QUARK AND DIQUARK FRAGMENTATION INTO NEUTRAL STRANGE PARTICLES
AS OBSERVED IN MUON-PROTON INTERACTIONS AT 280 GeV

The European Muon Collaboration

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(Submitted to Physics Letters)

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Abstract

The production of K^0 's, Λ 's and $\bar{\Lambda}$'s has been studied in a 280 GeV muon-proton scattering experiment with almost complete coverage of all kinematic regions. A study is made of the dependence of the multiplicities on the hadronic centre of mass energy, W , and of the Feynman x distributions. It is found that K^0 and $\bar{\Lambda}$ production is mostly central and increases strongly with W , whereas Λ production comes mainly from the remnant target system and is only weakly W dependent.

Among the results on hadron production in deep inelastic lepton-nucleon scattering, those concerning neutral strange particles have mainly been obtained with neutrino and anti-neutrino beams [1]. The existing results available on K^0 and Λ electro-production are at low energies [2], the only ones from muon-production are limited both by statistics and acceptance [3] and none covers the negative Feynman x region. This experiment presents data over the full range of Feynman x on inclusive K^0 , Λ and $\bar{\Lambda}$ production in deep inelastic muon scattering at 280 GeV. At this energy it has been shown that a good separation of struck quark and target fragments can be obtained [4].

In the usual fragmentation models strange quarks can come from the nucleon sea, either directly or from the decay of a charmed quark, or can be produced in the hadronisation process from the struck quark. In the latter case the ratio of strange to non-strange mesons is fixed by the value of a parameter giving the relative probability of creating a strange quark-antiquark pair to that of creating a non-strange pair [5], while the relative amount of strange baryons depends, in addition, on the probability of exciting a diquark with non-zero strangeness. The target remnant system, a diquark configuration in the case of scattering from a valence quark, can also fragment into a non-strange or a strange baryon. In the Lund model of the hadronisation process [6], the heavier s quark pairs are suppressed by a factor of about three relative to the light quark pairs due to the so-called tunneling effect which affects both strange meson and strange baryon production. In addition baryon production itself in the model depends on the diquark to quark probability ratio which is determined by a fit to the proton and antiproton data in low energy e^+e^- annihilation giving $P(QQ)/P(Q) = 0.065$ [7].

The results presented here have been obtained in a deep inelastic muon-proton scattering experiment performed at the CERN muon beam using the full NA9 large angle spectrometer [8]. The 280 GeV positive muons are incident on a 1 m long hydrogen target located in a 2 m long streamer chamber inside the vertex magnet. Wide angle hadrons are detected in the streamer chamber and in the vertex system while forward hadrons and the scattered muon are detected in the forward spectrometer. The present data were taken with a trigger requiring a minimum muon scattering angle of 0.5° .

The combination of the streamer chamber and the forward spectrometer allows the detection of charged tracks with good accuracy and with almost complete coverage in solid angle for momenta greater than 100 MeV/c. About half of these tracks enter the Cerenkov or time-of-flight identification counters.

Since the majority (~ 90%) of neutral strange particles do not decay in the sensitive region of the streamer chamber but rather inside the target or in the region confused by beam tracks, decay vertices are obtained by geometrical fits. The position of the primary vertex is given by the intersection of the beam track, the scattered muon and all compatible outgoing hadrons. A further search is made for hadrons emerging from any secondary vertex. In the case of electron pairs and neutral particle decays, the selection is based on the topology (i.e. 2 intersecting tracks of opposite charge) and on crude tests on the mass and the direction of the neutral particle. This leads to a large number of candidates (~ 0.25 per event) out of which the K^0 , Λ and $\bar{\Lambda}$ samples have been extracted by the various selection criteria described below.

1) Data reduction

The data presented here corresponds to a total of 14200 primary events satisfying the following cuts which are applied in order to keep the acceptance corrections, the smearing effects due to resolution and the radiative corrections relatively small:

$$\begin{aligned} Q^2 &= - (p_{\text{Beam}} - p_{\mu})^2 > 4.0 \text{ GeV}^2 \\ 16 &< W^2 < 400 \text{ GeV}^2 \\ y &= (E_{\text{Beam}} - E_{\mu}) / E_{\text{Beam}} = \nu / E_{\text{Beam}} < 0.90 \\ \theta_{\mu} &> 0.5^{\circ} \end{aligned}$$

where p_{μ} , E_{μ} , θ_{μ} represent the momentum, the energy and the scattering angle of the muon in the laboratory system, W the total energy in the virtual photon-nucleon centre of mass system and p_{Beam} , E_{Beam} the momentum and energy of the incident muon

In order to separate good V^0 's from secondary interactions, photon conversion and other backgrounds, it was demanded that the decay particles be consistent with the Cerenkov counter or the time-of-flight hodoscope information. Cuts at 1% were applied on the χ^2 probability for pointing to the main vertex and for having an acceptable neutral mass hypothesis. In addition it was required that the distance between the decay vertex and the main vertex be larger than twice the corresponding error. The final samples consist of 571 K^0 's, 208 Λ 's and 92 $\bar{\Lambda}$'s with mass resolutions of about 25 MeV for the K^0 's and 15 MeV for the Λ 's and the $\bar{\Lambda}$'s. Λ 's produced from Σ decays are included in the Λ sample.

As a check of the selection procedure, we have measured the mean lifetimes τ for the three types of neutral hadrons. The ratios τ/τ_0 (where τ_0 is the mean lifetime quoted by the Particle Data group) are found to be 0.87 ± 0.05 , 0.81 ± 0.10 and 1.31 ± 0.21 for K^0 's, Λ 's and $\bar{\Lambda}$'s respectively, in reasonable agreement with the expected value of unity.

The efficiency of the apparatus and of all phases of the data analysis has been evaluated by processing a sample of Monte Carlo events generated according to the Lund model [6] through the complete chain of programs, including the selection criteria described above. The effects of such phenomena as secondary interactions, smearing etc. are fully accounted for. The average passing rates (not including K_L^0 or neutral decay modes) are 32% for K^0 's, 26% for Λ 's and 40% for $\bar{\Lambda}$'s. The Monte Carlo data are used to correct for the acceptance bin by bin in each variable. Background effects as well as uncertainties in the selection procedure and the acceptance corrections induce systematic errors of about 20% on the total rates.

2) Neutral Kaon Production

The average number of neutral kaons ($K^0 + \bar{K}^0$) per event corrected for K_L^0 , for unseen decay modes and for decays too close or too far away from the primary vertex is determined to be 0.37 ± 0.02 . The average values obtained in four different intervals of the total hadronic energy, W , show a systematic increase of the K^0 multiplicity (table 1). The same effect has been observed previously in νN and $\bar{\nu} N$ interactions. The data points in this experiment align well with those from νN experiments generally at lower values of W (fig. 1). However our data taken alone cannot differentiate between a $W^{1/2}$ or a logarithmic dependence on W .

The K^0 yields in muon and neutrino induced reactions are not necessarily the same since some of the contributing mechanisms are different (e.g. a larger fraction of K^0 's in νN and $\bar{\nu} N$ interactions is expected to result from charm production and decay [1c].)

The reduced longitudinal momentum distribution $\frac{1}{N_{ev}} \frac{dN}{dx_F}$ (fig. 2a) is strongly peaked at zero and drops faster in the backward than in the forward hemisphere. The curve represents the predictions of the Lund string model [6] with the ratio of strange to u quark taken to be 0.3. Although the predictions are somewhat higher than the data in the region $0.1 < x_F < 0.4$, the model seems to provide a reasonable parameterisation of K^0 production, in shape and in absolute normalisation.

Fig. 2b shows the normalised z distribution $\frac{1}{N_{ev}} \frac{dN}{dz}$ together with the results of other experiments. Our data agree very well with those obtained in the region $z > 0.3$ by an 11.5 GeV electro-production experiment [2]. They also agree with those from a muon-proton experiment at 225 GeV [3] for $z > 0.1$ while for lower values of z the latter experiment quotes a value which is about 2.5 times smaller than the value from this experiment. However it should be noted that the present experiment has much better coverage in the negative Feynman x region which corresponds to the range $z \leq 0.1$. A strong similarity is observed in shape between the z distribution for K^0 's and that obtained for π^0 's in similar experimental conditions [9]. Both distributions decrease at the same rate with increasing z and their ratio remains compatible with a constant (~ 5) over the range $0.05 < z < 0.60$.

In table II the normalised x_F distribution is given in two W ranges for five intervals of x_F . A strong increase with increasing W is observed in the central bins of x_F while for $|x_F| > 0.2$ the distribution becomes independent of W or even decreases. This observation should be compared with the Q^2 and x_{Bj} dependence of the overall K^0 rate given in table I. The decrease of the K^0 rate by a factor of ~ 2 between the lowest and highest x_{Bj} interval is strongly correlated with the the previously mentioned W dependence since events at low (high) x_{Bj} tend to accumulate at high (low) W . A similar W dependence limited to the central region has been observed for charged pions in the same experiment [10]. The Lund model predictions are also given in table II and show that the W dependence of the x_F distribution is at least qualitatively reproduced by the model.

The average transverse momentum squared $\langle p_T^2 \rangle$ is shown as a function of x_F in fig. 3 for 2 intervals of W . In the forward hemisphere we observe an increase of $\langle p_T^2 \rangle$ with the longitudinal momentum ("seagull effect") and, at fixed x_F , also an increase with W . These features can be understood by QCD

corrections to the quark-parton model. In this model the transverse momentum is expected to contain - besides a component due to quark fragmentation to hadrons - a contribution from hard and soft gluon emission, which increases with W , and a contribution from a primordial k_T of the quarks, which increases with the particle energy fraction z [9,10].

3) Λ and $\bar{\Lambda}$ production.

The normalised x_F distributions for Λ 's and $\bar{\Lambda}$'s - corrected for neutral decay modes - show very different shapes (fig. 4a). The production rates are roughly equal around $x_F = 0$ and in the forward hemisphere but the $\bar{\Lambda}$ distribution falls rapidly for $x_F < -0.2$ while the Λ distribution remains nearly constant. Since Λ 's and $\bar{\Lambda}$'s are detected in a completely symmetric way and with the same efficiency when produced at the same point in phase space, the observed difference is directly related to the production mechanism.

The large value of the Λ cross section at negative Feynman x indicates that it arises from the fragmentation of the target fragments into a strange baryon. This process which is expected to be independent of the total energy W leads to a sizeable and nearly energy independent average Λ multiplicity as observed in fig. 1b. On the other hand, $\bar{\Lambda}$'s can only be produced by creating a diquark - anti-diquark pair in the fragmentation chain. Since such a process requires a large amount of available energy, it will lead to a faster increase of the $\bar{\Lambda}$ rate with W and to a Feynman x distribution peaked around zero. Both features are observed in the data (fig. 1b, fig. 4a). The Lund model predictions, also shown in fig. 4a, reproduce the general features of Λ and $\bar{\Lambda}$ production. However the model gives a Λ to $\bar{\Lambda}$ ratio larger than that observed and does not reproduce the details of x_F distributions.

For comparison the normalised z distributions for Λ 's and $\bar{\Lambda}$'s together with the results from ref. [3] are shown in fig. 4b. The two Λ distributions are in good agreement for $z > 0.1$ while they differ by a factor of about three at low z . This discrepancy is similar to the one observed in the same region for K^0 's and is probably related to the incomplete coverage of the backward hemisphere in the work reported in ref. [3].

4) Conclusions

Neutral strange particles have been studied in a high energy lepton-proton scattering experiment with almost complete kinematic coverage. The results are in good agreement with the expectations of the naive quark-parton picture. The total K^0 rate is compatible - within the rather large systematic errors - with a suppression factor of about one third for strange to non-strange quark pairs and shows an increase with W similar to the one observed in neutrino induced reactions. Λ 's are observed in the recombination of target remnants with a strange quark as well as in the fragmentation of the struck quark into a diquark - anti-diquark pair. Λ and $\bar{\Lambda}$ production are about equal in the x_F region where the second mechanism is dominant.

Acknowledgements

We would like to thank all the people in the various laboratories who have contributed to the construction, operation and analysis of this experiment. The support of the CERN staff in operating the SPS, muon beam and computer facilities is gratefully acknowledged.

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Table I

Average Numbers $\langle N \rangle$ of $K^0 + \bar{K}^0$ per event
as a function of W , Q^2 and x_{Bj}

W [GeV]	$\langle N \rangle$	Q^2 [GeV ²]	$\langle N \rangle$	x_{Bj}	$\langle N \rangle$
4- 8	0.25 ± 0.03	4 - 16	0.32 ± 0.02	0.008 - 0.05	0.47 ± 0.03
8-12	0.34 ± 0.03	16 - 32	0.46 ± 0.03	0.05 - 0.20	0.35 ± 0.02
12-16	0.44 ± 0.04	> 32	0.50 ± 0.06	0.20 - 1.0	0.25 ± 0.03
16-20	0.57 ± 0.04				

Table II

Values of $\frac{1}{N_{ev}} \frac{dN}{dx_F}(K^0)$ in two ranges of W and five intervals of x_F .

	Data		Lund Model	
W Range (GeV)	$4 < W < 12$	$12 < W < 20$	$4 < W < 12$	$12 < W < 20$
x_F Range				
$x_F < -0.2$	$0.019 \pm .008$	$0.043 \pm .010$	0.040	0.040
$-0.2 < x_F < -.05$	$0.31 \pm .05$	$0.71 \pm .07$	0.41	0.66
$-0.05 < x_F < .05$	$0.69 \pm .05$	$1.72 \pm .13$	0.76	1.81
$0.05 < x_F < .20$	$0.52 \pm .07$	$0.74 \pm .07$	0.54	1.15
$x_F > 0.20$	$0.082 \pm .016$	$0.074 \pm .010$	0.13	0.14

Figure captions

- Fig. 1 Variation of the average number of neutral kaons ($K_S^0 + K_L^0$) and Λ 's and $\bar{\Lambda}$'s per event with the total hadronic energy W .
- Fig. 2 a) Distribution of the reduced longitudinal momentum $x_F^* = 2p_{\parallel}^*/W$ for K^0 's.
- b) The fragmentation functions for K^0 's at several incident energies and for π^0 's at 200 GeV as a function of $z = E_{K^0}/v$.
- Fig. 3 Average transverse momentum squared
- $$\langle p_T^2 \rangle = \frac{1}{dN/dx_F} \int_{p_T^2} \frac{d^2N}{dx_F dp_T^2} dp_T^2 \quad \text{as a function of } x_F \text{ for 2 intervals of the total hadronic energy } W.$$
- Fig. 4 a) Reduced longitudinal momentum distribution for Λ 's and $\bar{\Lambda}$'s. The curves show the predictions of the Lund string model [6].
- b) The fragmentation functions $D^{\Lambda}(z)$ and $D^{\bar{\Lambda}}(z)$.

Fig.1

Fig. 2a

Fig. 2b

Fig. 3

Fig. 4a)

Fig. 4b