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A STUDY OF MULTIPLE PRODUCTION OF NEUTRAL STRANGE PARTICLES IN ν_μ CC INTERACTIONS IN THE NOMAD EXPERIMENT

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A study of multiple production of neutral strange particles in ν_μ charged current interactions has been performed using the full data sample from the NOMAD experiment. This analysis allows one to investigate mechanisms of strange particle production in neutrino interactions. In this study we have tried to build a model for the production of strange particles which would allow us to describe our measured rates of neutral strange particles, as well as the rates of the single-, double- and triple-V^0 production: Λ, K^0, $\bar{\Lambda}$, K^0K^0, ΛK^0, $\Lambda\bar{\Lambda}$, $K^0\bar{\Lambda}$, $\Lambda\Lambda$, $K^0K^0K^0$.

Исследование множественного рождения нейтральных странных частиц в нейтринных взаимодействиях по каналу заряженного тока выполнено с использованием полного набора данных, накопленных в эксперименте NOMAD. Результаты анализа важны для более правильного теоретического описания рождения странности в нейтринных взаимодействиях. В работе предложена модель рождения странности для описания измеренных выходов нейтральных странных частиц Λ, K^0, $\bar{\Lambda}$, а также множественного рождения нейтральных странных частиц по каналам K^0K^0, ΛK^0, $\Lambda\bar{\Lambda}$, $K^0\bar{\Lambda}$, $\Lambda\Lambda$ и $K^0K^0K^0$ в конечном состоянии.

INTRODUCTION

The production mechanisms of strange hadrons can be studied in neutrino-nucleon deep inelastic interactions measuring the rates of single-, double-, and triple-appearance of neutral strange particles. These neutral strange particles can be reliably identified in contrast to most other hadrons using the V^0-like signature of their decays. It is noteworthy that all previous investigations of strange particle production by neutrinos have come from bubble chamber experiments. No other technique has so far yielded results on this subject. We use a large sample of the NOMAD data corresponding to $1.3 \cdot 10^6\,\nu_\mu$ charged current interactions in order to improve our knowledge of the production properties and behavior of neutral strange particles in neutrino interactions.

We investigate the production mechanisms of strange hadrons in neutrino interactions by two independent ways:

(1) in a model-independent way measuring multiple rates of neutral strange particles;

(2) we develop an effective model of strange particle production, which allows us to tune its parameters using the NOMAD data: to determine the rates of single s-quark production (R_s), of $s\bar{s}$-pair production ($R_{s\bar{s}}$), etc. Within this model we can indirectly estimate the rates of $K^{\pm}$, which could not be identified explicitly in the NOMAD detector.

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We use the V^0 identification procedure described in [1–3] for our study of multiple production of neutral strange particles (K_S^0, Λ, $\bar{\Lambda}$) in ν_μ charged current (CC) interactions using the full set of the NOMAD data.

The production of strange (anti)quarks has been also investigated in a study of multi-V^0 production in neutrino interactions using the 15-ft bubble chamber at FNAL [4].

The paper is organized as follows. In Sec. 1 we shortly describe the NOMAD detector, the event selection and V^0 identification procedures. Section 2 is devoted to a study of multiple production of neutral strange particles, estimation of systematic errors and dicussion of the results obtained. In the final section we draw our conclusions.

1. THE NOMAD EXPERIMENT

The main goal of the NOMAD experiment [5] was the search for $\nu_\mu \to \nu_\tau$ oscillations in a wide-band neutrino beam from the CERN SPS. The ν_μ mean energy was about 24 GeV [6], increasing up to 61 GeV in events with observed strange particles. The oscillation search used kinematic criteria to identify ν_τ CC interactions [7] and required a very good quality of event reconstruction, similar to that of bubble chamber experiments. This has indeed been achieved by the NOMAD detector, and, moreover, the large data sample collected during four years of data taking (1995–1998) has allowed for detailed studies of neutrino interactions. The full data sample, corresponding to about $1.3 \cdot 10^6$ ν_μ CC interactions in the detector fiducial volume, is used in the present analysis. A complete reprocessing of the whole NOMAD data sample has been performed using improved reconstruction algorithms. The data are compared to the results of a Monte Carlo simulation based on modified versions of LEPTO 6.1 [8] and JETSET 7.4 [9] generators for neutrino interactions (with Q^2 and W^2 cutoff parameters removed, Q is the four-momentum transferred from the incoming neutrino to the nucleon, and W is the hadronic energy) and on a GEANT [10] based program for the detector response. The relevant JETSET parameters have been tuned in order to reproduce the yields of strange particles measured in ν_μ CC interactions in NOMAD [3]. A detailed description of the tuning of the MC simulation program is a subject of a forthcoming publication. To define the parton content of the nucleon for the cross-section calculation, we use the fixed-flavour parameterization [11] in the NNLO approximation. We do not include the parton shower treatment from JETSET. The reinteractions of hadrons with surrounding nucleons in target nuclei are described within the DPMJET [12] package. For the analysis reported below we used an MC sample consisting of about 3 million ν_μ CC events.

1.1. Event Selection. We select the ν_μ CC event sample requiring:
- presence of a negatively charged track identified as a muon,
- hadronic jet energy $E_{\rm jet} > 3$ GeV,
- momentum tranfser squared $Q^2 > 0.8$ GeV^2.

In the data sample we identified $8 \cdot 10^5$ ν_μ CC events with the efficiency $\epsilon_{\nu_\mu {\rm CC}} = (77.15 \pm 0.03)\%$. The efficiencies are computed with the help of the MC and are defined as ratios of the number of events reconstructed and identified as ν_μ CC to the number of simulated ν_μ CC events. The errors include only statistical uncertainties. The contamination of NC events in the CC event sample is estimated to be less than 0.1%.

The NOMAD experiment has observed an unprecedented number of neutral strange particle decays in a neutrino experiment [3]. These decays appear in the detector as a V^0-like vertex: two tracks of opposite charge emerging from a common vertex separated from the primary neutrino interaction vertex (see Fig. 1). The V^0-like signature is expected also for photon conversions.

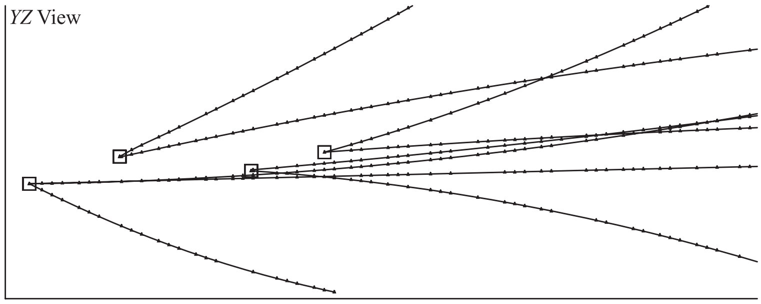

Fig. 1. A reconstructed data event containing 3 V^0 vertices identified as K^0_S decays by the identification procedure. The scale on this plot is given by the size of the vertex boxes (3×3 cm)

The following *selection criteria* have been applied to the reconstructed V^0 candidates:

• χ^2 probability of the V^0-vertex reconstruction larger than 0.01;

• transverse component $p_T^{\rm dirv}$ of the total momentum of the two outgoing charged tracks with respect to the line connecting the primary and V^0 vertices smaller than 100 MeV/c. This cut rejects V^0's with momentum not pointing to the primary vertex and also V^0's which do not come from two-body decays (e. g., neutron interactions);

• transverse component $p_T^{\rm int}$ of the momentum of one of the outgoing charged tracks with respect to the V^0 momentum greater than 20 MeV/c. This cut is crucial to eliminate a large fraction of photon conversions;

• measured proper decay time τ consistent with the tested hypothesis $\tau < 6\ \tau_{V^0}$ (PDG), where τ_{V^0} (PDG) is the lifetime as given in Ref. [13].

The selected candidates passed then the V^0 kinematic fit as explained in [1]. In Table 1 we summarize the numbers of identified $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ decays in ν_μ CC interactions as well as their identification and reconstruction efficiencies and purities evaluated with the help of the MC simulation.

Table 1. **The purity, efficiency, ratio MC/data and the number of identified $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\ \pi^+$ decays in ν_μ CC interactions in the data (efficiency includes the reconstruction and identification efficiencies of neutrino interactions)**

Particle	Number	Purity, %	Efficiency, %	MC/data
K^0_S	14280	97.1 ± 0.1	23.9 ± 0.1	0.99 ± 0.01
Λ	7384	93.5 ± 0.2	20.4 ± 0.1	0.99 ± 0.02
$\bar{\Lambda}$	606	85.5 ± 0.9	21.1 ± 0.5	1.03 ± 0.06

In Table 2 we present the observed multi-V^0 channels in both the real data and MC. The MC predictions are normalized to the same number of ν_μ CC events as in the data sample. The ratio MC/data is also given. The Table 2 entries should be read as follows. ΛX stands

Table 2. **The number of reconstructed multi-V^0 channels for the real data and for the MC normalized to the same number of ν_μ CC events as in the data sample. The ratio MC/data is also given**

Channels	Number of reconstructed events		MC/data
	MC	Data	
ΛX	6842	7060	0.97 ± 0.02
$K^0_S X$	12948	13396	0.97 ± 0.01
$\bar{\Lambda} X$	549	556	0.99 ± 0.06
$K^0_S K^0_S X$	397	300	1.32 ± 0.10
$\Lambda K^0_S X$	368	265	1.39 ± 0.11
$\Lambda \bar{\Lambda} X$	53	37	1.42 ± 0.31
$K^0_S \bar{\Lambda} X$	18	13	1.40 ± 0.51
$\Lambda\Lambda X$	13	11	1.15 ± 0.47
$K^0_S K^0_S K^0_S X$	3	2	1.39 ± 1.29

for the number of reconstructed events in which among of three V^0-like decays (Λ, K^0_S and $\bar{\Lambda}$) only one Λ hyperon was reconstructed and no other V^0. $\Lambda K^0_S X$ stands respectively for the number of reconstructed events with one Λ hyperon and one K^0_S meson reconstructed and no other V^0. The same conventions are used for the rest of the entries.

2. MULTI-V^0 ANALYSIS

Strange particles can be produced both at the primary vertex and in secondary interactions of particles from the primary vertex with the detector material (see Fig. 2). The fraction of secondary produced strange particles as predicted by the MC simulation is not negligible (see the second column in Table 3). Our quality cuts applied to the samples of neutral strange particles suppress this fraction to a level of a few percent, also our quality cuts suppress the

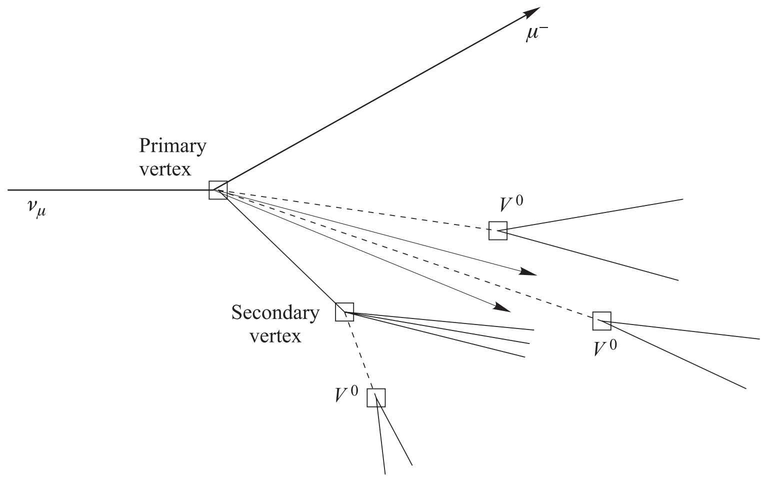

Fig. 2. A schematic view of multiple V^0 production in ν_μ CC interaction

Table 3. **Fractions of V^0's (in %) containing V^0's coming from «fakes» and secondary interactions in simulated and reconstructed MC events**

Particle	Simulated MC	Reconstructed MC	
	From sec. int.	From sec. int.	«Fakes»
Λ	38.1 ± 0.2	2.4 ± 0.1	3.8 ± 0.1
K^0_S	31.5 ± 0.1	1.1 ± 0.1	1.2 ± 0.1
$\bar{\Lambda}$	32.2 ± 0.6	2.4 ± 0.4	8.7 ± 0.8

contribution from «fake» V^0's that consists of gamma conversions, neutron interactions and random track associations (see the third and fourth columns of Table 3). From Table 3 we conclude that after our V^0 selection procedure we deal mainly with the sample of neutral strange particles produced at the primary vertex.

2.1. Multi-V^0 Channels and the Unfolding Procedure. Let us introduce the following notations: R — the vector of observed rates of V^0's; F^{true} — the vector of true rates of strange particles; N — the observed number of V^0's:

$$R = \begin{pmatrix} R_\Lambda \\ R_{K^0_S} \\ R_{\overline{\Lambda}} \\ R_{K^0_S K^0_S} \\ R_{K^0_S \Lambda} \\ R_{\overline{\Lambda}\Lambda} \\ R_{K^0_S \overline{\Lambda}} \\ R_{\Lambda\Lambda} \\ R_{K^0_S K^0_S K^0_S} \end{pmatrix} = \frac{1}{N_{\nu_\mu \text{CC}}} \begin{pmatrix} N_\Lambda \\ N_{K^0_S} \\ N_{\overline{\Lambda}} \\ N_{K^0_S K^0_S} \\ N_{K^0_S \Lambda} \\ N_{\overline{\Lambda}\Lambda} \\ N_{K^0_S \overline{\Lambda}} \\ N_{\Lambda\Lambda} \\ N_{K^0_S K^0_S K^0_S} \end{pmatrix}, \quad F^{\text{true}} = \begin{pmatrix} F_\Lambda \\ F_{K^0_S} \\ F_{\overline{\Lambda}} \\ F_{K^0_S K^0_S} \\ F_{K^0_S \Lambda} \\ F_{\overline{\Lambda}\Lambda} \\ F_{K^0_S \overline{\Lambda}} \\ F_{\Lambda\Lambda} \\ F_{K^0_S K^0_S K^0_S} \end{pmatrix}, \quad (1)$$

where $N_{\nu_\mu \text{CC}}$ is the number of reconstructed ν_μ CC events. The vectors R and F^{true} obviously differ from each other because of inefficiencies of the detector, migration of particles from channel to channel due to misidentification and misreconstruction, or due to the existence of neutral decay modes: $\Lambda \to n\pi^0$, $\bar{\Lambda} \to \bar{n}\pi^0$, $K \to \pi^0\pi^0$ (which we do not reconstruct in our detector). The R and F^{true} can be easily related to each other by the following matrix equation:

$$R = \frac{1}{\epsilon_{\nu_\mu \text{CC}}} \varepsilon B F^{\text{true}}, \quad (2)$$

where $\epsilon_{\nu_\mu \text{CC}}$ is the reconstruction efficiency of ν_μCC events; ε is the efficiency matrix whose diagonal elements show the probability for a given channel to be reconstructed as the same channel (for example, simulated $K^0_S K^0_S$ to be reconstructed as $K^0_S K^0_S X$), while the off-diagonal elements show probabilities of migration from one channel to another (for example, $K^0_S K^0_S$ to be reconstructed as $K^0_S \Lambda X$ or $K^0_S X$, etc.). B is the branching matrix whose elements show the probability of decay via the charged modes (for example, $(\text{Br}\,(\Lambda \to p\pi), \text{Br}\,(K \to \pi^+\pi^-)) = 0.639 \times 0.686/2$ where $\text{Br}\,(\Lambda \to p\pi) = 0.639$, and $\text{Br}\,(K \to \pi^+\pi^-) = 0.686$, the factor of 2 is due to the condition that the K^0 sample consists of both K^0_S and K^0_L, but in the NOMAD detector we observe only the K^0_S component).

As an example let us write down one equation of (2) for single Λ channel:

$$R_\Lambda = \frac{\varepsilon_{\Lambda\to\Lambda}}{\epsilon_{\nu_\mu \mathrm{CC}}}\mathrm{Br}_\Lambda\big\{F_\Lambda + (1-\mathrm{Br}_\Lambda)\ (F_{\Lambda\bar\Lambda} + 2F_{\Lambda\Lambda}) + (1-\mathrm{Br}_K)F_{K\Lambda} + \ldots\big\} + \\ + \frac{\varepsilon_{K^0_S\to\Lambda}}{\epsilon_{\nu_\mu \mathrm{CC}}}\mathrm{Br}_K\big\{F_K + (1-\mathrm{Br}_\Lambda)\,(F_{K\Lambda} + F_{K\bar\Lambda}) + 2(1-\mathrm{Br}_K)F_{KK} + \ldots\big\} + \\ + \frac{\varepsilon_{K^0_S\Lambda\to\Lambda}}{\epsilon_{\nu_\mu \mathrm{CC}}}\mathrm{Br}_K\,\mathrm{Br}_\Lambda\big\{F_{K\Lambda} + \ldots\big\} + \ldots$$

The system of equations (2) can be solved in two ways:

(1) in terms of model-independent yields F^{true} as a system of linear equations;

(2) in terms of a model of strange particle production in which F^{true} depends on a set of free parameters to be fitted. For example, within this model F_Λ is predicted as a sum of contributions from single s-quark production ($R_s P_{s\Lambda}$), associated production of s and $\bar s$ quarks ($R_{s\bar s} P_{s\Lambda} P_{\bar s X}$) and other mechanisms of strangeness production in neutrino deep inelastic scattering: $F(\Lambda) = R_s P_{s\Lambda} + R_{s\bar s} P_{s\Lambda} P_{\bar s X} + \ldots$ The model has the following free parameters: $r_{s\bar s}$ — the probability of the one-$s\bar s$-pair production from the string fragmentation, $P_{s\Lambda}$ (P_{sK^0}) — the probability that s quark will appear as a Λ hyperon (K^0 meson), $P_{\bar s\bar\Lambda}$ ($P_{\bar s K^0}$) — the probability that $\bar s$ quark will appear as a $\bar\Lambda$ hyperon (K^0 meson). A fit of these parameters to the observed rates of multiple strange particle appearance allows us to obtain an estimate of the rates for single and associated production of s and $\bar s$ quarks (R_s, $R_{\bar s}$, $R_{s\bar s}$). Also it allows us to estimate indirectly rates of charged kaons $K^\pm$. The details of the model are summarized in Appendix.

2.2. Systematic Errors. We have studied different sources of systematic uncertainties.

To investigate the dependence of the results on the V^0 selection criteria, we varied them within the following ranges (variations of these cuts correspond to changes of up to 6% in the statistics of the V^0 sample):

• cut on the transverse momentum of the charged track from V^0 decay from 0.01 to 0.03 GeV/c. The default value is 0.02 GeV/c;

• cut on the V^0 momentum component perpendicular to the V^0 line of flight from 0.09 to 0.115 GeV/c. The default value is 0.1 GeV/c;

• cut on the χ^2 probability of the V^0 vertex reconstruction changed from 0.005 to 0.035. The default value is 0.01;

• cut on the measured decay path of K^0_S mesons varied from 10 to 40 cm. The default value is 16 cm;

• cut on the measured decay path of Λ and $\bar\Lambda$ hyperons varied from 40 to 64 cm. The default value is 48 cm;

• cut on invariant mass for $\bar\Lambda$ ($|M_{\mathrm{rec}\ \bar\Lambda} - M_{\mathrm{true}\ \bar\Lambda}| < \Delta M$) was varied from 0.02 to 0.04 GeV. The default value is 0.025 GeV.

We estimate the systematic uncertainty for each parameter as the sum in quadrature of the largest deviation in the variable range obtained with respect to the reference result. The systematic errors for production rates were calculated assuming that contributions from different parameters are not correlated.

As a check of possible detector acceptance problem we reduced the detector fiducial volume by about 60% and repeated the whole analysis. We found that the results are very stable with respect to this fiducial volume reduction.

Another possible source of systematic uncertainty could be related to different V^0 reconstruction efficiencies in the MC and real data. To check the possible V^0 reconstruction efficiency problem, we measured the rates of Λ and K_S^0 at the primary vertex. The double ratio

$$(\epsilon_{V^0})_{\rm MC/data} = \frac{({\rm MC/data})_{V^0}}{({\rm MC/data})_{\rm PV}}$$

provides us with an estimate of possible deviations of V^0 reconstruction efficiency in the real data from the one predicted by the MC simulation program. In this ratio the index V^0 means the measured ratio for neutral strange particles, reconstructed as V^0 vertex, the index PV stands for the strange particles reconstructed from the primary vertex. The measured double ratios for K_S^0 and Λ are

$$(\epsilon_K)_{\rm MC/data} = 0.98 \pm 0.08, \tag{3}$$

$$(\epsilon_\Lambda)_{\rm MC/data} = 1.05 \pm 0.07. \tag{4}$$

From the values (3) and (4) we conclude that there is no difference in the V^0 reconstruction efficiencies in the MC and real data. Nevertheless we check that the solution of the system of equations (2) is stable with respect to possible deviation of MC-predicted efficiencies of V^0's in the data within the range allowed by (3), (4). The maximum deviation of thus obtained results is included into the final systematic uncertainty of the fitting parameters. Let us note, however, that such an estimation of the systematic uncertainty is dominated by the statistical accuracy of the available data used to obtain double ratios $(\epsilon_{V^0})_{\rm MC/data}$.

2.3. Results. The results for the measured yields of both single and multiple production of neutral strange particles, strange particle production parameters and rates are given in Tables 4–6 (see Appendix for the details of the model). The production rates presented in Table 4 correspond to the rates of exclusive appearance of Λ, K_S^0 and $\bar{\Lambda}$ particles in various combinations. In the second column of Table 4 we also present the yields of the single and multiple V^0 channels obtained at the NOMAD event generator level (NEGLIB). These yields are in good agreement with those obtained using our measurement procedure (see column 3 in Table 4). Results of Ref. [4] are compared to ours in the last column of Tables 4–6. There is in general a reasonable agreement between these results, while the statistical errors of Ref. [4] are somewhat smaller than those one would expect in an experiment with 4–5 times smaller statistics of observed neutral strange hadrons.

2.4. Discussion. It is important to note that the dominant mechanism for the strange particle production is due to the $s\bar{s}$-pair production. We verified at the MC level that even channels with «open» strangeness like ΛX, $K_S^0 X$, or $\bar{\Lambda} X$ in fact often contain charged strange hadrons with compensating strangeness. Say, ΛX mostly contains K^+ meson, $K_S^0 X$ contains single $\overline{K}^0$ meson, or are accompanied by K^+ or K^- mesons or other strange particles. Thus, the yields of channels with single- and multi-V^0 productions are sensitive to the yields of neutral strange particles and to the yields of charged strange particles, particularly to the ratio between yields of $\overline{K}^0/K^-$ and K^0/K^+ mesons.

Examination of Table 4 leads to an interesting conclusion: even if the raw numbers of events with single channels like ΛX, $K^0 X$, $\bar{\Lambda} X$ are close in the data and MC (as shown in Table 2), the correspoding measured yields show a discrepancy (compare columns 3 and 4 of Table 4). This discrepancy can be due to different rates of the $s\bar{s}$-pair production

Table 4. **Yields for channels (in %) with single and multiple production of neutral strange particles for both the MC and real data. The errors include statistical and systematic errors**

Channels	NEGLIB	MC	Data	FNAL [4]
ΛX	2.92	2.58 ± 0.31	3.47 ± 0.47	3.2 ± 0.3
$K^0 X$	7.89	6.81 ± 1.26	9.17 ± 1.60	8.0 ± 0.8
$\bar{\Lambda} X$	0.15	0.14 ± 0.09	0.21 ± 0.13	0.24 ± 0.06
$K^0 K^0 X$	2.81	3.07 ± 1.27	2.62 ± 1.24	1.6 ± 0.8
$\Lambda K^0 X$	2.41	2.63 ± 0.32	1.84 ± 0.46	2.3 ± 0.4
$\Lambda \bar{\Lambda} X$	0.22	0.21 ± 0.07	0.15 ± 0.09	0.09 ± 0.03
$K^0 \bar{\Lambda} X$	0.10	0.10 ± 0.07	0.07 ± 0.10	0.14 ± 0.05
$\Lambda \Lambda X$	0.01	0.02 ± 0.06	0.01 ± 0.24	0.02 ± 0.07
$K^0 K^0 K^0 X$	0.19	0.38 ± 0.49	0.15 ± 0.38	0.6 ± 0.3

Table 5. **Strange particle production parameters (in %) for both the MC and real data. Values for the FNAL [4] results were recalculated from the originally published ones**

Parameters	MC	Data	FNAL
$r_{s\bar{s}}$	$10.56 \pm 1.35 \pm 0.10$	$18.65 \pm 3.50 \pm 2.08$	—
$r_{2(s\bar{s})}$	$1.26 \pm 0.35 \pm 0.03$	$4.53 \pm 2.03 \pm 1.20$	—
$P_{s\Lambda}$	$25.92 \pm 2.37 \pm 0.17$	$15.93 \pm 3.20 \pm 2.02$	23.0 ± 3.6
P_{sK^0}	$35.02 \pm 7.40 \pm 0.60$	$23.89 \pm 11.10 \pm 3.73$	22.3 ± 2.0
$P_{\bar{s}\bar{\Lambda}}$	$2.54 \pm 0.33 \pm 0.02$	$1.40 \pm 0.35 \pm 0.20$	2.3 ± 4.0
$P_{\bar{s}K^0}$	$51.65 \pm 5.97 \pm 0.19$	$26.63 \pm 6.82 \pm 3.78$	47.3 ± 0.5

Table 6. **Production rates (in %) for both the MC and real data. The errors include statistical and systematic errors and do not contain errors on quark momentum distribution parameters and Cabibbo matrix elements**

Production rates	MC	Data	FNAL [4]
R_s	$3.67 \pm 0.07 \pm 0.01$	$3.20 \pm 0.23 \pm 0.14$	5.0 ± 1.5
$R_{\bar{s}}$	$0.61 \pm 0.01 \pm 0.01$	$0.53 \pm 0.02 \pm 0.01$	—
$R_{s\bar{s}}$	$13.64 \pm 1.11 \pm 0.09$	$20.40 \pm 2.90 \pm 1.72$	19.5 ± 1.4
$R_{ss\bar{s}}$	$0.44 \pm 0.06 \pm 0.01$	$0.78 \pm 0.15 \pm 0.09$	—
$R_{s\bar{s}\bar{s}}$	$0.26 \pm 0.01 \pm 0.01$	$0.27 \pm 0.02 \pm 0.01$	—
$R_{ss\bar{s}\bar{s}}$	$1.63 \pm 0.37 \pm 0.03$	$4.95 \pm 1.99 \pm 1.18$	—

and/or different production rates of charged $K^{\pm}$ mesons. Indeed, the ΛX channel is basically equivalent to the ΛK^+ production, while the $K^0 X$ can be considered as a sum of contributions from the K^0 and $K^0 K^{\pm}$ channels. It is possible to check the idea that the production rates of charged $K^{\pm}$ mesons can be different in the data and MC using a simple observation: the ratio of $\Lambda K^+/\Lambda K^0$ rates largely cancels the dependence on the $s\bar{s}$-pair production rate and is mainly sensitive to the K^+/K^0 ratio. In the MC this ratio is close to unity as one would expect for equal production rates of $K^{\pm}$ and K^0, while in the data this ratio is almost two times larger, which provides a hint in favour of higher K^+ production probability in the data than in the MC. Another example is to consider the $K^0 X/K^0 K^0$ ratio. Again, qualitatively one can expect that $K^0 X$ is equivalent to $K^0 K^+ + K^0 K^-$. In the MC this ratio

$(K^0K^+ + K^0K^-)/K^0K^0$ is close to 2, which can be interpreted as equal probabilities for K^+, K^- and K^0 production. In the data the same ratio is closer to 4, which is in agreement with the hypothesis that the $K^\pm$ production yields are higher than that of the K^0 mesons in the data.

Table 7. **Predicted yields of strange particles (containing strange quark) measured with the help of our strange particle production model (in %) for both the MC and real data**

Yields	NEGLIB	MC	Data
T_Λ	5.87	$5.63 \pm 0.72 \pm 0.05$	$5.63 \pm 1.58 \pm 0.97$
$T_{\bar{K}^0}$	8.18	$7.61 \pm 1.75 \pm 0.14$	$8.44 \pm 4.26 \pm 1.65$
$T_{X(s)}$	9.39	$8.48 \pm 0.86 \pm 0.07$	$21.26 \pm 4.48 \pm 2.57$
T_s	23.43	$21.72 \pm 1.94 \pm 0.15$	$35.33 \pm 6.96 \pm 4.13$

Table 8. **Predicted yields of strange particles (containing strange antiquark) measured with the help of our strange particle production model (in %) for both the MC and real data**

Yields	NEGLIB	MC	Data
$T_{\bar{\Lambda}}$	0.50	$0.47 \pm 0.08 \pm 0.01$	$0.45 \pm 0.15 \pm 0.09$
T_{K^0}	9.03	$9.54 \pm 1.50 \pm 0.08$	$8.56 \pm 2.88 \pm 1.65$
$T_{X(\bar{s})}$	12.53	$8.46 \pm 0.94 \pm 0.07$	$23.14 \pm 5.14 \pm 3.05$
$T_{\bar{s}}$	22.06	$18.48 \pm 1.95 \pm 0.15$	$32.15 \pm 7.03 \pm 4.17$

Yields of K^+ and K^- mesons can be estimated with the help of our strangeness production model. We estimate the yields of K^- and K^+ mesons in real data as 21 and 23%, respectively, which could be compared to smaller rates of production of neutral K^0 mesons (in %): $8.56 \pm 2.88 \pm 1.65$ (K^0) and $8.44 \pm 4.26 \pm 1.65$ ($\overline{K}^0$).

The details are given in Tables 7 and 8. The notations are the following: T_i are the yields of the corresponding particles, $T_{X(s)}$ and $T_{X(\bar{s})}$ are the yields of charged particles containing strange quarks and antiquarks, T_s and $T_{\bar{s}}$ are the yields of strange quarks and antiquarks.

CONCLUSION

In this work we present a study of multiple production of neutral strange particles in ν_μ CC interactions performed using the full data sample from the NOMAD experiment.

The measurement of multiple production of neutral strange particles provides us with valuable information on strange quark hadronization mechanisms in neutrino interactions. We observed the production of strange particles in the following combinations of appearance: Λ, K^0, $\bar{\Lambda}$, K^0K^0, ΛK^0, $\Lambda\bar{\Lambda}$, $K^0\bar{\Lambda}$, $\Lambda^0\Lambda^0$, $K^0K^0K^0$; and measured the corresponding yields. We also tried to remeasure these yields in the framework of a simple model built on the basis of the FNAL approach [4]. The results are basically consistent within these two approaches.

Using the information about the yields of single and multiple channels of V^0 production, we measured in a model-dependent way the total yields of s and $\bar{s}$ (anti)quarks produced in ν_μ CC interactions at the average energy of the NOMAD experiment: $T_s(\%) = 35.33 \pm$

6.96 (stat.)$\pm$4.13 (syst.) and $T_{\bar{s}}(\%) = 32.15 \pm 7.03$ (stat.)$\pm$4.17 (syst.). Within the developed model we see a hint that the production rates of charged kaons can be higher than those of neutral kaons by a factor of 2.7 ± 1.1 in the real data, while these rates are of the same order in the MC.

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APPENDIX

Extending the FNAL Model of Strange Particle Production. In this appendix we describe our extention of the FNAL model of strange particle production [4]. More details can be found in [14].

Let us consider possible production mechanisms of hadrons containing a strange quark ($h(s)$) and a strange antiquark ($h(\bar{s})$) which are relevant in the energy region of the NOMAD experiment:

$$\begin{array}{rl}
h(s) & \nu_\mu d \to \mu^- c(\to s \to h(s)),\\
h(\bar{s}) & \nu_\mu s(\bar{s}) \to \mu^- u(\bar{s} \to h(\bar{s})),\\
 & \nu_\mu s(\bar{s}) \to \mu^- c(\to d)(\bar{s} \to h(\bar{s})),\\
 & \nu_\mu \bar{u} \to \mu^- \bar{s}(\to h(\bar{s})),\\
h(s)h(\bar{s}) & \nu_\mu d \to \mu^- u(s \to h(s), \bar{s} \to h(\bar{s})),\\
 & \nu_\mu s(\bar{s}) \to \mu^- c(\to s \to h(s))(\bar{s} \to h(\bar{s})),\\
 & \nu_\mu \bar{u} \to \mu^- \bar{d}(s \to h(s), \bar{s} \to h(\bar{s})),\\
h(s)h(s)h(\bar{s}) & \nu_\mu d \to \mu^- c(\to s \to h(s))(s \to h(s), \bar{s} \to h(\bar{s})),\\
h(s)h(\bar{s})h(\bar{s}) & \nu_\mu s(\bar{s}) \to \mu^- u(\bar{s} \to h(\bar{s}))(s \to h(s), \bar{s} \to h(\bar{s})),\\
 & \nu_\mu s(\bar{s}) \to \mu^- c(\to d)(\bar{s} \to h(\bar{s}))(s \to h(s), \bar{s} \to h(\bar{s})),\\
 & \nu_\mu \bar{u} \to \mu^- \bar{s}(\to h(\bar{s}))(s \to h(s), \bar{s} \to h(\bar{s})),\\
h(s)h(s)h(\bar{s})h(\bar{s}) & \nu_\mu d \to \mu^- u(s \to h(s), \bar{s} \to h(\bar{s}))(s \to h(s), \bar{s} \to h(\bar{s})),\\
 & \nu_\mu s(\bar{s}) \to \mu^- c(\to s \to h(s))(\bar{s} \to h(\bar{s}))(s \to h(s), \bar{s} \to h(\bar{s})),\\
 & \nu_\mu \bar{u} \to \mu^- \bar{d}(s \to h(s), \bar{s} \to h(\bar{s}))(s \to h(s), \bar{s} \to h(\bar{s})).
\end{array}$$

By analyzing the multiple production of strange particles we could extract information about the probability of producing one (or several) $s\bar{s}$ pair(s) *per neutrino interaction* (not the probability of creating an $s\bar{s}$ pair over the probability to make a nonstrange $q\bar{q}$ pair *during the fragmentation process*).

The rate of the $s\bar{s}$-pair production from the string fragmentation can be written in the following unitarity form:

$$I \equiv r_{q\bar{q}} + r_{s\bar{s}} + r_{2(s\bar{s})} + r_{3(s\bar{s})} + \ldots, \tag{A.1}$$

$$\begin{aligned} r_{q\bar{q}} &= \frac{1}{1 + P_{s\bar{s}} + P_{s\bar{s}}^2 + P_{s\bar{s}}^3}, \\ r_{s\bar{s}} &= \frac{P_{s\bar{s}}}{1 + P_{s\bar{s}} + P_{s\bar{s}}^2 + P_{s\bar{s}}^3}, \\ r_{2(s\bar{s})} &= \frac{P_{s\bar{s}}^2}{1 + P_{s\bar{s}} + P_{s\bar{s}}^2 + P_{s\bar{s}}^3}, \end{aligned} \tag{A.2}$$

where $r_{q\bar{q}}$ — the probability of the light (nonstrange) quark production only; $r_{s\bar{s}}$ — the probability of the one-$s\bar{s}$-pair production from the string fragmentation; $r_{2(s\bar{s})}$ — the probability of the two-$s\bar{s}$-pair production from the string fragmentation, etc. In these equations we assumed that in the energy region of the NOMAD experiment we could not have more than three $s\bar{s}$ pairs produced per neutrino interaction. Instead of relation (A.1) we could write the total probability in the form $(P_{\mathrm{nonstrange}} + \lambda_s)^n = 1$, where λ_s represents the relative probability of producing the $s\bar{s}$ pair to the probability of producing any $q\bar{q}$ pair *in one single act of the pair creation during the string fragmentation* and n is the total number of produced $q\bar{q}$ pairs per neutrino event (unfortunately we do not know this number).

Using relations (A.2) and strangeness production cross section in neutrino CC interactions, we calculate the following rates of strangeness production in neutrino interactions on isoscalar target (the NOMAD target is nearly isoscalar [15]):

- R_s — the rate for single s-quark production (via charm):

$$R_s = \frac{\sigma_0}{\sigma_{\nu_\mu}^{\mathrm{CC}}} (U + D)\, |V_{cd}|^2 |V_{cs}|^2 r_{q\bar{q}}; \tag{A.3}$$

- $R_{\bar{s}}$ — the rate for single $\bar{s}$-quark production:

$$R_{\bar{s}} = \frac{\sigma_0}{\sigma_{\nu_\mu}^{\mathrm{CC}}} \left[\frac{1}{3} (\bar{U} + \bar{D})\, |V_{us}|^2 + 2S \left(|V_{us}|^2 + |V_{sc}|^2 |V_{cd}|^2 \right) \right] r_{q\bar{q}}; \tag{A.4}$$

- $R_{s\bar{s}}$ — the rate for associated production of s and $\bar{s}$:

$$R_{s\bar{s}} = \frac{\sigma_0}{\sigma_{\nu_\mu}^{\mathrm{CC}}} \left[(U + D)\, |V_{ud}|^2 r_{s\bar{s}} + 2S\, |V_{cs}|^4 r_{q\bar{q}} + \frac{1}{3} (\bar{U} + \bar{D})\, |V_{ud}|^2 r_{s\bar{s}} \right]; \tag{A.5}$$

- $R_{ss\bar{s}}$ — the rate for associated production of two s and one $\bar{s}$:

$$R_{ss\bar{s}} = \frac{\sigma_0}{\sigma_{\nu_\mu}^{\mathrm{CC}}} (U + D)\, |V_{cd}|^2 |V_{cs}|^2 r_{s\bar{s}}; \tag{A.6}$$

- $R_{s\bar{s}\bar{s}}$ — the rate for associated production of one s and two $\bar{s}$:

$$R_{s\bar{s}\bar{s}} = \frac{\sigma_0}{\sigma_{\nu_\mu}^{\mathrm{CC}}} \left[\frac{1}{3} (\bar{U} + \bar{D})\, |V_{us}|^2 + 2S \left(|V_{us}|^2 + |V_{sc}|^2 |V_{cd}|^2 \right) \right] r_{s\bar{s}}; \tag{A.7}$$

• $R_{ss\bar{s}\bar{s}}$ — the rate for associated production of two $s\bar{s}$ pairs:

$$R_{ss\bar{s}\bar{s}} = \frac{\sigma_0}{\sigma^{\rm CC}_{\nu_\mu}} \left[(U+D)\,|V_{ud}|^2 r_{2(s\bar{s})} + 2S\,|V_{cs}|^4 r_{s\bar{s}} + \frac{1}{3}(\bar{U}+\bar{D})\,|V_{ud}|^2 r_{2(s\bar{s})} \right], \quad (A.8)$$

$$\frac{\sigma_0}{\sigma^{\rm CC}_{\nu_\mu}} = \frac{1}{\mathcal{Q}+S+\frac{1}{3}(\bar{\mathcal{Q}}-\bar{S})}, \quad (A.9)$$

$$R_{\rm nonstrange} + R_s + R_{\bar{s}} + R_{s\bar{s}} + \ldots = 1, \quad (A.10)$$

where $U,\ D,\ S,\ \bar{U},\ \bar{D},\ \bar{S}$ — the fraction of momentum carried by the corresponding (anti)quark in the nucleon; $\mathcal{Q} = U + D + S$ ($\bar{\mathcal{Q}} = \bar{U} + \bar{D} + \bar{S}$), $V_{qq'}$ — Cabibbo matrix elements.

In our calculations we used the following values: $\mathcal{Q} = 0.452,\ \bar{\mathcal{Q}} = 0.072,\ U = 0.296,\ D = 0.144,\ \bar{U} = 0.026,\ \bar{D} = 0.034,\ S = \bar{S} = 0.013$, which correspond to the parameterization [11] (selected for the NOMAD MC simulation program) at $Q^2 = 14\ {\rm GeV}^2/c^2$ (the average value for events containing an identified V^0). Though quark distributions are Q^2-dependent we checked that the rates $R_s,\ R_{\bar{s}},\ \ldots$ do not depend significantly on the 4-momentum transfer.

To calculate the yields of single and multiple V^0 production, the following four parameters have been defined:

• $P_{s\Lambda}$ — the probability that s quark will appear as a Λ hyperon;
• $P_{\bar{s}\bar{\Lambda}}$ — the probability that $\bar{s}$ quark will appear as a $\bar{\Lambda}$ hyperon;
• P_{sK^0} — the probability that s quark will appear as a K^0 meson;
• $P_{\bar{s}K^0}$ — the probability that $\bar{s}$ quark will appear as a K^0 meson.

It is possible to account for channels with unidentified charged strange hadrons by introducing:

• P_{sX} — the probability that s quark appears as a charged strange hadron (invisible in this analysis):

$$P_{sX} = 1 - P_{sK^0} - P_{s\Lambda}; \quad (A.11)$$

• $P_{\bar{s}X}$ — the probability that $\bar{s}$ quark appears as a charged strange hadron:

$$P_{\bar{s}X} = 1 - P_{\bar{s}K^0} - P_{\bar{s}\bar{\Lambda}}. \quad (A.12)$$

We have derived equations for production rates F of all V^0 combinations which correspond to the following production mechanisms: R_s, $R_{\bar{s}}$, $R_{s\bar{s}}$, $R_{ss\bar{s}}$, $R_{s\bar{s}\bar{s}}$ and $R_{ss\bar{s}\bar{s}}$.

A simple way to derive equations for different channels of single and multiple V^0 production is to consider the following probability unitarity relations:

$$I_s = P_{sK^0} + P_{s\Lambda} + P_{sX},$$
$$I_{\bar{s}} = P_{\bar{s}K^0} + P_{\bar{s}\bar{\Lambda}} + P_{\bar{s}X}, \quad (A.13)$$

which correspond to a trivial statement that the produced s ($\bar{s}$) quark will end up in a hadron: K^0_S, Λ ($\bar{\Lambda}$) or X.

The rate for strangeness production can be experessed as

$$R_{\rm strangeness} = R_s I_s + R_{\bar{s}} I_{\bar{s}} + R_{s\bar{s}} I_s \otimes I_{\bar{s}} + R_{ss\bar{s}} I_s \otimes I_s \otimes I_{\bar{s}} + \\ + R_{s\bar{s}\bar{s}} I_s \otimes I_{\bar{s}} \otimes I_{\bar{s}} + R_{ss\bar{s}\bar{s}} I_s \otimes I_s \otimes I_{\bar{s}} \otimes I_{\bar{s}} + \ldots \quad (A.14)$$

Therefore, the rate for any given channel of multiple production of neutral strange particles can be found directly from Eqs. (A.13) and (A.14). For example,

$$\begin{aligned}
F(\Lambda) &= R_s P_{s\Lambda} + R_{s\bar{s}} P_{s\Lambda} P_{\bar{s}X} + 2R_{ss\bar{s}} P_{s\Lambda} P_{sX} P_{\bar{s}X} + R_{s\bar{s}\bar{s}} P_{s\Lambda} P^2_{\bar{s}X} + \\
&\qquad + 2R_{ss\bar{s}\bar{s}} P_{s\Lambda} P_{sX} P^2_{\bar{s}X}, \\
F(K^0) &= R_s P_{sK^0} + R_{\bar{s}} P_{\bar{s}K^0} + + R_{s\bar{s}}(P_{sK^0} P_{\bar{s}X} + P_{\bar{s}K^0} P_{sX}) + \\
&+ R_{ss\bar{s}}(2P_{sK^0} P_{\bar{s}X} P_{sX} + P_{\bar{s}K^0} P^2_{sX}) + \\
&+ R_{s\bar{s}\bar{s}}(2P_{\bar{s}K^0} P_{\bar{s}X} P_{sX} + P_{sK^0} P^2_{\bar{s}X}) + \\
&+ 2R_{ss\bar{s}\bar{s}}(P_{sK^0} P^2_{\bar{s}X} P_{sX} + P_{\bar{s}K^0} P_{\bar{s}X} P^2_{sX}), \\
F(\bar{\Lambda}) &= R_{\bar{s}} P_{\bar{s}\bar{\Lambda}} + R_{s\bar{s}} P_{\bar{s}\bar{\Lambda}} P_{sX} + R_{ss\bar{s}} P_{\bar{s}\bar{\Lambda}} P^2_{sX} + 2R_{s\bar{s}\bar{s}} P_{\bar{s}\bar{\Lambda}} P_{sX} P_{\bar{s}X} + \\
&\qquad + 2R_{ss\bar{s}\bar{s}} P_{\bar{s}\bar{\Lambda}} P_{\bar{s}X} P^2_{sX}, \\
F(K^0K^0) &= R_{s\bar{s}} P_{sK^0} P_{\bar{s}K^0} + R_{ss\bar{s}}(2P_{sK^0} P_{\bar{s}K^0} P_{sX} + P^2_{sK^0} P_{\bar{s}X}) + \\
&+ R_{s\bar{s}\bar{s}}(2P_{sK^0} P_{\bar{s}K^0} P_{\bar{s}X} + P^2_{\bar{s}K^0} P_{sX}) + \\
&+ R_{ss\bar{s}\bar{s}}(P^2_{sK^0} P^2_{\bar{s}X} + P^2_{\bar{s}K^0} P^2_{sX} + 4P_{sK^0} P_{sX} P_{\bar{s}K^0} P_{\bar{s}X}),
\end{aligned}$$

etc.

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