fragments, Λ s mainly target fragments and $\bar{\Lambda}$ s coming from baryon-antibaryon pair production. Similar conclusions may be drawn from the z distributions. The average number of K^0 s, Λ s and $\bar{\Lambda}$ s falls exponentially with their p_T^2 with respect to the current direction.

In the νp sample $K^{*+}(892)$ production is observed, whereas there is a much poorer $K^{*-}(892)$ signal. $K^{*\pm}(892)$ signals are both evident in the $\bar{\nu} p$ sample. The production is mainly forwards.

There is evidence of $\Sigma^{*+}(1385)$ production in the νp data, and of both charged $\Sigma^*(1385)$ states in the $\bar{\nu} p$ sample. The production is mainly backward. The absence of the $\Sigma^{*-}(1385)$ in the νp sample indicates that processes where neither quark of the spectator diquark system resides in the baryon are negligible; there is no evidence for "diquark exclusion". The presence of the $\Sigma^{*\pm}(1385)$ signals with $x_B > 0.2$ in $\bar{\nu} p$ scattering implies that processes occur where the quarks in the spectator diquark system end up in different hadrons (diquark break-up).

Using the observed $\Sigma^{*\pm}(1385)$, Λ and $\bar{\Lambda}$ multiplicities, the probability that the diquark will break up is determined. The results indicate that the ud diquark in the $\bar{\nu} p$ case seems more likely to break up than the uu in the νp case. This contradicts some theoretical predictions. An experiment with a neon target has led to the same conclusion [19], although the ambiguity as to the struck nucleon type makes this determination less clear. The decuplet to octet baryon production ratio (after diquark break-up) is also determined and found to be much less than the SU(6) prediction, and in reasonable agreement with other experiments if the same analysis is applied.

A semi-empirical model (Wells model) is able to reproduce the mean forward, backward and total multiplicities of $K^0, \Lambda, \bar{\Lambda}$ and $K^{*\pm}(892)$, but not of $\Sigma^{*\pm}(1385)$.

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Table 1: Relative contributions to strange quark production in νp and $\bar{\nu} p$ CC interactions. For $U_v, D_v, U_s, D_s, \bar{U}, \bar{D}$ and S the values 0.214, 0.107, 0.028, 0.028, 0.028, 0.028 and 0.009 were chosen, $N_{s\bar{s}}$ and $\sin^2 \theta_c$ were taken to be 0.2 and 0.05 respectively [12].

	Mechanism	Cross section factor	Rate (%)
i	$\nu d_v \rightarrow \mu^- u + s\bar{s}$	$D_v \cos^2 \theta_c N_{s\bar{s}}$	47.0
ii	$\nu d_s \rightarrow \mu^- u + s\bar{s}$	$D_s \cos^2 \theta_c N_{s\bar{s}}$	12.3
iii	$\nu \bar{u} \rightarrow \mu^- \bar{d} + s\bar{s}$	$\frac{1}{3} \bar{U} \cos^2 \theta_c N_{s\bar{s}}$	4.1
iv	$\nu \bar{u} \rightarrow \mu^- \bar{s}$	$\frac{1}{3} \bar{U} \sin^2 \theta_c$	1.1
v	$\nu d_v \rightarrow \mu^- (c \rightarrow s)$	$D_v \sin^2 \theta_c \cos^2 \theta_c$	11.7
vi	$\nu d_s \rightarrow \mu^- (c \rightarrow s)$	$D_s \sin^2 \theta_c \cos^2 \theta_c$	3.1
vii	$\nu s(+\bar{s}) \rightarrow \mu^- c(+\bar{s})$	$S \cos^2 \theta_c$	19.8
viii	$\nu s(+\bar{s}) \rightarrow \mu^- u(+\bar{s})$	$S \sin^2 \theta_c$	1.0
i	$\bar{\nu} u_v \rightarrow \mu^+ d + s\bar{s}$	$\frac{1}{3} U_v \cos^2 \theta_c N_{s\bar{s}}$	38.7
ii	$\bar{\nu} u_s \rightarrow \mu^+ d + s\bar{s}$	$\frac{1}{3} U_s \cos^2 \theta_c N_{s\bar{s}}$	5.1
iii	$\bar{\nu} \bar{d} \rightarrow \mu^+ \bar{u} + s\bar{s}$	$\bar{D} \cos^2 \theta_c N_{s\bar{s}}$	15.2
iv	$\bar{\nu} \bar{d} \rightarrow \mu^+ (\bar{c} \rightarrow \bar{s})$	$\bar{D} \sin^2 \theta_c \cos^2 \theta_c$	3.8
v	$\bar{\nu} u_v \rightarrow \mu^+ s$	$\frac{1}{3} U_v \sin^2 \theta_c$	10.2
vi	$\bar{\nu} u_s \rightarrow \mu^+ s$	$\frac{1}{3} U_s \sin^2 \theta_c$	1.3
vii	$\bar{\nu} \bar{s}(+s) \rightarrow \mu^+ \bar{c}(+s)$	$S \cos^2 \theta_c$	24.4
viii	$\bar{\nu} \bar{s}(+s) \rightarrow \mu^+ \bar{u}(+s)$	$S \sin^2 \theta_c$	1.3

Table 2: Average values of E_ν , W^2 , W and Q^2 for CC event samples

	Variable	$W > 1.5 \text{ GeV}$	$W > 1.8 \text{ GeV}$ $x_B > 0.2$
νp	E_ν (GeV)	50.8	50.0
	W^2 (GeV ²)	34.7	27.6
	W (GeV)	5.2	4.7
	Q^2 (GeV ²)	8.7	14.0
	no. of events	16896	7623
$\bar{\nu} p$	E_ν (GeV)	39.5	40.7
	W^2 (GeV ²)	20.4	15.2
	W (GeV)	4.0	3.6
	Q^2 (GeV ²)	5.2	8.2
	no. of events	9764	4528

Table 3: Mean multiplicities of K^0 , Λ and $\bar{\Lambda}$

	νp	$\bar{\nu} p$
K^0	0.190 $\pm$ 0.009	0.161 $\pm$ 0.009
Λ	0.052 $\pm$ 0.003	0.057 $\pm$ 0.004
$\bar{\Lambda}$	0.0034 $\pm$ 0.0007	0.0016 $\pm$ 0.0006
total	0.245 $\pm$ 0.010	0.220 $\pm$ 0.010

Table 4: Numbers of events with a given combination of seen V^0 decays. X denotes a hadronic system which does not contain seen neutral strange particles

$V^0 X$ combination	νp	$\bar{\nu} p$
$K^0 X$	701	341
$2(K^0)X$	42	17
ΛX	440	308
$2(\Lambda)X$	1	4
$\bar{\Lambda} X$	19	7
$K^0 \Lambda X$	43	26
$K^0 \bar{\Lambda} X$	2	0
$\Lambda \bar{\Lambda} X$	5	2
$K^0 \Lambda \bar{\Lambda} X$	1	0
no. of CC events	16896	9764

Table 5: Fraction $F(V_i X)$ of CC events with certain combinations of neutral strange particles. X denotes a hadronic system which does not contain neutral strange particles. Error regions extending to negative values indicate that the corresponding rates are compatible with 0

$V_i X$	νp	$\bar{\nu} p$
$\geq 1 V^0$	0.188 ± 0.007	0.174 ± 0.009
$1(V^0)X$	$0.132 \pm \begin{smallmatrix} 0.014 \\ 0.012 \end{smallmatrix}$	$0.129 \pm \begin{smallmatrix} 0.019 \\ 0.015 \end{smallmatrix}$
$2(V^0)X$	$0.055 \pm \begin{smallmatrix} 0.009 \\ 0.019 \end{smallmatrix}$	$0.045 \pm \begin{smallmatrix} 0.009 \\ 0.010 \end{smallmatrix}$
$3(V^0)X$	$0.0009 \pm \begin{smallmatrix} 0.0053 \\ 0.0007 \end{smallmatrix}$	$0. \pm \begin{smallmatrix} 0.0085 \\ 0. \end{smallmatrix}$
$\geq 1 K^0$	0.153 ± 0.007	0.134 ± 0.009
$1(K^0)X$	0.097 ± 0.012	$0.091 \pm \begin{smallmatrix} 0.017 \\ 0.014 \end{smallmatrix}$
$2(K^0)X$	$0.037 \pm \begin{smallmatrix} 0.007 \\ 0.011 \end{smallmatrix}$	$0.027 \pm \begin{smallmatrix} 0.008 \\ 0.017 \end{smallmatrix}$
$3(K^0)X$	$0. \pm \begin{smallmatrix} 0.0039 \\ 0. \end{smallmatrix}$	$0. \pm \begin{smallmatrix} 0.0071 \\ 0. \end{smallmatrix}$
$\geq 1 \Lambda$	0.052 ± 0.002	0.056 ± 0.003
$1(\Lambda)X$	0.033 ± 0.003	0.037 ± 0.004
$2(\Lambda)X$	$0.0002 \pm \begin{smallmatrix} 0.0004 \\ 0.0006 \end{smallmatrix}$	$0.0011 \pm \begin{smallmatrix} 0.0008 \\ 0.0010 \end{smallmatrix}$
$\geq 1 \bar{\Lambda}$	$0.0034 \pm \begin{smallmatrix} 0.0009 \\ 0.0006 \end{smallmatrix}$	$0.0016 \pm \begin{smallmatrix} 0.0009 \\ 0.0005 \end{smallmatrix}$
$1(\bar{\Lambda})X$	$0.0015 \pm \begin{smallmatrix} 0.0015 \\ 0.0012 \end{smallmatrix}$	$0.0010 \pm \begin{smallmatrix} 0.0019 \\ 0.0008 \end{smallmatrix}$
$K^0 \Lambda X$	$0.017 \pm \begin{smallmatrix} 0.003 \\ 0.004 \end{smallmatrix}$	$0.017 \pm \begin{smallmatrix} 0.004 \\ 0.006 \end{smallmatrix}$
$K^0 \bar{\Lambda} X$	$0.0006 \pm \begin{smallmatrix} 0.0013 \\ 0.0034 \end{smallmatrix}$	$0. \pm \begin{smallmatrix} 0.0008 \\ 0.0047 \end{smallmatrix}$
$\Lambda \bar{\Lambda} X$	$0.0005 \pm \begin{smallmatrix} 0.0009 \\ 0.0016 \end{smallmatrix}$	$0.0006 \pm \begin{smallmatrix} 0.0008 \\ 0.0010 \end{smallmatrix}$
$K^0 \Lambda \bar{\Lambda} X$	$0.0009 \pm \begin{smallmatrix} 0.0020 \\ 0.0007 \end{smallmatrix}$	$0. \pm \begin{smallmatrix} 0.0013 \\ 0. \end{smallmatrix}$

Table 6: Comparison of mean V^0 multiplicities from various experiments. N_{K^0} and N_Λ are the numbers of seen K^0 and Λ decays. A ‘*’ indicates that the data are not given in the publication.

Ref.	Reaction	$\langle E_\nu \rangle$ (GeV)	N_{K^0}	$\langle n_{K^0} \rangle$	N_Λ	$\langle n_\Lambda \rangle$
This expt.	νp	50.8	831	0.190 ± 0.009	491	0.052 ± 0.003
[24]	νNeon	46	2279	0.168 ± 0.012	1843	0.065 ± 0.005
[10]	νNeon	103	203	0.230 ± 0.017	98	0.057 ± 0.007
[14]	νn	~ 60	234	0.205 ± 0.011	157	0.066 ± 0.007
[14]	νp	~ 60	154	0.174 ± 0.012	77	0.044 ± 0.005
[11]	νp	~ 45	23	0.15 ± 0.04	4	*
[4]	νp	~ 45	89	*	58	*
[3]	νp	~ 45	19	*	20	*
[8]	νd	~ 3	13	0.024 ± 0.009	26	0.028 ± 0.010
[2]	νFreon	~ 3	14	*	40	*
This expt.	$\bar{\nu} p$	39.5	401	0.161 ± 0.009	344	0.057 ± 0.004
[10]	$\bar{\nu} \text{Neon}$	81	64	0.219 ± 0.028	37	0.065 ± 0.012
[14]	$\bar{\nu} n$	~ 45	95	0.208 ± 0.020	68	0.076 ± 0.008
[14]	$\bar{\nu} p$	~ 45	193	0.184 ± 0.013	113	0.057 ± 0.006
[7]	$\bar{\nu} \text{Neon}$	~ 45	350	0.164 ± 0.009	257	0.063 ± 0.004
[11]	$\bar{\nu} p$	~ 45	88	0.151 ± 0.032	46	0.045 ± 0.009
[29]	$\bar{\nu} \text{Neon}$	40	518	0.157 ± 0.008	469	0.082 ± 0.005

Table 7: Mean neutral strange particle multiplicities compared with the predictions of the Wells model [38]

		νp		$\bar{\nu} p$	
		measured	pred.	measured	pred.
K^0	Forward	0.131 ± 0.007	0.170	0.123 ± 0.007	0.159
	Backward	0.059 ± 0.003	0.026	0.038 ± 0.003	0.013
	Total	0.190 ± 0.009	0.196	0.161 ± 0.009	0.172
Λ	Forward	0.014 ± 0.002	0.001	0.013 ± 0.002	0.0006
	Backward	0.037 ± 0.002	0.031	0.044 ± 0.003	0.047
	Total	0.052 ± 0.003	0.032	0.057 ± 0.004	0.048
$\bar{\Lambda}$	Forward	$\lesssim 0.0015$	0.0011	0.0009 ± 0.0004	0.0006
	Backward	0.0019 ± 0.0005	0.0011	0.0007 ± 0.0004	0.0006
	Total	0.0034 ± 0.0007	0.0021	0.0016 ± 0.0006	0.0012

Table 8: Slopes of p_T^2 distributions, determined in the region $p_T^2 < 0.5 \text{ GeV}^2$

	V^0	$b \text{ (GeV}^{-2}\text{)}$
νp	K^0	-5.46 ± 0.30
	Λ	-4.58 ± 0.39
	$\bar{\Lambda}$	-6.85 ± 1.80
$\bar{\nu} p$	K^0	-6.19 ± 0.45
	Λ	-5.01 ± 0.48
	$\bar{\Lambda}$	-8.75 ± 3.30

Table 9: Mean $\Sigma^{*\pm}(1385)$ multiplicities (for $W > 1.8$ GeV)

	number of decays		Mean Multiplicity	$\chi^2/\text{D.O.F.}$
	seen	corrected		
νp				
$\Sigma^{*+}(1385)$	134 ± 19	266 ± 40	0.016 ± 0.002	27.3/26
$x_F > 0$	$\lesssim 12$	$\lesssim 24$	$\lesssim 0.002$	25.1/26
$x_F < 0$	123 ± 16	244 ± 34	0.015 ± 0.002	24.0/26
$x_B > 0.2$	85 ± 13	169 ± 27	0.022 ± 0.005	31.9/26
$\Sigma^{*-}(1385)$	$\lesssim 10$	$\lesssim 20$	$\lesssim 0.001$	24.5/26
$x_F > 0$	$\lesssim 6.6$	$\lesssim 13$	$\lesssim 0.0008$	24.9/26
$x_F < 0$	$\lesssim 7.8$	$\lesssim 15$	$\lesssim 0.0009$	23.1/26
$x_B > 0.2$	$\lesssim 7.2$	$\lesssim 14$	$\lesssim 0.002$	36.2/26
$\bar{\nu} p$				
$\Sigma^{*+}(1385)$	53 ± 11	101 ± 22	0.011 ± 0.002	14.2/26
$x_F > 0$	24 ± 6	46 ± 12	0.005 ± 0.001	23.9/26
$x_F < 0$	40 ± 9	76 ± 18	0.008 ± 0.002	13.0/26
$x_B > 0.2$	35 ± 8	67 ± 16	0.015 ± 0.004	20.3/26
$\Sigma^{*-}(1385)$	26 ± 12	50 ± 23	0.006 ± 0.003	20.9/26
$x_F > 0$	12 ± 7	23 ± 13	0.003 ± 0.002	20.8/26
$x_F < 0$	16 ± 9	31 ± 18	0.003 ± 0.002	42.1/26
$x_B > 0.2$	26 ± 8	50 ± 16	0.011 ± 0.003	32.2/26

Table 10: Mean $\Sigma^{*\pm}(1385)$ multiplicities compared with the predictions of the Wells model [38]

		νp		$\bar{\nu} p$	
		measured	pred.	measured	pred.
$\Sigma^{*+}(1385)$	Forward	$\lesssim 0.002$	0.0003	0.005 ± 0.001	0.0002
	Backward	0.015 ± 0.002	0.0320	0.008 ± 0.002	0.0002
	Total	0.016 ± 0.002	0.0323	0.011 ± 0.002	0.0003
$\Sigma^{*-}(1385)$	Forward	$\lesssim 0.0008$	0.0003	0.003 ± 0.002	0.0002
	Backward	$\lesssim 0.0009$	0.0003	0.003 ± 0.002	0.0002
	Total	$\lesssim 0.001$	0.0006	0.006 ± 0.003	0.0003

Table 11: Mean $K^{*\pm}(892)$ multiplicities

	number of decays		Mean Multiplicity	$\chi^2/\text{D.O.F.}$
	seen	corrected		
νp				
$K^{*+}(892)$	149 ± 29	811 ± 158	0.048 ± 0.009	59.95/54
$x_F > 0$	109 ± 25	594 ± 139	0.036 ± 0.009	55.24/54
$x_F < 0$	42 ± 16	229 ± 88	0.014 ± 0.005	55.11/54
$K^{*-}(892)$	42 ± 19	229 ± 104	0.014 ± 0.006	48.43/54
$x_F > 0$	22 ± 16	120 ± 87	0.007 ± 0.005	51.96/54
$x_F < 0$	15 ± 8	82 ± 44	0.005 ± 0.003	47.26/54
$\bar{\nu} p$				
$K^{*+}(892)$	70 ± 16	386 ± 91	0.040 ± 0.009	49.49/54
$x_F > 0$	46 ± 13	253 ± 73	0.027 ± 0.007	32.43/54
$x_F < 0$	26 ± 8	143 ± 45	0.015 ± 0.005	47.38/54
$K^{*-}(892)$	80 ± 15	441 ± 87	0.045 ± 0.009	53.94/54
$x_F > 0$	77 ± 14	424 ± 81	0.043 ± 0.008	42.07/54
$x_F < 0$	$\lesssim 8.5$	$\lesssim 47$	$\lesssim 0.005$	57.30/54

Table 12: Forward-backward asymmetries A for the $K^{*\pm}(892)$

	V^0	A
νp	$K^{*+}(892)$	0.44 ± 0.18
	$K^{*-}(892)$	0.19 ± 0.43
	K^0	0.38 ± 0.03
$\bar{\nu} p$	$K^{*+}(892)$	0.28 ± 0.20
	$K^{*-}(892)$	$\gtrsim 0.80$
	K^0	0.53 ± 0.03

Table 13: Mean $K^{*\pm}(892)$ multiplicities compared with the predictions of the Wells model [38]

		νp		$\bar{\nu} p$	
		measured	pred.	measured	pred.
$K^{*+}(892)$	Forward	0.036 ± 0.009	0.043	0.026 ± 0.007	$0.018 - 0.026$
	Backward	0.014 ± 0.005	0.006	0.015 ± 0.005	0.003
	Total	0.048 ± 0.009	0.048	0.040 ± 0.009	$0.021 - 0.029$
$K^{*-}(892)$	Forward	0.007 ± 0.005	$0.008 - 0.032$	0.043 ± 0.008	0.026
	Backward	0.005 ± 0.003	0.005	$\lesssim 0.005$	0.003
	Total	0.014 ± 0.006	$0.013 - 0.037$	0.045 ± 0.009	0.029

Table 14: Maximum number of valence quarks from the target remnant contained in the strange baryon in neutrino and antineutrino interactions on valence and sea quarks

Baryon	Λ Σ^0 Σ^{*0}		Σ^{*+}		Σ^{*-}	
val. quark composition	(uds)		(uus)		(dds)	
scattering on	valence	sea	valence	sea	valence	sea
	νp					
two quarks		x	x	x		
one quark	x					x
no quark					x	
	$\bar{\nu} p$					
two quarks	x	x		x		
one quark			x		x	x

In case of scattering on a valence quark the classification “two quarks”, “one quark”, and “no quark” implies “no diquark break-up”, “diquark break-up”, and “diquark exclusion” respectively.

Table 15: Mean Λ and $\bar{\Lambda}$ multiplicities for $W > 1.8$ GeV

	no x_B cut	$x_B > 0.2$
νp		
Λ	0.054 ± 0.003	0.051 ± 0.004
$\bar{\Lambda}$	0.0035 ± 0.0007	0.0025 ± 0.0009
$\bar{\nu} p$		
Λ	0.061 ± 0.004	0.051 ± 0.004
$\bar{\Lambda}$	0.0017 ± 0.0006	0.0012 ± 0.0007

Table 16: Decuplet to octet baryon production ratios R_D and diquark break-up probabilities B_{qq}

		no x_B cut	$x_B > 0.2$
νp	B_{uu}	0.42 ± 0.06	0.33 ± 0.07
	R	0.18 ± 0.03	0.25 ± 0.06
	R_D	0.22 ± 0.04	0.33 ± 0.11
$\bar{\nu} p$	RB_{ud}	0.10 ± 0.02	0.15 ± 0.03
	B_{ud}	0.57 ± 0.17	0.62 ± 0.24

Table 17: Comparison of the extracted R and B_{qq} values with results from various (anti)neutrino experiments

Diquark qq	$\langle W \rangle$ (GeV)	Selection	B_{qq}	R	Ref.
uu	5.2	no x_B cut	0.42 ± 0.06	0.18 ± 0.03	this exp.
uu	4.6		0.35 ± 0.08	0.15 ± 0.04	[12]
uu	~ 6		0.61 ± 0.07	0.10 ± 0.03	[3, 4]
uu	7.5		0.57 ± 0.08	0.13 ± 0.02	[19]
uu	4.7	$x_B > 0.20$	0.33 ± 0.07	0.25 ± 0.06	this exp.
uu	5.7	$x_B > 0.15$	0.27 ± 0.11	0.22 ± 0.07	[20]
dd	4.9	$x_B > 0.15$	0.65 ± 0.20	0.26 ± 0.10	[20]
uu	~ 5	$x_B > 0.20$	0.56 ± 0.20	0.26 ± 0.11	[44, 45]
uu	6.9	$x_B > 0.20$	0.46 ± 0.11	0.23 ± 0.06	[19]

Figure Captions

1. Mean V^0 multiplicities as a function of E_ν . The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
2. Mean V^0 multiplicities as a function of W^2 . The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
3. Mean V^0 multiplicities as a function of Q^2 . The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
4. $\langle n(K^0) \rangle$ versus W for forwards and backwards K^0 s. a) νp , b) $\bar{\nu} p$ scattering
5. Mean V^0 multiplicities as a function of x_B . The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
6. Normalized p_T^2 distribution of V^0 s. The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
7. Normalized x_F distribution of V^0 s. The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
8. Normalized z distribution of V^0 s. The curves are the LUND model predictions. a) νp , b) $\bar{\nu} p$ scattering
9. The $\Lambda\pi^+$ mass spectrum. The curves show the fitted function (resonance plus background) and the background contribution. a) νp , b) $\bar{\nu} p$ scattering
10. The $\Lambda\pi^-$ mass spectrum. The curves show the fitted function (resonance plus background) and the background contribution. a) νp , b) $\bar{\nu} p$ scattering
11. The $K^0\pi^+$ mass spectrum. The curves show the fitted function (resonance plus background) and the background contribution. a) νp , b) $\bar{\nu} p$ scattering
12. The $K^0\pi^-$ mass spectrum. The curves show the fitted function (resonance plus background) and the background contribution. a) νp , b) $\bar{\nu} p$ scattering
13. Production of $\Sigma^{*+}(1385)$ (a,b) and $\Sigma^{*-}(1385)$ (c,d) in νp (a,c) and $\bar{\nu} p$ (b,d) interactions on valence quarks by “no diquark break-up” (a), “diquark break-up” (b,d) and “diquark exclusion” (c)

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13