Study of the formation of neutral strange particles in neutrino–nuclear interactions in the energy range 3-30 GeV using a streamer-chamber-plus-photoemulsion spectrometer

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We examine the processes of formation of neutral strange particles in interactions of neutrinos with the nuclei of a photoemulsion on a wide-aperture streamer-chamber-plus-photoemulsion spectrometer. We have determined the contributions to the total cross section of the νN-interactions going through a charged current and have obtained estimates of the total yields of events with strange and charmed particles.

1. INTRODUCTION

A study of the processes of formation of strange and charmed hadrons in deeply inelastic interactions of neutrinos with nuclei is of especial interest and is one of the most important challenges of any neutrino program. Despite their extended history and the large number of experimental efforts,[1–8] studies of such processes are of great interest to this day. There are deep reasons for this. First of all, for a qualitative description of $d \rightarrow c$ and $s \rightarrow c$ transitions in weak interactions, the effects of which are manifested in neutrino reactions in pure form, further detailed research of the structure of these transitions is necessary. Even for strange particles much less attention has been given to the dynamics of their formation in neutrino beams than has been the case for nonstrange hadrons. As for charmed particles, theoretical representations of the mechanisms of their formation, especially in the near-threshold region, where the contributions of quasi-elastic and weakly inelastic reactions are important, still do not have a unique interpretation to this day.

Second, a study of the formation of strange particles also provides information on the formation of charmed particles since the dominant quark transition in the Glashow–Illiopoulos–Maiani scheme[9] is the $c \rightarrow s$ transition, and charmed hadrons decay preferentially into strange hadrons with the characteristic signature of the process. On the other hand, this same transition also plays a defining role in the formation of charmed particles.

From the experimental point of view, a study of processes of formation of short-lived particles in neutrino–nuclear interactions is fraught with significant difficulties which are determined by the complexity of the technique for their detection. Most often, such studies make use of a nuclear photoemulsion (as the target) in conjunction with an external spectrometer for analyzing the reaction products. The present paper reports the results of a reduction of experimental data obtained using a wide-aperture neutrino spectrometer in the form of a streamer chamber and photoemulsion (SCAP).

2. EXPERIMENTAL SETUP

A SCAP spectrometer is operating in the neutrino channel of the accelerator of the Institute of High-Energy Physics of the Russian Academy of Sciences in connection with an experiment underway for studying the formation of charmed particles in neutrino interactions (Experiment E-128).[10] The experiment is based on a hybrid technique: it uses a photoemulsion as the vertex detector/target, and as the track-extrapolating and spectrometric detector it uses a large streamer chamber, placed in a magnetic field.

The photoemulsion vertex detector/target[11] consists of a special container which houses 24 photoemulsion chambers, 12 of which are parallel-irradiation chambers with dimensions $160\times50\times80\ \mathrm{mm}^3$, and 12 are perpendicular-irradiation chambers, with dimensions $160\times100\times50\ \mathrm{mm}^3$, located in the lower and upper parts of the container, respectively. The target is situated as closely as possible to the streamer chamber; the sensitive spaces of the chambers are separated from one another by $30\ \mathrm{mm}^3$. This enhances the accuracy of the track extrapolation to the vertex of the interaction and increases the light-gathering power of the setup. Each exposure uses up 22 liters of substrate-free emulsion of type BR-2.

The streamer chamber serves for track extrapolation to the vertex of the neutrino interaction in the photoemulsion target and for determination of the kinematic characteristics of the secondary particles.[12] The sensitive space of the

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streamer chamber is formed from two large $160\times695\times400\ \mathrm{mm}^3$ modules and four small modules, two of which are $160\times100\times400\ \mathrm{mm}^3$ in dimensions, and the remaining two, $160\times70\times400\ \mathrm{mm}^3$, molded out of PVC stock. The large modules (forward along the neutrino beam) serve to determine the kinematic characteristics of the secondary particles and the coordinates of the vertices of the neutrino interactions in the emulsion target. The rear (small) modules are intended to record and identify electrons and γ-ray photons. As converters, the setup uses lead-glass slugs, which are three radiation lengths in overall thickness.

The streamer chamber has the following technical specifications:

1. Position measured with an accuracy $\sigma_{x,y}\leqslant0.4$ mm in the photographic plane, and $\sigma_z\leqslant1.5$ mm in depth.
2. Mean error of reconstructing the momentum of the charged particle $\langle\Delta p/p\rangle=7\%$.
3. Mean measurement errors of the track angles in the streamer chamber $\langle\Delta\lambda\rangle=20$ mrad (depth angle) and $\langle\Delta\varphi\rangle=17$ mrad (azimuthal angle).
4. Maximum magnetic field strength at the center of the chamber 10 G.

The technique for reconstructing the parameters of the charged particle tracks in the streamer chamber and the procedure for reconstructing the coordinates of the vertices of the neutrino interactions in the emulsion target are laid out in Ref. 13.

The muon identifier[14] consists of 14 spark chambers of dimensions $2.5\times2\ \mathrm{m}^2$, separated by steel filters. The total length of a filter along the beam is 84 cm of Fe ($\simeq5$ scattering lengths), and the total weight is 36 tonnes. The spatial accuracy with which points can be reconstructed in the spark chamber is $\sigma_x\leqslant1.2$ mm, $\sigma_y\leqslant0.5$ mm, and $\sigma_z\leqslant0.2$ mm. The muon identifier ensures separation of muons and hadrons with an efficiency of 90% for momenta greater than 0.6 GeV/c. Hadron energies can be measured in the identifier structure with an accuracy of $\Delta E_h/E_h=0.7/\sqrt{E(\mathrm{GeV})}$.

The efficiency of the trigger scintillation system of the entire setup when up to three secondary charged particles are formed by the interaction of the neutrino with the photoemulsion is 96%.

The total exposure time of the spectrometer in the neutrino be3am was around 3000 hours for a total discharge of 1.2×10^{18} protons onto the target of the neutrino channel.

3. ANALYSIS OF DECAYS OF NEUTRAL STRANGE PARTICLES

In this study we investigate processes of inclusive scattering of neutrons by nuclei of the photoemulsion

$$\nu_\mu A\rightarrow\mu^-X, \tag{1}$$

going through a charged current and satisfying the criteria: a) the presence of a negatively charged muon recorded in the streamer chamber and muon identifier; b) the presence of more than two tracks of secondary particles (including the muon) recorded in the streamer chamber and issuing from a common vertex in the interior of the target.

After processing the collected statistics we selected 710 neutrino interactions in the charged current. To reduce the contribution of background processes to the investigated sample, we imposed the following selection criteria on the muon momentum and neutrino energy:

$$p_\mu>0.5\ \mathrm{GeV}/c, \tag{2}$$

$$E_\nu>3.0\ \mathrm{GeV}. \tag{3}$$

In the sample of neutrino interactions we examined the reactions of include formation of K^0 muons and Λ^0 hyperons

$$\nu_\mu A\rightarrow\mu^-K^0X, \tag{4}$$

$$\nu_\mu A\rightarrow\mu^-\Lambda^0X, \tag{5}$$

and in our analysis of the candidates to reactions (4) and (5) we imposed an additional selection criterion on the invariant mass of the hadron of the system W (at the threshold of strange particle formation)

$$W>1.5\ \mathrm{GeV}/c^2. \tag{6}$$

Reactions (4) and (5) have an additional characteristic feature in the streamer chamber—a fork of two oppositely charged particles issuing from one point along the track (V^0-decay). From the total sample of neutrino interactions, $N_\nu=570$ events satisfied criteria (2), (3), and (6), and of these, seventeen contained the characteristic V^0-decays.

The type of decaying neutral strange particle (K^0 or Λ^0) was determined by kinematic testing of the hypotheses that their decay parameters correspond to the modes

$$K^0\rightarrow\pi^-\pi^+, \tag{7}$$

$$\Lambda^0\rightarrow p\pi^- \tag{8}$$

with the help of the kinematic fitting program N-KINE,[15] adapted to the conditions of the experiment. The procedure for separating the K^0-mesons and Λ^0-hyperons is a special case of the general problem of separating the reaction channels, which mathematically reduces to finding the minimum of the functional

$$\chi^2=\sum(X_i-X_i^m)C_{ij}(X_j-X_j^m),\quad i,j=1,\ldots,N, \tag{9}$$

with the imposed coupling equations in the form of conservation laws

$$F_k(X,Y)=0,\quad k=1,\ldots,L. \tag{10}$$

In Eqs. (9) and (10) the variables X_i denote the varied values of the ith kinematic parameter, X_i^m denote the values of the ith parameter determined by the program of geometric and kinematic reconstruction, C_{ij} is the weight matrix, which is the inverse of the error matrix of the measured parameters, N is the number of measured parameters, Y are the unknown (not measured) parameters, and L is the number of coupling equations. If $L>M$ holds (M is the number of unknown quantities Y), then the value of the functional (9) at the minimum obeys the χ^2-distribution with $N-(L-M)$ degrees of freedom. For our case of kinematic testing of candidates for the V^0-particle (the K^0-meson or the Λ^0-hyperon) the measured parameters are the parameters of the product particles of the decay: the momentum p, the depth angle λ and azimuthal angle φ measured in the coordinate system of the streamer chamber, and also the angles defining the direction of motion of the V^0-particle: λ_V and φ_V. In this case the momentum of the V^0-particle is unknown. The coupling equations are the laws of conservation of the 4-momentum at the vertex of the decay of the V^0-particle. The coupling equations, which are nonlinear in p, λ, and φ, are linearized; after this an iteration procedure is performed. The corrected values of the momenta of the charged particles and their track angles, the angles λ_V and φ_V, and also the values of the momentum of the V^0-particle and the χ^2-probability of the given hypothesis are determined by minimizing the functional (9). By introducing bounds on the probability of the hypothesis it is possible to assign the V^0-decays to either channel (7) or (8). Hypothesis (7) or (8) was accepted if its χ^2-probability exceeded 0.5%.

In some cases of V^0-decays both (K^0 and Λ^0) hypotheses had a probability greater than the minimum and a unique assignment could not be made. This is because even for zero measurement errors of the track parameters there exists a configuration of particle momenta for which the conservation laws are fulfilled for both decays, (7) and (8). As the experimental errors of the track parameters increase, the region in which one cannot uniquely determine whether the given V^0-particle is the product of the decay of a K^0-meson or a Λ^0-hyperon also grows. Under the conditions of our experiment 20% of the V^0-particles had an ambiguous (nonunique) χ^2-fit. For these cases we chose the hypothesis with the greater probability. The correctness of such an algorithm for choosing the hypothesis was tested by an analysis of the $\cos q$ distributions of the V^0-particles, where q is the angle between the direction in which the V^0-particle moved away and the momentum of its decay products in the rest frame. These distributions show that the ambiguously identified (according to the χ^2-fit) K^0-mesons have values of $|\cos q|<0.5$ while the Λ^0-hyperons, as a consequence of the large mass difference of their decay products, give an asymmetric decay and group in the region $|\cos q|>0.5$. Ambiguously identified V^0-particles having a large χ^2-probability also fell into the corresponding intervals.

From 17 neutrino interactions in which a neutral strange particle formed this procedure for choosing hypotheses made it possible to unambiguously identify seven as containing K^0-mesons and ten as containing Λ^0-hyperons. A photograph of a V^0-event in the streamer chamber, identified as a $\Lambda^0 \rightarrow p\pi^-$ decay, is shown in Fig. 1. The mean experimental effective masses for the identified events are

$$M_K = 0.492 \pm 0.008 \ \mathrm{GeV}/c^2,$$

$$M_\Lambda = 1.113 \pm 0.006 \ \mathrm{GeV}/c^2,$$

and lifetimes

$$\tau_K = (0.81 \pm 0.10) \cdot 10^{-10}\mathrm{s}, \quad \tau_\Lambda = (2.52 \pm 0.25) \cdot 10^{-10}\mathrm{s},$$

which is in good agreement with the tabulated values of these quantities. During the course of the experiment in the streamer chamber not one case of associated formation of neutral strange particles was observed.

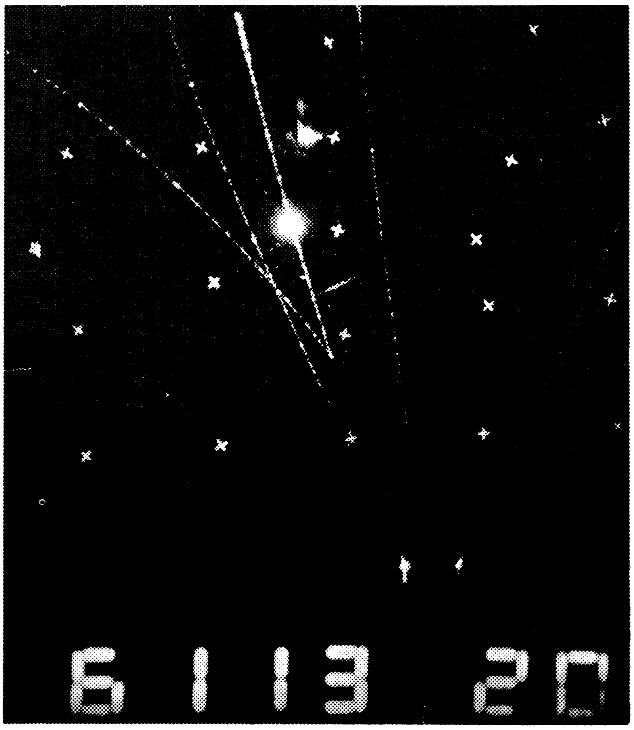

FIG. 1. Photograph of the decay of a strange Λ^0-hyperon in the sensitive space of the streamer chamber, by the channel $\Lambda^0 \rightarrow p\pi^-$.

4. NEUTRAL STRANGE PARTICLE YIELD

The total yield of V^0-particles in the neutrino interactions is made up from contributions from their solitary formation, associated formation, and formation connected with the creation and subsequent decay of charmed particles. To estimate the total yield of neutral strange particles, we determined their detection efficiency in the streamer chamber. In this we took account of the following factors:

1. "Loss" of V^0-particles due to incomplete coverage by the spectrometer of the kinematically allowed region for escape of secondary particles due to limited acceptance of the streamer chamber. The probability of such events was taken into account by the Monte Carlo method using the geometry of the spectrometer and the angle and energy distributions of the K^0-mesons and Λ^0-hyperons in the given process at neutrino energies $E_\nu = 3$–30 GeV. Its value was 10% for the K^0-mesons and 8% for the Λ^0-hyperons.

2. The probabilities of decay of the K^0-mesons and Λ^0-hyperons over all neutral modes. We took

$$K^0 + K^0 = 50\% K_s^0 + 50\% K_l^0,$$

$$\Gamma(K_s^0 \rightarrow \pi^0\pi^0)/\Gamma_{\mathrm{tot}} = 0.314 \pm 0.003,$$

$$\Gamma(K_l^0 \rightarrow \pi^0\pi^0\pi^0)/\Gamma_{\mathrm{tot}} = 0.216 \pm 0.008,$$

$$\Gamma(\Lambda_l^0 \rightarrow n\pi^0)/\Gamma_{\mathrm{tot}} = 0.358 \pm 0.005.$$

3. The probability of decay or interaction of a V^0-particle between where it forms in the target and the sensitive volume of the streamer chamber. Some of the neutral strange particles drop out due to interactions with nucleons

in the intervening manner. The probability for the particle to traverse a distance D without interacting is given by

$$P_{\mathrm{int}}=-\exp\left[-\sum_i n_i\sigma D\right],$$

where D is the distance from where the strange particle forms, determined by extrapolation to the vertex of the neutrino interaction in the emulsion, to the front wall of the streamer chamber, $n_i=N_A\rho_i/M_i$ (N_A is Avogadro's number), ρ_i and M_i are the density and molecular weight of the intervening matter (photoemulsion, walls of the photoemulsion container and streamer chamber, trigger scintillation counters), σ is the cross section for the interaction of the V^0-particle with a nucleon. The probability of decay of a V^0-particle before and after the streamer chamber was calculated by the formula

$$P_d=1-\exp[-D/\tau\gamma\beta c]+\exp[-(D+l)/\tau\gamma\beta c],$$

where l is the length (along the beam) of the track-extrapolating part of the streamer chamber, τ is the lifetime of the particle at rest, γ is the Lorentz factor, and βc is the velocity of the particle. If we take the interaction of the neutral strange particles and their decays into account, the calculated probability for a V^0-particle to interact in the intervening matter or decay outside the sensitive space of the streamer chamber was 52% for the K^0-mesons and 40% for the Λ^0-hyperons.

If we take these factors into account, the detection efficiency of the V^0-particles in the streamer chamber was $\varepsilon_K=0.15$ (for the K^0-mesons) and $\varepsilon_\Lambda=0.36$ (for the Λ^0-hyperons) for solitary creation of the indicated particle, and $\varepsilon_{K\bar{K}}=0.022$ and $\varepsilon_{K\Lambda}=0.054$ for their associated creation. This gives a total number of K^0-mesons $N_K=48\pm19$, a total number of Λ^0-hyperons $N_\Lambda=28\pm9$, and also the yields of reactions (4) and (5) from the ratio to the total cross section of reaction (1):

$$n(K^0)=\sigma(K^0)/\sigma_t=0.084\pm0.031,$$

$$n(\Lambda^0)=\sigma(\Lambda^0)/\sigma_t=0.049\pm0.016.$$

Here the total number of events of associated formation of neutral strange particles ($N_{K\bar{K}}=1.4\pm7.5$, $N_{K\Lambda}=0.4\pm2.8$) was calculated, starting from the 98% probability of not observing these processes in the experiment.

These results correspond to a mean invariant mass of the hadron system $\langle W\rangle=3.4$ GeV/c^2 and agree with the experimental results of Ref. 7. Note that events including formation of a neutral strange particle have on average a higher value of the invariant mass than the mass $\langle W\rangle=2.75$ GeV/c^2 of the events $\nu_\mu A\rightarrow\mu^-X$.

5. ESTIMATE OF CHARMED PARTICLE YIELD

Decays of neutral strange particles in the streamer chamber are identified by the V^0-decays. It is also possible to record charged strange particles. In the analysis of the total strange particle yield, we made use of a technique based on the results for neutral strange particles. According to Ref. 1, the fraction of neutral interactions containing strange particle in the final state, from the total cross section of reaction (1), is given by

$$n(S)=\sigma_s/\sigma_t=2[n(K^0)+n(\Lambda^0)]-4[n(K^0K^0)+n(K^0\Lambda^0)], \quad (11)$$

where $n(K^0)$, $n(\Lambda^0)$, $n(K^0K^0)$, and $n(K^0\Lambda^0)$ are the yields determined by the corresponding processes of solitary and associated creation of strange particles. The relative yield of events with strange particles, calculated according to the formula (11), in $n(S)=0.194\pm0.088$.

The yield of events with charmed particles was estimated using the quark–parton model from the relative contributions of νN-scattering processes in which strange and charmed particles form. According to Ref. 7, 28% of the events with formation of a strange particle are due to creation and subsequent decay of a charmed particle. Introducing the selection criterion based on the threshold for formation of a charmed particle $W>3$ GeV/c^2, we obtained a sample of 311 events, for which the total yield of strange particles was $n'(S)=0.288\pm0.117$. Then the total yield of events with charmed particles is $n(C)=\sigma_c/\sigma_t=0.081\pm0.033$, which is in good agreement with the data of other neutrino experiments: 0.10 ± 0.02 (Ref. 1), 0.082 ± 0.020 (Ref. 3), and 0.075 ±0.037 (Ref. 7).

6. CONCLUSION

The accumulated experimental material on the interactions of neutrinos with photoemulsion nuclei requires further analysis in order to estimate the cross section of formation of charmed particles in the near-threshold region. At the present time, 23 neutrino interactions have been found in the photoemulsions, in which secondary vertices due to charm decay were not detected. This allows us to place a limit $\sigma_c<0.05\sigma_t$ on the cross section of charm formation. As the statistics of the neutrino interactions improves, the upper bound on the cross section of charmed particle formation will be substantially refined. In addition, information from the muon identifier and the γ-converter makes it possible to determine the yields of the charmed particles from reactions in which μ^-e^+ and μ^+e^- form in pairs and compare them with the model-dependent estimates presented here.

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