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A STUDY OF THE NEUTRINO PRODUCTION OF ϕ AND D_s^+ MESONS

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Abstract

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The charged current neutrino production of ϕ and D_s^+ mesons is studied, using the data obtained with the SKAT bubble chamber exposed to the Serpukhov accelerator neutrino beam. It is found that the ϕ production occurs predominantly in the forward hemisphere of the hadronic c.m.s. (at $x_{\rm F} > 0$, $x_{\rm F}$ being the Feynman variable), with the mean yield strongly exceeding the expected yield of directly produced ϕ mesons and varying from $\langle n_\phi(x_{\rm F} > 0)\rangle = (0.92 \pm 0.34) \cdot 10^{-2}$ at $W > 2$ GeV up to $(1.23 \pm 0.53) \cdot 10^{-2}$ at $W > 2.6$ GeV and $(1.44 \pm 0.69) \cdot 10^{-2}$ at $W > 2.9$ GeV, W being the invariant mass of the hadronic system. For the first time, the inclusive yield of leading D_s^+ mesons carrying more than $z = 0.85$ of the current c-quark energy is estimated: $\langle n_{D_s^+}(z > 0.85, W > 2.9 \text{ GeV})\rangle = (6.64 \pm 1.91) \cdot 10^{-2}$. It is shown, that the shape of measured ϕ meson differential spectrum on $x_{\rm F}$ is reproduced by that expected from the $D_s^+ \to \phi X$ decays. An indication was obtained that this expected spectrum underestimates the measured ϕ yield.

Аннотация

Агабабян Н.М., Григорян Н., Иванилов А.А. и др. Исследование нейтринорождения ϕ- и D_s^+-мезонов: Препринт ИФВЭ 2010–5. – Протвино, 2010. – 11 с., 3 рис., 1 табл., библиогр.: 16.

Изучено нейтринорождение через заряженный ток ϕ-и D_s^+-мезонов в эксперименте на пузырьковой камере СКАТ, экспонированной в нейтринном пучке Серпуховского ускорителя. Полученные данные свидетельствуют о том, что образование ϕ-мезонов происходит преимущественно в переднюю полусферу адронной с.ц.м. ($x_{\rm F} > 0$, где $x_{\rm F}$ – переменная Фейнмана). Средний выход ϕ-мезонов намного превышает ожидаемое значение пряморожденных ϕ-мезонов и варьируется от $\langle n_\phi(x_{\rm F} > 0)\rangle = (0.92 \pm 0.34) \cdot 10^{-2}$ при $W > 2$ ГэВ до величины $(1.23 \pm 0.53) \cdot 10^{-2}$ при $W > 2.6$ ГэВ и $(1.44 \pm 0.69) \cdot 10^{-2}$ при $W > 2.9$ ГэВ, где W – инвариантная масса адронной системы. Впервые получена оценка инклюзивного выхода лидирующих D_s^+ мезонов, уносящих долю энергии c-кварка, большую чем $z = 0.85$: $\langle n_{D_s^+}(z > 0.85, W > 2.9 \text{ GeV})\rangle = (6.64 \pm 1.91) \cdot 10^{-2}$. Показано, что форма измеренного дифференциального спектра ϕ-мезона по $x_{\rm F}$ воспроизводится спектром, ожидаемым от распада $D_s^+ \to \phi X$. Получено указание на то, что этот ожидаемый спектр недооценивает измеренный выход ϕ-мезонов.

1. INTRODUCTION

The total and differential yields of hadrons in leptonuclear reactions reflect the space-time structure of the quark string fragmentation and the formation of hadrons, both produced directly or as a result of secondary intranuclear interactions or originated from the decays of resonances. The latter play a significant role in the production of stable hadrons (pions and kaons). For example, in the case of neutrino induced reactions the fraction of pions from the decays of light meson resonances (up to masses ~ 1 GeV/c^2) composes about 20–40%, depending on the pion type and the neutrino energy E_ν (see [1] and references therein). The information on the space-time structure of the hadron formation based only on the data on stable hadrons would, therefore, be rather incomplete and should be complemented by the data on the resonance production. The latter data themselves provide more direct information on the quark string fragmentation, since they are, in general, expected to be less contaminated by a contribution from the decays of the higher-mass resonances. This contribution can be rather different for various resonances and in various kinematic regions of their production.

In our recent work [1] it has been shown that unfavored ϕ meson (not containing the current quark of the main sub-process $\nu d \to \mu^- u$) production occurs predominately in the forward hemisphere in the hadronic c.m.s. (with $x_{\rm F} > 0$, $x_{\rm F}$ being the Feynman variable), quite the contrary with other unfavored resonances. So we should pay more attention to the ϕ neutrinoproduction.

Note first of all, that the neutrino production of direct ϕ mesons both unfavored and especially favored (containing the current quark of specific sub-process of their creation, which differs with the main sub-process $\nu d \to \mu^- u$) is expected to be strongly suppressed as compared to other favored vector mesons, for example, ω meson (with the same spin and isospin) which can be produced via the main sub-process $\nu d \to \mu^- u$ followed by the recombination of the current u-quark with a $\bar{u}$-antiquark created at the string breaking. The production of a favored ϕ meson, which proceeds via the sub-process $\nu\bar{u} \to \mu^-\bar{s}$ followed by the recombination with a s-quark, is triple-suppressed as compared to the ω

production due to: i) the suppressed magnitude of the V_{us} element of Cabbibo-Kobayashi-Maskawa matrix [2]; ii) the strangeness suppression in the quark string fragmentation [3]; iii) the smallness of the fraction of the nucleon momentum (integrated over the Bjorken x_B variable) carried by the $\bar{u}$-antiquark as compared to that for the d-quark (see e.g. [4]). The product of these suppression factors is about $5 \cdot 10^{-4}$. Even when taking into account the contribution from the competing recombination processes, e.g. $u\bar{u} \to \pi^0, \rho^0, \eta, \eta^{'}$ for the case of ω and $s\bar{s} \to \eta, \eta^{'}$ for the case of ϕ, the expected ratio of the yields of favored ϕ and ω mesons remains very small, no more than 10^{-3}.

This value is in strict contrast with experimentally estimated ratio $\langle n_\phi(x_{\rm F} > 0)\rangle / \langle n_\omega(x_{\rm F} > 0)\rangle = 0.18 \pm 0.08$ at $x_{\rm F} > 0$ [1], indicating on the dominant role of indirect processes in the ϕ neutrino production. One of them is, probably, related to the production of the charmed, strange D_s^+ meson via the sub-process on a strange sea quark, $\nu s \to \mu^- c$, followed by the recombination of the charm quark with the sea $\bar{s}$-antiquark from the nucleon remnant, $(c\bar{s}) \to D_s^+$. Since here no creation of an extra $(q\bar{q})$ pair is necessary, the D_s^+ meson can carry the overwhelming fraction z of the current c-quark energy and then transfer a significant part of the latter to the ϕ meson in $D_s^+ \to \phi X$ decays (which occur with a summary rate 16.1±1.6% [2]). An alternative sub-process, leading to the D_s^+ production (with approximately the same probability as in the previous case), is $\nu d \to \mu^- c$ followed by the recombination of the c-quark with a $\bar{s}$-antiquark created at the string breaking. In this case, however, D_s^+ carries on an average a lesser energy fraction z.

This work is devoted to the experimental study of the neutrino production of ϕ and D_s^+ mesons, with a particular aim to check the aforesaid mechanism of the indirect ϕ production. In Section 2, the experimental procedure is described. Section 3 presents the experimental data on the total and differential yields of ϕ meson. In Section 4, several decay modes of D_s^+ meson are analyzed and an estimation of its yields is inferred for the case of the leading D_s^+ meson carrying the overwhelming fraction ($z > 0.85$) of the current quark energy. The results are summarized in Section 5.

2. EXPERIMENTAL PROCEDURE

The experiment was performed with SKAT bubble chamber [5], exposed to a wideband neutrino beam obtained with a 70-GeV primary protons from the Serpukhov accelerator. The chamber was filled with a propane-freon mixture containing 87 vol% propane (C_3H_8) and 13 vol% freon (CF_3Br) with the percentage of nuclei H:C:F:Br = 67.9:26.8:4.0:1.3 %. A 20-kG uniform magnetic field was provided within the operating chamber volume.

Charged current (CC) interactions containing a negative muon with momentum p_μ >0.5 GeV/c were selected. Other negatively charged particles were considered to be π^- mesons, except for the cases explained below. Protons with momentum below 0.6 GeV/c and a fraction of protons with momentum 0.60–0.85 GeV/c were identified by their stopping in the chamber. Non-identified positively charged particles were considered to be π^+ mesons, except for the cases explained below. Events in which errors in measuring the momenta of all charged secondaries and photons were less than 60%

and 100%, respectively, were selected. The mean relative error $\langle \Delta p/p \rangle$ in the momentum measurement for muons, pions and gammas was, respectively, 3%, 6.5% and 19%. Each event is given a weight which corrects for the fraction of events excluded due to improperly reconstruction. More details concerning the experimental procedure, in particular, the estimation of the neutrino energy E_ν and the reconstruction of $\pi^0 \to 2\gamma$ and neutral strange particle decays can be found in our previous publications [6, 7, 8].

The events with $3 < E_\nu < 30$ GeV were accepted, provided that the reconstructed mass W of the hadronic system exceeds $W_{\rm min} = 2$ GeV. No restriction was imposed on the transfer momentum squared Q^2. The number of accepted events was 4577 (5784 weighted events). The mean values of the kinematic variables were $\langle E_\nu \rangle = 10.7$ GeV, $\langle W \rangle = 3.0$ GeV, $\langle W^2 \rangle = 9.6$ GeV^2, $\langle Q^2 \rangle = 2.8$ (GeV/c)^2. About 8% of neutrino interactions occur on free hydrogen. This contribution was subtracted using the method described in [9, 10].

When considering the production of resonances decaying into charged kaons, the K^- and K^+ hypothesis was applied, respectively, for negatively charged particles and non-identified positively charged particles with momenta $p > p_{\rm cut} = 0.55$ GeV/c, introducing a proper corrections for the momentum of these particles. It has been checked that the choice of lower values of $p_{\rm cut}$ does not practically influence the results presented in next sections.

3. THE TOTAL AND DIFFERENTIAL YIELDS OF ϕ MESON

The K^+K^- effective mass distributions for three different ranges of $x_{\rm F}$ are plotted in Figure 1. The main problem in the ϕ signal separation is the large background from misidentified $\pi^+\pi^-$ pairs having small effective masses. The background related to the correlated low-mass $\pi^+\pi^-$ from $\eta \to \pi^+\pi^-\pi^0$, $\omega \to \pi^+\pi^-\pi^0$ and $\rho \to \pi^+\pi^-$ decays was subtracted from experimental distributions using the data on these resonances obtained in [1].

To describe the remaining (combinatorial) background, two methods were applied. Firstly, it is the mixed event method, in which the shape of the background distribution was determined combining kaons from different events of the same topology and ranges of global kinematic variables (E_ν, W). The normalization of the background distribution was kept as a free parameter when fitting the experimental mass distribution. Another method is the fitted background method, in which the background was approximated by

$$\mathrm{BG}(m) = B \cdot (m - 2m_K)^\beta \cdot \exp\left(-\gamma m\right) , \tag{1}$$

where m_K is the charged kaon mass, while B, β and γ are free parameters (in some cases γ was fixed to zero).

The signal distribution was parametrized by a Gaussian form

$$G_\phi(m) = \alpha_\phi \cdot \exp[-\frac{(m - m_\phi)^2}{2\sigma_\phi^2}] , \tag{2}$$

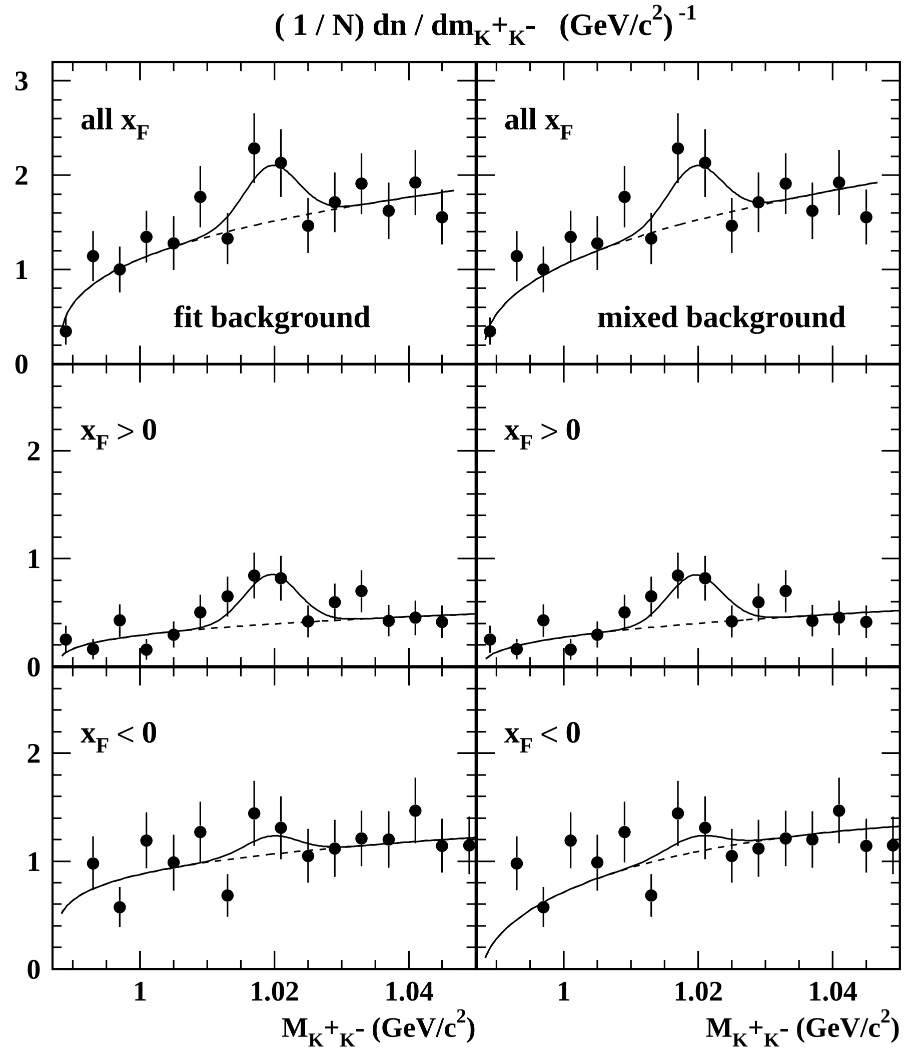

Figure 1. The K^+K^- effective mass distributions at $W > 2$ GeV. The curves are the fit results for two cases of the background description: using the analytical form (1) (the left panel) and the mixed event method (the right panel).

with the fixed pole mass $m_\phi = 1019$ MeV and the experimental resolution $\sigma_\phi = 4$ MeV (estimated by simulations, resulting in a FWHM value $\Gamma_\phi^{\rm res} \approx 10$ MeV exceeding largely the ϕ natural width $\Gamma_\phi^0 \approx 4.3$ MeV).

The mass distributions shown in Figure 1 were fitted as a sum of the signal and background distributions. The fit results for both background methods turned out to be practically the same. As it is seen, the data exhibit a clear ϕ signal at $x_{\rm F} > 0$, with the corresponding yield $\langle n_\phi(x_{\rm F} > 0)\rangle = (0.92 \pm 0.34) \cdot 10^{-2}$ (corrected for unobserved ϕ decay modes). No ϕ production is observed in the backward hemisphere ($x_{\rm F} < 0$), where the data are consistent with the background distribution. As a result, the ϕ signal in the full $x_{\rm F}$-range turns out to be less expressed as compared to that at $x_{\rm F} > 0$, leading to a less accurate estimation of the total yield: $\langle n_\phi\rangle = (1.19 \pm 0.61) \cdot 10^{-2}$.

We have also obtained the $W_{\rm min}$-dependence of $\langle n_\phi(x_{\rm F} > 0)\rangle$ and found it to increase continuously from $\langle n_\phi(x_{\rm F} > 0)\rangle = (0.8 \pm 0.3) \cdot 10^{-2}$ at $W_{\rm min} = 1.8$ GeV [1] to $\langle n_\phi(x_{\rm F} > 0)\rangle = (1.23 \pm 0.53) \cdot 10^{-2}$ and $(1.44 \pm 0.69) \cdot 10^{-2}$ at $W_{\rm min} = 2.6$ GeV and 2.9 GeV, respectively.

The differential spectrum $dn_\phi/dx_{\rm F}$, compared to that for ρ^0 meson [11] (at $W > 2$ GeV), is presented in Figure 2, from which two observations emerge. Firstly, unlike ϕ meson, the yield of ρ^0 in the backward hemisphere is not much smaller than that in the forward hemisphere. This fact can be explained [11] by a contribution from secondary intranuclear interactions of pions, $\pi N \to \rho^0 X$, resulting in a ρ^0 multiplicity gain, mainly at $x_{\rm F} < 0$. Nothing similar happens with ϕ, due to a much smaller probability of the ϕ production in secondary interactions (see Section 5 for details). Secondly, the yield of ρ^0 is rather prominent at large $x_{\rm F} > 0.6$ – a characteristic feature for the direct leptoproduction of a favored hadron. On the contrary, the yield of ϕ is more concentrated around moderate positive values of $x_{\rm F}$, indicating on its origin from the decay of a favored leading resonance. A probable candidate for the latter is, as it was mentioned in Introduction, the charmed, strange D_s^+ meson the production of which is considered in the next section.

4. THE YIELD OF D_s^+ MESON

As it was mentioned above, the $x_{\rm F}$-dependence of the ϕ meson yield indicates on its origin from the decay of leading D_s^+ mesons which can be produced, for example, in exclusive reactions

$$\nu N \to \mu^- + N^* + D_s^+\,(D_s^{*+})\,, \tag{3}$$

and

$$\nu N \to \mu^- + Y + D_s^+\,(D_s^{*+})\,, \tag{4}$$

with the vector D_s^{*+} state decaying into $D_s^+\gamma$ (94.2%) or $D_s^+\pi^0$ (5.8%), a nucleon remnant N^* (turning into a nucleon or a low-state resonance), and a hyperon Y. In reactions (3) and (4), most of D_s^+ mesons carry the overwhelming fraction z of the current c-quark energy.

The mean yield of the leading D_s^* vector meson (with $z > 0.75$) was measured earlier in $\bar{\nu}Ne$ interactions at $W > 3$ GeV, resulting in $\langle n_{D_s^{*-}}(z > 0.75)\rangle = 0.051 \pm 0.016$ [12]. One can assume, that the mean yield of the pseudo-scalar D_s^- (direct production) composes 1/3 of that for D^{*-}, i.e. the summary yield of D_s^- is expected to be about 0.068 ± 0.021, This result is leading to the mean yield of the decay ϕ mesons $\langle n_\phi^{\rm dec}\rangle = 0.014 \pm 0.006$

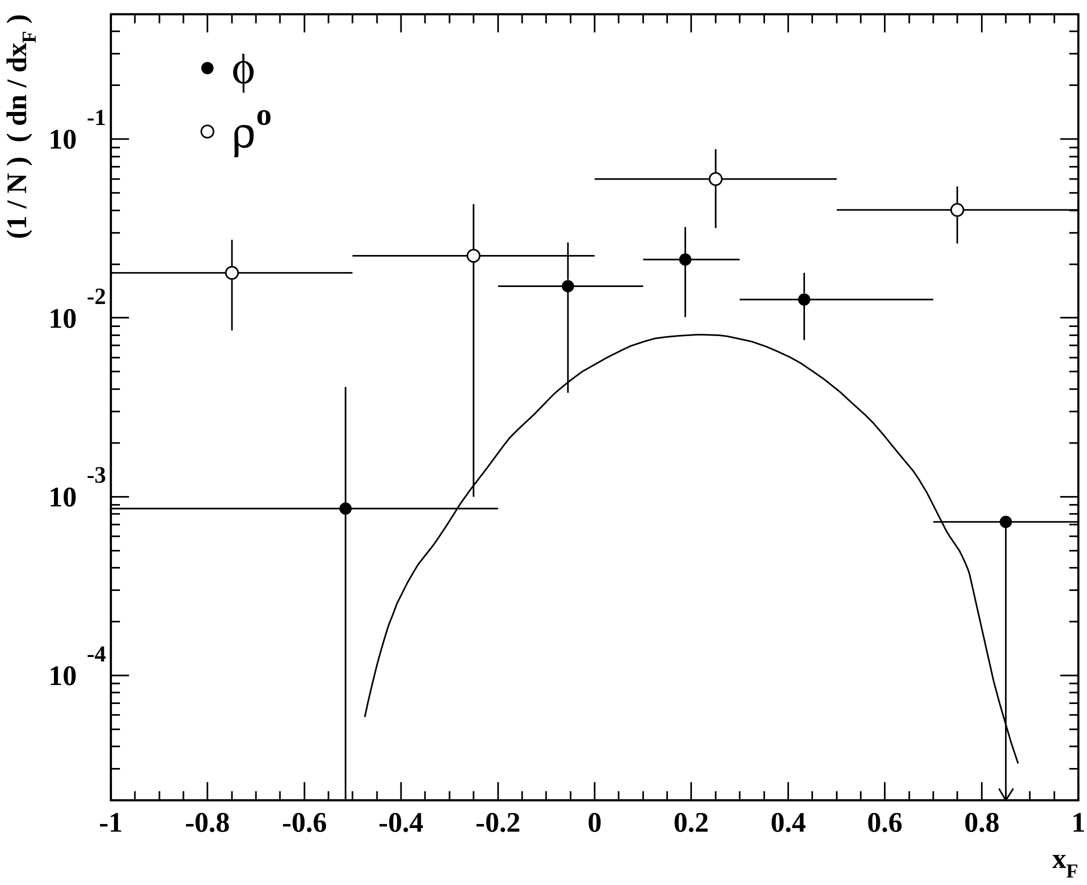

Figure 2. The x_{F}-spectra for ϕ and ρ^0 at $W > 2$ GeV. The curve is the expected distribution for ϕ mesons from the D_s^+ decays.

per CC $\bar{\nu}Ne$ interaction. This estimation is close to our measurement at $W > 2.9$ GeV: $\langle n_\phi \rangle = 0.014 \pm 0.007$.

Below we consider hadronic decay modes A–F (Table 1) of D_s^+ with decay fractions exceeding a few percent. A rather severe cut was applied on z (> 0.85) of the D_s^+ in order to reduce the contribution from the background processes. The events with $W <$ 2.9 GeV, i.e. below the threshold of the D_s^+ production, were excluded (it should be, however, noted, that the experimental resolution of W is about 10% in this experiment, and hence the events with the estimated value of W in between $2.6 < W < 2.9$ GeV can also have a small contribution to the D_s^+ production). The experimental mass resolutions (estimated by simulations) for considered channels are quoted in Table 1.

The main channels with a K^+K^- pair in the final states are: $K^+K^-\pi^+$ (A) and $K^+K^-\pi^+\pi^0$ (B). The contamination from $\pi^+\pi^-$ pairs is expected [12] to be more promi-

Table 1. The considered D_s^+ decay modes, experimental mass resolutions, estimated yields at $z > 0.85$ and decay fractions

D_s^+ decay mode	Mass resolution (MeV)	Estimated yield ($z > 0.85$, in 10^{-2})	Decay fraction (%) [2]
A. $K^+K^-\pi^+$	22	0.56±0.26	5.5±0.3
B. $K^+K^-\pi^+\pi^0$	45	0.50±0.25	5.6±0.5
C. $3\pi^+2\pi^-\pi^0$	42	0.17±0.12	4.9±3.2
D. $\rho^+\eta'$, $\eta' \to \rho^0\gamma$	52	0.25±0.20	3.6±0.6
E. $\rho^+\eta$, $\eta \to \pi^+\pi^-\pi^0$	120	0.09±0.09	3.0±0.5
F. $\rho^+\eta$, $\eta \to \gamma\gamma$	200	0.27±0.20	5.1±0.8
	sum	1.84±0.48	27.7±3.4

nent at large (in the absolute value) negative values of $\cos\vartheta^*_{KK}$, ϑ^*_{KK} being the angle between the K^+K^- direction in the D_s^+ candidate rest frame and the direction of the Lorentz boost from the lab system to the D_s^+ rest frame. We excluded the combination with $\cos\vartheta^*_{KK} < -0.9$ where a significant enhancement of the number of combinations was observed. For channel B containing a π^0, a cut $115 < m_{\gamma\gamma} < 155$ MeV was applied for the $\gamma\gamma$ effective mass (the same cut was also applied for channels C–F containing one or two neutral pions in the final state). The effective mass distributions for channels A and B are plotted in Figure 3a and 3b. For both channels, an excess of events around the D_s^+ mass is observed above the combinatorial background which can be satisfactorily described using the mixed event method (the dashed curves). The experimental distributions were fitted by a sum of a Gaussian (with the width quoted in Table 1) and the mixed background distribution. The resulting yields, corrected for the applied cuts and the contamination from the background $\gamma\gamma$ combinations (see [13] for details), are quoted in Table 1.

A rough estimation for the yield of the channel C was extracted from the excess of events above the combinatorial background in the D_s^+ mass region (Fig. 3c). The combinatorial background was obtained with the mixed event method and normalized to the experimental distribution above 2.15 GeV/c^2 (dashed curve). The mean yield, obtained after introducing corrections related to the π^0 reconstruction, is quoted in Table 1.

To select events, candidates to channel $\rho^+\eta', \eta' \to \rho^0\gamma$ (D), the following cuts were applied: the effective mass of $\pi^+\pi^-$ from the ρ^0 decay is enclosed in the range 0.60–0.95 GeV/c^2; the effective mass of $\pi^+\pi^0$ from the ρ^+ decay is enclosed in a slightly wider (as compared to ρ^0) range of 0.57−0.97 GeV/c^2, in view of worse mass resolution

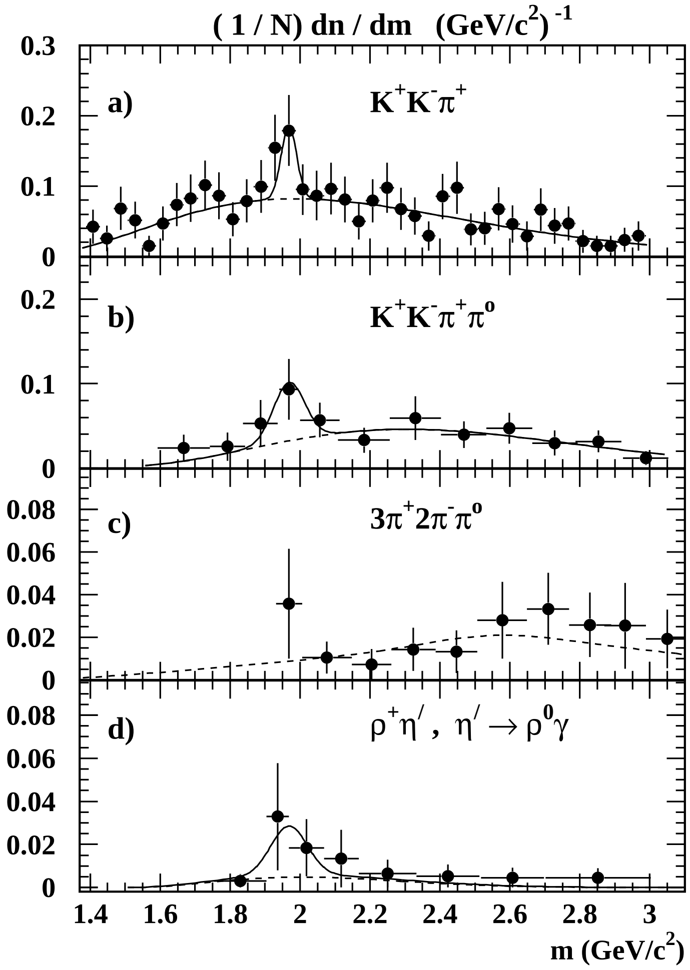

Figure 3. The effective mass distribution for channels A–D (see Table 1) at $W > 2.9$ GeV. The curves are the fit results (see the text).

($\sigma_{\rho^+} = 47$ MeV) as compared to $\sigma_{\rho^0} = 20$ MeV (see [1] for details); the effective mass of $\rho^0\gamma$ from the η' decay is enclosed in the range of $m_{\eta'} \pm 2\sigma(\eta' \to \rho^0\gamma)$, with the mass resolution $\sigma(\eta' \to \rho^0\gamma) = 30$ MeV. The effective mass distribution for channel D plotted in Fig. 3d is fitted as a sum of a Gaussian (with the width quoted in Table 1) and the mixed background distribution. The resulting yield, corrected for the applied cuts, is quoted in Table 1.

To select events, candidates to channels $\rho^+\eta, \eta \to \pi^+\pi^-\pi^0$ (E) and $\rho^+\eta, \eta \to \gamma\gamma$ (F), the following cuts were applied: the effective masses of $\pi^+\pi^-\pi^0$ and $\gamma\gamma$ from the η decay are enclosed in the ranges of $m_\eta \pm 2\sigma(\eta \to \pi^+\pi^-\pi^0)$ and $m_\eta \pm 2\sigma(\eta \to \gamma\gamma)$, with the mass resolutions, respectively, $\sigma(\eta \to \pi^+\pi^-\pi^0) = 28$ MeV [1] and $\sigma(\eta \to \gamma\gamma) = 62$ MeV. After these cuts, only one event, candidate to channel E, and two events, candidates to channel F, survived. All three events had effective masses compatible with the D_s^+ mass within $\pm$ 1.5 mass resolution for the corresponding channel (see Table 1). The corresponding yields, corrected for the applied cuts, are quoted in Table 1.

Finally, we looked for decay channels with a K_s^0 in the final state: $K^+K_s^0$, $K_s^0K^-\pi^+\pi^-$ and $K^+K_s^0\pi^+\pi^-$, with the summary decay fraction (4.09$\pm$0.22)% [2]. No combination with $z > 0.85$ was found in the D_s^+ mass region, probably due to smallness of their decay fractions and the restricted statistics of K_s^0 mesons in our experiment.

The summary experimental yield of channels A–F (with the summary decay fraction (27.7$\pm$3.4) %) is equal to $(1.84 \pm 0.48) \cdot 10^{-2}$, resulting to the total yield of leading D_s^+ mesons equal to $\langle n_{D_s^+}(z > 0.85, W > 2.9 \text{ GeV}) \rangle = (6.64 \pm 1.91) \cdot 10^{-2}$. This value can be compared with the mean yield of the vector D_s^{*-} in $\bar{\nu}Ne$ interactions measured at slightly different kinematics: $\langle n_{D_s^{*-}}(z > 0.75, W > 3 \text{ GeV}) \rangle = (5.1 \pm 1.6) \cdot 10^{-2}$ [12].

5. DISCUSSION AND SUMMARY

The inclusive production of ϕ mesons in neutrino-nucleus interactions is studied for the first time. It is found that the ϕ production occurs predominantly in the forward hemisphere of the hadronic c.m.s., with the mean yield varying from $\langle n_\phi(x_\text{F} > 0)\rangle = (0.92 \pm 0.34) \cdot 10^{-2}$ at $W > 2$ GeV up to $(1.23 \pm 0.53) \cdot 10^{-2}$ at $W > 2.6$ GeV and $(1.44 \pm 0.69) \cdot 10^{-2}$ at $W > 2.9$ GeV. The measured yields are much larger than expected for the case of the direct ϕ neutrino production, hence indicating on a dominant role of indirect mechanisms.

A possible candidate to the latter are the secondary intranuclear interactions like

$$M + N \to \phi + X \,, \qquad (5)$$

where M denotes pions, kaons, non-strange (ρ, ω) and strange $(K^*(892))$ vector mesons, as well as η and η' mesons. To estimate the multiplicity gain $\langle n(M \to \phi)\rangle$ of ϕ meson in reactions (5), we used a simple model described and applied in [10, 11, 14]. The quantities determining $\langle n(M \to \phi)\rangle$ are the mean multiplicities $\langle n_M(x_\text{F} > 0)\rangle$ of intermediate mesons produced in νN interactions at $x_\text{F} > 0$, as well as the meson-nucleon inelastic cross sections and the cross sections $\sigma(M \to \phi)$ of reactions (5) which were used for determination of the probabilities of the secondary intranuclear interactions in the framework of the Glauber model, taking also into account the finiteness of the hadron formation time (see for details [10] and references therein).

The pion-nucleon inelastic cross sections were taken from [15]. Values of $\langle n_\pi(x_\text{F} > 0)\rangle$ were taken from [1], subtracting the contribution from the decays of meson resonances. The values of $\sigma(\pi \to \phi)$ were taken from [15] and averaged over the pion momentum range from $p_\pi \sim 2$ GeV/c up to ~ 12 GeV/c (above which the pion yield is negligible in this experiment). The mean value of $\sigma(\pi \to \phi)$ averaged over the pion and target nucleon species is in the range of $\bar{\sigma}(\pi \to \phi) = 0.035 \pm 0.015$ mb, resulting in $\langle n(\pi \to \phi)\rangle =$

$(0.05 \pm 0.03) \cdot 10^{-2}$. The cross sections $\bar{\sigma}(\rho \to \phi)$ and $\bar{\sigma}(\omega \to \phi)$ are expected to be slightly larger as compared to $\bar{\sigma}(\pi \to \phi)$ due to larger mean momenta of ρ and ω. Nevertheless, due to the smallness of their mean multiplicities [1], the contribution to the ϕ production is approximately by one order of the magnitude smaller as compared to $\langle n(\pi \to \phi) \rangle$.

The averaged cross section for kaon-induced reactions, estimated from the data compiled in [16], is in the range of $\bar{\sigma}(K \to \phi) = 0.12 \pm 0.04$ mb. The mean multiplicity of charged kaons is assumed to be equal to that of neutral ones taken from [14]. The mean multiplicities of vector mesons $K^*(890)$ were taken from [1], while the cross section $\bar{\sigma}(K^* \to \phi)$ was assumed to be equal to $\bar{\sigma}(K \to \phi)$. As a result, the summary contribution $\langle n(K \to \phi) \rangle + \langle n(K^* \to \phi) \rangle$ was estimated to be $(0.01 \pm 0.01) \cdot 10^{-2}$.

The mean multiplicities of η and η' were taken from [1]. In view of the $s\bar{s}$ content of η and η' (with probabilities 2/3 and 1/3, respectively), the ϕ production cross sections were assumed to be related to that of ρ^0 production by pions: $\bar{\sigma}(\eta \to \phi) \approx 2/3\bar{\sigma}(\pi \to \rho^0) \approx 2$ mb and $\bar{\sigma}(\eta' \to \phi) \approx 1/3\bar{\sigma}(\pi \to \rho^0) \approx 1$ mb (at p_π around a few GeV/c). Under this assumption, one obtains $\langle n(\eta \to \phi) \rangle = (0.102 \pm 0.054) \cdot 10^{-2}$ and $\langle n(\eta' \to \phi) \rangle = (0.016 \pm 0.010) \cdot 10^{-2}$, where the uncertainty in cross sections is not included in the quoted errors.

The summary contribution from all aforesaid processes does not exceed $0.2 \cdot 10^{-2}$. This value, even when assuming that all produced ϕ mesons acquire $x_{\mathrm{F}} > 0$ (which is not the case), composes only a minor fraction of the measured yield $\langle n_\phi(x_{\mathrm{F}} > 0) \rangle = (0.92 \pm 0.34) \cdot 10^{-2}$ at $W > 2$ GeV. An appreciable contribution to the latter can be provided if only the unknown cross sections $\bar{\sigma}(\eta \to \phi)$ and $\bar{\sigma}(\eta' \to \phi)$ were a few times larger than supposed above. It might be worthwhile to note, that an information about the role of secondary intranuclear interactions can be, in principle, inferred from the data (not yet existing) on the A-dependence of the ϕ yield in neutrino-nucleus reactions.

Another source of indirect ϕ production at $x_{\mathrm{F}} > 0$ are the decays of leading D_s^+ mesons carrying the overwhelming fraction z of the hadron energy. To look the neutrino production of D_s^+ mesons, six different final states of D_s^+ decays are considered requiring $z > 0.85$. For all of them, an excess of events is observed at the D_s^+ mass region, allowing to infer, for the first time in neutrino induced reactions, an estimation for its yield: $\langle D_s^+(z > 0.85, W > 2.9 \text{ GeV}) \rangle = (6.64 \pm 1.91) \cdot 10^{-2}$.

The events, candidates of the D_s^+ production, were collected to a sub-sample used furthermore for simulation of the $D_s^+ \to \phi + \rho^+$ and $D_s^+ \to \phi + \pi^+$ decays composing the overwhelming fraction (85%) of the $D_s^+ \to \phi X$ decays [2]. The simulated differential spectrum $dn_\phi^{\mathrm{dec}}/dx_{\mathrm{F}}$ at $W > 2.9$ GeV turned out to be strongly shifted towards the forward hemisphere in the hadronic c.m.s., providing 85.4% of ϕ mesons to have $x_{\mathrm{F}} > 0$ and resulting in the expected mean yield of decay indirect ϕ mesons equal to $\langle n_\phi^{\mathrm{dec}}(x_{\mathrm{F}} > 0, W > 2.9 \text{ GeV}) \rangle = (0.91 \pm 0.26) \cdot 10^{-2}$. Although the latter within errors does not contradict the measured value $\langle n_\phi(x_{\mathrm{F}} > 0, W > 2.9 \text{ GeV}) \rangle = (1.44 \pm 0.69) \cdot 10^{-2}$, an indication is obtained that the expected yield of the decay ϕ mesons underestimate the measured one.

In order to make a comparison with the measured differential spectrum at $W > 2$ GeV (plotted in Fig. 2), the yield of D_s^+ was properly re-normalized to the number of events with $W > 2$ GeV, assuming that the D_s^+ production at $W < 2.9$ GeV can be neglected. This lead to $\langle n_{D_s^+}(z > 0.85, W > 2 \text{ GeV}) \rangle = (2.74 \pm 0.79) \cdot 10^{-2}$, resulting in the expected yields of the decay ϕ mesons $\langle n_\phi^{\text{dec}}(\text{all } x_{\text{F}}, W > 2 \text{ GeV}) \rangle = (0.44 \pm 0.13) \cdot 10^{-2}$ and $\langle n_\phi^{\text{dec}}(x_{\text{F}} > 0, W > 2 \text{ GeV}) \rangle = (0.38 \pm 0.11) \cdot 10^{-2}$. These compose about the half of experimentally estimated values, respectively, $\langle n_\phi(\text{all } x_{\text{F}}, W > 2 \text{ GeV}) \rangle = (1.19 \pm 0.61) \cdot 10^{-2}$ and $\langle n_\phi(x_{\text{F}} > 0, W > 2 \text{ GeV}) \rangle = (0.92 \pm 0.34) \cdot 10^{-2}$. As a result, the magnitude of the predicted spectrum $dn_\phi^{\text{dec}}/dx_{\text{F}}$ approximately twice underestimates that for the measured one (Fig. 2). However, the discrepance between estimated and measured yields amount no more than ~ 1.5 standard deviations. Therefore we cannot make definite conclusions about this discrepance. This underestimation of the predicted spectrum can, at least partly, caused by the cut $z_{D_s} > 0.85$ applied in calculations, while some contribution from softer D_s mesons with $z_{D_s} < 0.85$ is also possible. The shape of the predicted spectrum is compatible with the experimental one.

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