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S.V.Golovkin, A.P.Kozhevnikov, V.P.Kubarovsky, A.I.Kulyavtsev,
V.F.Kurshetsov, L.G.Landsberg, V.V.Molchanov, V.A.Mukhin,
I.N.Nikitin, V.I.Solyanik, D.V.Vavilov, V.A.Viktorov
Institute for High Energy Physics, Protvino

M.Ya.Balatz, G.V.Dzubenko, G.S.Lomkatsi, V.T.Smolyankin
Institute of Theoretical and Experimental Physics, Moscow

STUDY OF THE OZI SELECTION RULE IN HADRONIC PROCESSES

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Abstract

Golovkin S.V. et al. Study of the OZI Selection Rule in Hadronic Processes: IHEP Preprint 97-20. – Protvino, 1997. – p. 19, figs. 14, refs.: 44.

In the experiments with LEPTON-F and SPHINX spectrometers the pion-induced charged exchange reactions $\pi^- + p \to \phi + n$ and $\pi^- + p \to \omega + n$ at P_{π^-}=32.5 GeV, as well as proton-induced diffractive reactions $p + N \to [p\phi] + N$ and $p + N \to [p\omega] + N$ at E_p=70 GeV were studied. The comparison of the cross-sections for ϕ and ω-production in these reactions is used for testing the OZI selection rule in hadronic processes. It has been demonstrated that in pion reactions the ratio of the yields of ϕ and ω-mesons $R(\phi/\omega) = (3\pm1)\cdot 10^{-3}$ is in a good agreement with naive quark model prediction based on the mixing in vector meson nonet and on the OZI rule ($R(\phi/\omega)_{OZI} = tg^2\Delta\theta_V \simeq 4\cdot 10^{-3}$). At the same time in proton reactions the effective ratio of ϕ and ω yields is $\sim (4 \div 7)\cdot 10^{-2}$, i.e. a strong violation of the OZI rule is observed in proton-nucleon interactions. This violation can be in favor of possible existence of some exotic $s\bar{s}$ component in the quark structure of protons.

Аннотация

Головкин С.В. и др. Исследование правила отбора OZI в адронных процессах: Препринт ИФВЭ 97-20. – Протвино, 1997. – 19 с., 14 рис., библиогр.: 44.

В экспериментах на установках ЛЕПТОН-Ф и СФИНКС исследовались пионные зарядово-обменные реакции $\pi^- + p \to \phi + n$ и $\pi^- + p \to \omega + n$ при импульсе P_{π^-}=32.5 ГэВ, а также протонные дифракционные реакции $p + N \to [p\phi] + N$ и $p + N \to [p\omega] + N$ при энергии E_p=70 ГэВ. Данные по сечениям процессов образования ϕ- и ω-мезонов использовались для проверки правила отбора OZI в адронных процессах. Показано, что для пионных реакций отношение выходов ϕ- и ω-мезонов $R(\phi/\omega) \simeq (3\pm1)\cdot 10^{-3}$ находится в хорошем согласии с предсказаниями наивной кварковой модели, основанными на данных об угле смешивания в нонете векторных мезонов и на правиле отбора OZI ($R(\phi/\omega)|_{OZI} = tg^2\Delta\theta_V \simeq 4\cdot 10^{-3}$). В то же время в протонных реакциях эффективное отношение выходов ϕ- и ω-мезонов составляет $\sim (4 \div 7)\cdot 10^{-2}$, т.е. имеет место сильное нарушение правила OZI в этих процессах. Возможно, что это свидетельствует о существовании экзотической $s\bar{s}$ компоненты в кварковом составе протонов.

1. The OZI rule

The selection rule for connected and disconnected quark diagrams that is referred to as the OZI rule has been known for a long time [1-3]. According to this rule, processes involving the annihilation or creation of a quark-antiquark pair entering into the composition of the same hadron are forbidden or, strictly speaking, strongly suppressed. The OZI rule may be illustrated by the diagrams for the production and decay of the vector mesons ω and ϕ (see Fig.1).

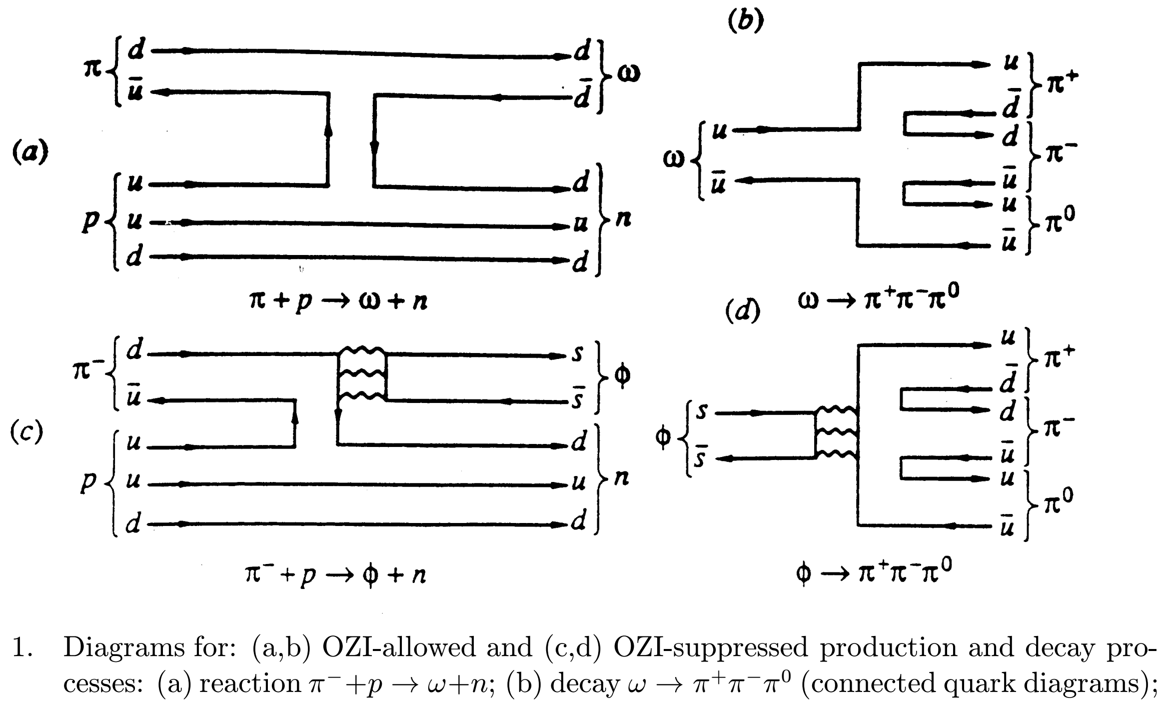

Fig. 1. Diagrams for: (a,b) OZI-allowed and (c,d) OZI-suppressed production and decay processes: (a) reaction $\pi^-+p \to \omega+n$; (b) decay $\omega \to \pi^+\pi^-\pi^0$ (connected quark diagrams); (c) reaction $\pi^-+p \to \phi+n$, and (d) decay $\phi \to \pi^+\pi^-\pi^0$ (disconnected quark diagrams).

Let us consider exclusive reaction of $q\bar{q}$ pair production $A+B \to C_1+C_2+...+C_n+(q\bar{q})$ $(q = u; d; s)$ with particles $A,\ B,\ C_i$ without strange quarks (see Ref. [4]). The ratio of amplitudes of the corresponding reactions

$$Z = \frac{\sqrt{2}M[(A+B \to C_1+C_2+...+C_n+(s\bar{s})]}{M[A+B \to C_1+C_2+...+C_n+(u\bar{u})]+M[A+B \to C_1+C_2+...+C_n+(d\bar{d})]} \qquad (1)$$

determines the violation of the OZI rule in these processes (the OZI rule demands $Z = 0$).

It is well known that neutral mesons from meson nonets are the mixture of SU(3) octet and singlet states

$$\left.\begin{array}{lcl} |\omega_8> & = & |\frac{1}{\sqrt{6}}(u\bar{u}+d\bar{d}-2s\bar{s})> \\ |\omega_1> & = & |\frac{1}{\sqrt{3}}(u\bar{u}+d\bar{d}+s\bar{s})> \end{array}\right\}.$$

For vector meson nonet

$$\left.\begin{array}{l} |\phi>= cos\theta_V \cdot |\omega_8> -sin\theta_V \cdot |\omega_1>= -cos\alpha \cdot |s\bar{s}> -sin\alpha \cdot |\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})> \\ |\omega>= sin\theta_V \cdot |\omega_8> +cos\theta_V \cdot |\omega_1>= -sin\alpha \cdot |s\bar{s}> +cos\alpha \cdot |\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})> \end{array}\right\}.$$

Here θ_V is a mixing angle for vector nonet; $\alpha = \Delta\theta_V = \theta_V - \theta_V^o$; $\theta_V^o = arc\ tg\frac{1}{\sqrt{2}} = 35.3^o$ is an ideal mixing angle (for this ideal mixing $|\phi>= -|s\bar{s}>$; $|\omega>= \frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})>$), as on diagrams in Fig.1).

For the ratio of amplitudes of ϕ and ω production the following expression was derived [4]:

$$\beta = \frac{M(A+B \to C_1+C_2+...+C_n+\phi)}{M(A+B \to C_1+C_2+...+C_n+\omega)} = -\frac{Z+tg\alpha}{1-Z \cdot tg\alpha} \qquad (2)$$

or

$$Z = (\beta + tg\alpha)/(\beta \cdot tg\alpha - 1). \qquad (3)$$

Thus the ratio of corresponding cross sections is

$$R(\phi/\omega) = \frac{\sigma(A+B \to C_1+C_2+...+C_n+\phi)}{\sigma(A+B \to C_1+C_2+...+C_n+\omega)} = |\beta|^2 \cdot f = \left(\frac{Z+tg\alpha}{1-Z \cdot tg\alpha}\right)^2 \cdot f, \qquad (4)$$

where f is a kinematical phase space correction factor.

Because the phase of β is unkown it is only possible to estimate the limits for the OZI violation factor $|Z|$:

$$|\frac{-|\beta|+tg\alpha}{1+|\beta| \cdot tg\alpha}| < |Z| < \frac{|\beta|+tg\alpha}{1-|\beta| \cdot tg\alpha}. \qquad (5)$$

Many measurements of the R ratio and testing of the OZI rule in different reactions were made in the last thirty years. It is the generalization of the OZI rule for the processes with charmed quarks which explaines the anomalously small decay width of the J/ψ particle, representing a bound $c\bar{c}$ state (in analogy with ϕ meson).

Recent years have seen a revived interest in the OZI rule. First, intensive searches for exotic hadrons (see the surveys in [5-10] and references therein) are greatly facilitated by choosing production reactions in which the formation of conventional particles is suppressed by the OZI rule [11-14]. Since this rule may be significantly violated for exotic hadrons because of their complex color structure, signals from exotic and cryptoexotic particles are expected to benefit from more favorable background conditions in OZI-suppressed production processes. While the $\phi\pi$ and $\phi\rho$ decays of isovector mesons with conventional quark structure $|(u\bar{u}-d\bar{d})/\sqrt{2}>$ are suppressed by the OZI rule (the corresponding probabilities are reduced more than by two orders of magnitude), the same decay channels may prove much more probable for exotic multiquark mesons with hidden strangeness $|(u\bar{u}-d\bar{d})s\bar{s}/\sqrt{2}>$ and hybrids states like $|(u\bar{u}-d\bar{d})g/\sqrt{2}>$. Farthermore, the unexpected results obtained in deep-inelastic lepton scattering on polarized nucleons led to the well-known nucleon-spin crisis [15,16]. To explain this phenomenon, it has been hypothesized that nucleons involve an enchanced quark component with hidden strangeness, which may induce substantial violations of the OZI rule in nucleon processes [17-20]. Strong violations of the OZI rule were indeed observed in the relative ϕ and ω yields from some channels of $\bar{p}p$ annihilation (the reactions $\bar{p}p \to \phi\pi^o$, $\bar{p}p \to \omega\pi^o$, $\bar{p}p \to \phi\gamma$ and $\bar{p}p \to \omega\gamma$ [19-21]).

The above arguments suggest that the OZI rule must be further tested in various production and decay processes involving conventional particles. Toward this, we analyzed a number of processes studied in experiments with LEPTON-F and SPHINX detectors. In particular, in earlier measurements on the LEPTON-F setup the investigation of this selection rule was performed in the OZI-suppressed charge-exchange reaction

$$\pi^- + p \to \phi + n \tag{6}$$

at a relatively high primary momentum of P_{π^-}=32.5 GeV [22], as well as in the decay of the isovector meson $B/b_1(1235)$ with conventional quark structure $\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d})$ on the channel:

$$B/b_1(1235) \to \phi\pi^o \tag{7}$$

(see [23]). Preliminary results of these studies were reported in [24]. In the experiments with the SPHINX spectrometer (which evolved from the LEPTON apparatus) a comparative analysis of $[p\phi]$ and $[p\omega]$ systems produced in pN diffractive-like reactions was carried out and the OZI rule in nucleon processes was tested by these data [25].

2. Charge exchange reaction $\pi^- + p \to \phi + n$ at P_π=32.5 GeV [22]

Reaction (6) was studied in several experiments at different energies in the region between 2.1 and 16 GeV (see [26],[27] and the summary of other data in [26]). There is a strong energy dependence of the cross sections for (6) and $R(\phi/\omega)$ ratio in these data and some inconsistency for the $R(\phi/\omega)$ values in different experiments. This makes it quite desirable to measure the cross section of (6) and $R(\phi/\omega)$ at higher energy. This measurement was made in our experiment at P_π=32.5 GeV [22]. In this experiment reaction (6) was studied with the LEPTON-F spectrometer simultaneously with the main research program for this setup aimed at the investigation of $\phi\pi^o$ system in meson reaction [12,24,28], as well as at the search for rare meson radiative decays on $\phi\gamma$ and $\pi^+\pi^-\gamma$ channels [24,28-31].

The LEPTON-F setup included a magnetic spectrometer with proportional chambers and scintillator hodoscopes and multichannel γ-spectrometer with total absorption lead glass detectors. Three gas Cherenkov counters $\check{C}_1 - \check{C}_3$ were used to identify beam particles, while a wide-aperture threshold gas counter $\check{C}_4$ placed downstream the target in front of magnetic spectrometer identified charged secondaries. A detailed description of the LEPTON-F setup was published in [28, 32].

The material and geometry of the target of the LEPTON-F setup were chosen so as to maximize the overall yields of $\phi\pi^o$, $\phi\gamma$ and $\pi^+\pi^-\gamma$ production in the corresponding charge exchange reactions ($\pi^- + p \to M + n;\ M \to \phi\pi^o$ or $M \to \phi\gamma;\ \pi^+\pi^-\gamma$). A 40 cm thick LiH target (28 g/cm^2) was found to be optimal for these purposes. The target was enclosed by special guard veto system (scintillator counters, lead-scintillator sandwiches) aimed at selecting exclusive processes under study. In these measurements 4×10^{11} π^- and 8×10^9 K^--mesons passed through the target [24,28-31].[1]

In the analysis of two-track events detected in the LEPTON-F magnetic spectrometer and identified by Cherenkov detectors the reactions

$$\pi^- + p \to [K^+K^-] + (n;\ \Delta,\ N^*) \tag{8}$$

and

$$K^- + p \to [K^+K^-] + Y \tag{9}$$

were selected after the "elastic" restriction $29 < E_{K^+} + E_{K^-} < 34$ GeV was imposed. In the invariant mass spectra on reactions (8) and (9) clear peaks corresponding to the ϕ-meson production in processes

$$\pi^- + p \to \phi + (n,\ \Delta,\ N^*) \tag{10}$$

and

$$K^- + p \to \phi + Y \tag{11}$$

were observed (Figs.2 and 3). In selection of the OZI forbidden processes (10) a special attention was paid to suppress the background from the OZI allowed reaction (11) which has two orders of magnitude higher cross section as compared with (10). Special choice of the working regime for $\check{C}_1 - \check{C}_3$ counters allowed one to suppress this background to a negligibly small level.

In order to determine the number of ϕ mesons, produced in "elastic" processes (10) (i.e. the number of events in the ϕ-peak in Fig.2), the corresponding distribution was fitted by the sum of polynomial background and the convolution of a P-wave Breit-Wigner resonance with a Gaussian function of the spectrometer resolution. Reaction (11), in which the background under the ϕ-peak is very small (see Fig.3), was used to determine the shape of the peak. Fixing the standard value of the ϕ meson width (Γ=4.22 MeV), the spectrometer resolution was found to be $\sigma_\phi = (3.0 \pm 0.3)$ MeV. Finally, the total number of events of reactions (10) was determined to be:

$$N_{n;\Delta;N^*}(\phi) = 2890 \pm 160. \tag{12}$$

[1] The fraction of K^--mesons in the negative beam with P_π=32.5 GeV was $\simeq 2\%$.

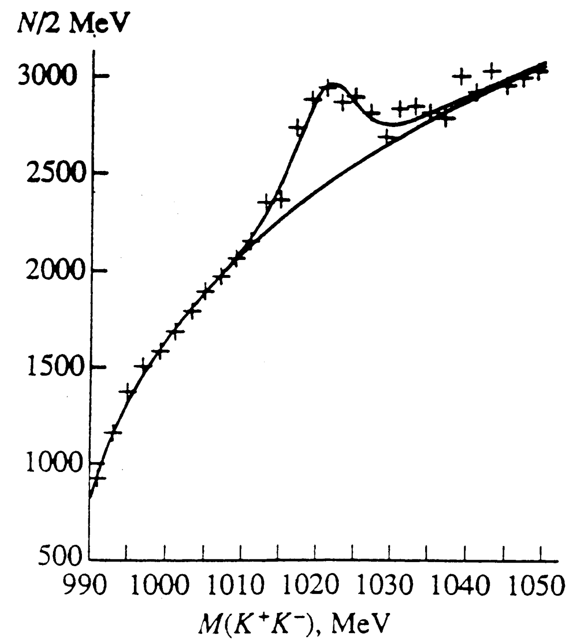

Fig. 2. Effective mass spectrum of K^+K^- system in OZI-suppressed reaction (8): $\pi^- + p \to K^+K^- + (n; \Delta; N^*)$.

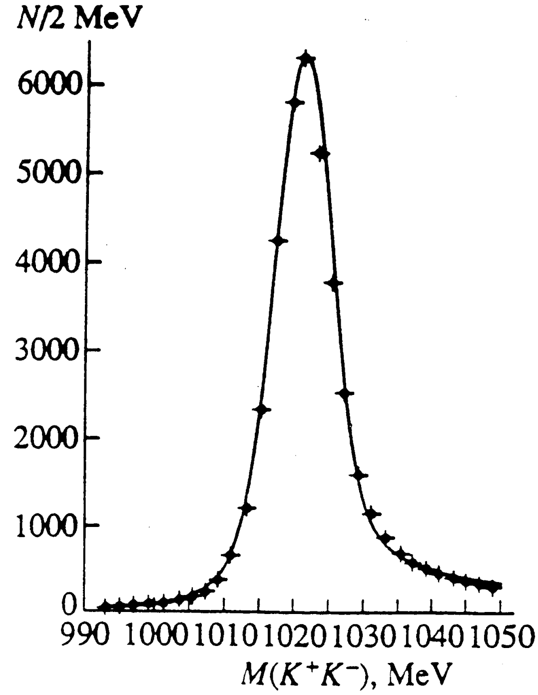

Fig. 3. Effective mass spectrum of K^+K^- system in OZI-allowed reaction (9): $K^- + p \to K^+K^- + Y$.

At the next step of data processing it was necessary to single out reaction (6) with neutron in the final state. In order to separate contributions from the reactions $\pi^- + p \to \phi + n$ and $\pi^- + p \to \phi + (\Delta; N^*)$ the information from the veto counters arranged around the target was used. The special procedure for such analysis and for absolute normalization of cross section (6) with the help of the known value of cross section for ρ^o meson production in the charge exchange reaction $\pi^- + p \to \rho^o + n$ are detailed in [22]. As a result, the number of the events for $\pi^- + p \to \phi + n$

$$N_n(\phi) = 1670 \pm 410 \tag{13}$$

and the value of the total cross section for OZI suppressed reaction (6) at P_{π^-}=32.5 GeV

$$\sigma(\pi^- + p \to \phi + n)|_{P_\pi = 32.5 \text{ GeV}} = (11.5 \pm 3.3) \cdot 10^{-33} \text{ cm}^2 \tag{14}$$

were obtained. The quoted error is largely due to systematic uncertainties associated with the normalization of the cross sections and with the separation of the contributions from different reaction channels of (10).

The cross-sections for the reaction $[\pi^- + p \to \omega + n$ were most accurately measured in two experiments [33,34]. Taking the average value from these measurements, we can determine the cross-section ratio

$$R(\phi/\omega) = \frac{\sigma(\pi^- + p \to \phi + n)}{\sigma(\pi^- + p \to \omega + n)} = \frac{(11.5 \pm 3.3) \cdot 10^{-33}}{(4.0 \pm 0.5) \cdot 10^{-30}} = (0.29 \pm 0.09) \cdot 10^{-2}. \tag{15}$$

This ratio characterizes the OZI suppression of the ϕ meson production in the pion charge exchange reaction (6) — see diagrams on Fig.1. The available data on the cross-sections of the reactions $\pi^- + p \to \phi + n$ and $\pi^- + p \to \omega + n$ at different energies [33-35] are presented in Fig.4.

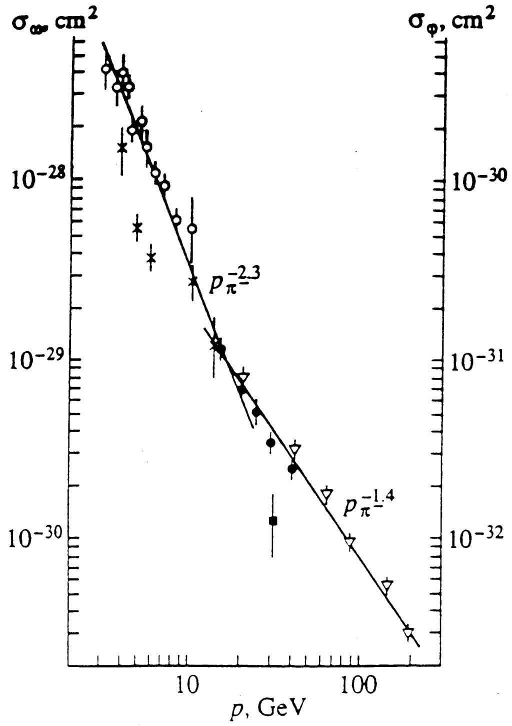

Fig. 4. Total cross sections for the reactions $\pi^- + p \to \phi + n$ and $\pi^- + p \to \omega + n$ as functions of the beam momentum P_{π^-}. Results for the reaction $\pi^- + p \to \omega + n$ correspond to the left-hand scale: (o) low-energy data [35],($\bullet$) data from [33], ∇ data from [34]. Straight lines correspond to power-law parametrizations $\sigma \sim P_{\pi^-}^{-2.3}$ and $\sigma \sim P_{\pi^-}^{-1.4}$. Results for the reaction $\pi^- + p \to \phi + n$ correspond to the right-hand scale: $\times$ — data from [35] for relatively low energies; $\blacksquare$ — results of this investigation with the LEPTON-F detector.

Ratio (15) can be used in the naive quark model by the OZI rule to determine the mixing angle θ_V for the vector meson nonet from the relation $tg^2\alpha_V = R(\phi/\omega)$, which can be obtained from (5) in the assumption of the OZI rule accomplishing, i.e. for $Z = 0$ (see also [36]). Here $\alpha_V = \theta_V - \theta_V^o$ and $\theta_V^o = 35.3^o$ is the angle of ideal mixing. It follows from (15) that $|\alpha_v| = (3.1 \pm 0.5)^o$, in excellent agreement with the data on the radiative widths $\Gamma(\phi \to \pi^o\gamma)$ and $\Gamma(\omega \to \pi^o\gamma)$ ($|\alpha_V| = (3.0 \pm 0.2)^o$ [37]) and on the quadratic mass formula for the vector nonet ($\alpha_V = (3.7 \pm 0.4)^o$ [38]). In another approach we can fix the value of the angle $\alpha_V = (3.7 \pm 0.4)^o$ from quadratic mass formula and estimate from (5) and (15) the upper limit for the OZI rule violation parameter Z:

$$|-(0.054 \pm 0.008) + (0.065 \pm 0.007)| \leqslant |Z| \leqslant (0.054 \pm 0.008) + (0.065 \pm 0.007) \quad (16)$$

or

$$|Z| < 0.13 \qquad (95\% \text{ C.L.}). \quad (17)$$

Let us compare the data for $R(\phi/\omega)$ obtained in our experiment with the data on lower energies. From the ZGS experiment [26,27] it is possible to obtain $R(\phi/\omega)|_{P_{\pi^-}=6 \text{ GeV}} = (3.2 \pm 0.4) \cdot 10^{-3}$ in good agreement with the LEPTON-F data. But this ratio increases by about an order of magnitude as P_π decreases from 6 GeV to 2.1 GeV. Such strong violation of the OZI rule at lower energies was explained in [39] by introduction of s-channel box diagrams with the threshold and duality cancellation in the intermediate states of the box. The agreement between 6 GeV data [27] and 32.5 GeV data (our experiment) and the upper limit of Z (17) are in favor of a good accomplishing of the OZI rule in pion charge exchange reactions $\pi^- + p \to \phi + n$ and $\pi^- + p \to \omega + n$ at relatively high beam momenta.

3. Search for the OZI suppressed decay $B/b_1(1235) \to \phi\pi^o$ [23]

For isovector neutral mesons with quark structure $|M_{I=1}>=|(u\bar{u}-d\bar{d})\sqrt{2}>$ the decay to $\phi\pi^o$ is OZI-forbidden and should be strongly suppressed with respect to $\omega\pi^o$ decay channel. Here are presented the LEPTON-F data on the search for the decay $B/b_1(1235) \to \phi\pi^o$ (7). It is known that the main decay channel of the $B/b_1(1235)$ meson ($M = 1231 \pm 3$ MeV, $\Gamma = 142 \pm 8$ MeV, $J^{PC} = 1^{+-}$, $I^G = 1^+$) is $B/b_1(1235) \to \omega\pi^o$ [38]. The search for decay (7) was performed in the study of the charge exchange reaction

$$\pi^- + p \to \underbrace{(\phi\pi^o)}_{\hookrightarrow K^+K^-} + n. \tag{18}$$

In these measurements (see [12,24,28] for more details) the new vector meson C(1480) was observed in the reaction

$$\pi^- + p \to \underbrace{C(1480)}_{\hookrightarrow \phi\pi^o} + n, \tag{19}$$

which made a dominant contribution to (18) and which was a major source of background for the decay signal (7). Reaction (19) is largely due to one-pion exchange mechanism (OPE) and is therefore characterized by a narrow $|t'|$ distribution. At the same time OPE is forbidden for the reaction

$$\pi^- p \to [B/b_1(1235)]^o + n, \tag{20}$$

because of the $B/b_1(1235)$-meson quantum numbers (opposite parity and charge parity). Reaction (20) is expected to be dominated by the A_2 exchange leading to a broader $|t'|$ distribution.

Therefore, the “anti OPE-cut” $|t'|$ >0.1 GeV^2 decreases the efficiency of $B/b_1(1235)$ detection in reaction (20) by no more than 25%, while $C(1480)$ production and other OPE background processes are suppressed by a factor of about 5 [12, 28].

The effective mass spectrum of the $\phi\pi^o$-system in reaction (18) at $|t'|$ >0.1 GeV^2 weighted with the efficiency of the setup is shown on Fig.5. For the evaluation of the upper limit for the cross section $\sigma[\pi^- + p \to B/b_1(1235)^o + n] \cdot BR[B/b_1(1235)^o \to \phi\pi^o]$ the number of events in the interval $1150 < M(\phi\pi) < 1330$ MeV was determined to be 78 ± 167. Therefore the upper limit for the cross section of (20) with decay mode (7) is

$$\sigma[\pi^- + p \to B/b_1(1235)^o + n]|_{p_{\pi^-}=32.5\ \mathrm{GeV}} \cdot BR[B/b_1(1235) \to \phi\pi^o] < 5\ \mathrm{nb} \quad (95\%\ \mathrm{C.L.}). \tag{21}$$

In the experiment with the GAMS-2000 facility [40] the cross section of $B/b_1(1235)$ production was determined to be

$$\sigma[\pi^- + p \to B/b_1(1235)^o + n]|_{p_{\pi^-}=38\ \mathrm{GeV}} \cdot BR[b_1(1235) \to \omega\pi^o] = 0.8 \pm 0.2\ \mu\mathrm{b}. \quad (22)$$

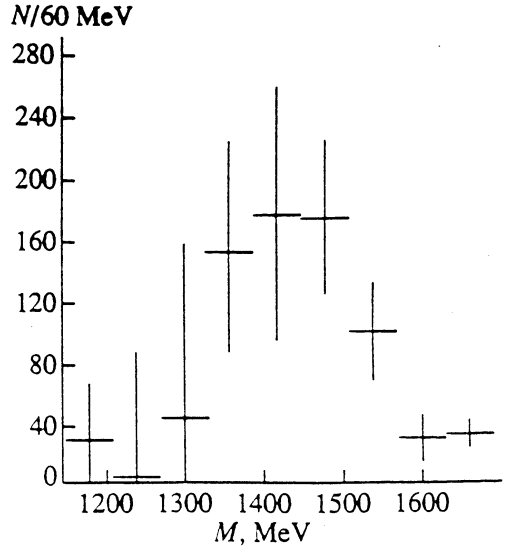

Fig. 5. Effective mass spectrum of the $\phi\pi^0$ system in the reaction $\pi^-+p \to (\phi\pi^0)+n$ (the results are weighted with detector efficiency). An "anti-OPE" selection $|t'| > 0.1$ (GeV)^2 is applied, which affects only slightly the efficiency for the reaction $\pi^- + p \to B/b_1(1235) + n$ (not proceeding via OPE exchange), but which reduces the background from the OPE-mediated reaction $\pi^- + p \to C(1480)^0 + n$ by a factor close to 5.

Taking into consideration the energy dependence of the cross section for this process $\sigma \sim P_\pi^{-1.5\pm0.2}$ [40], the upper limit for the ratio of decay branchings for $B/b_1(1235)$-meson can be obtained from (21) and (22) to be

$$R_B = BR[B/b_1(1235) \to \phi\pi^o]/BR[B/b_1(1235) \to \omega\pi^o] < 4 \cdot 10^{-3} \quad (95\%\ C.L.). \quad (23)$$

Since the decay $B/b_1(1235)^o \to \omega\pi^o$ proceeds mostly with zero orbital angular momentum [38], we can represent (23) in the form

$$R_B = [p_\phi^{(B)}/p_\omega^{(B)}]|g^2_{B\phi\pi}/g^2_{B\omega\pi}| < 4 \cdot 10^{-3} \quad (24)$$

or

$$|g^2_{B\phi\pi}/g^2_{B\omega\pi}| \leqslant 1 \cdot 10^{-2} \quad (25)$$

(after some small correction for possible contributions from D-wave decays of $B/b_1(1235)$ meson). Here, $p_\phi^{(B)}$ and $p_\omega^{(B)}$ are the decay momenta of ϕ and ω mesons in the rest frame of the $B/b_1(1235)$ meson, and $g_{B\phi\pi}$ and $g_{B\omega\pi}$ are the corresponding coupling constants. Thus, in a framework of naive quark model it is possible to obtain from (25) the limitation $|g_{B\phi\pi}/g_{B\omega\pi}|^2 \simeq tg\alpha_V^2 < 1 \cdot 10^{-2}$ for the mixing angle $\alpha_V = \vartheta_V - \vartheta_V^o$ and to conclude that the decays of the ordinary isovector meson $B/b_1(1235)$ do not contradict the OZI selection rule for connected and disconnected quark diagrams.

4. Study the OZI rule in the nucleon diffractive-like reactions $p + N \to [p\phi] + N$ and $p + N \to [p\omega] + N$

The test of the OZI selection rule for ϕ and ω meson production in proton-nucleon processes was performed in the experiments with the SPHINX spectrometer in the study of diffractive reactions

$$p + N \to [p\phi] + N \tag{26}$$

and

$$p + N \to [p\omega] + N. \tag{27}$$

Process (26) should by suppressed by the OZI rule because of disconnected character of quark diagram for ϕ production. In the naive quark model (assuming the strict OZI rule) the ratio of cross sections for ϕ and ω production is related to $\phi - \omega$ mixing and should be

$$R(\phi/\omega)|_{OZI} = tg^2\alpha_V \simeq 0.4 \cdot 10^{-2}. \tag{28}$$

Here $\alpha_V = \theta_V - \theta_V^o$ and $\theta_V^o = 35.3^o$ is the angle of ideal mixing in vector nonet (see Section 2).

Toward separating transitions (26) and (27), we investigated the reactions

$$p + N \to pK^+K^- + N, \tag{29}$$

$$p + N \to p\pi^+\pi^-\pi^o + N. \tag{30}$$

The SPHINX detector used in these measurements had already been described in detail [41]. This detector is a new modification of the LEPTON-F setup. It comprises a wide-aperture magnetic spectrometer instrumented with scintillation hodoscopes and proportional and drift chambers, a beam-determinating system, a veto system, and a multichannel γ spectrometer consisting of lead-glass full-absorption Cherenkov counters. Charged secondaries were identified by using a differential RICH device detecting several rings of Cherenkov light in a matrix of small-size photomultipliers FEU-60 and two multichannel gas threshold Cherenkov counters employed mostly for triggering.

A target (12-cm-long polyethylene of effective thickness 0.48×10^{24} CH_2/cm^2) was irradiated by 0.9×10^{11} protons of 70 GeV energy. The trigger for reaction (29) selected events with three charged secondaries, some of which were required to be slow ($\gamma < 43$, see [41]). The trigger for (30) did not require any slow secondaries and was implemented with a suppression factor of 4 because of technical limitations imposed by the data-acquisition system.

Toward isolating reaction (29) geometrically reconstructed events were required to satisfy the following selection criteria:

(1) the presence of three charged secondaries that are identified as p, K^+ and K^- in the RICH and in threshold Cherenkov counters and which originate from a common vertex within the target;

(2) the absence of photons with energy above the threshold ($E_\gamma >$0.65 GeV) detected in the γ spectrometer;

(3) fulfillment of the "elasticity" condition 65 GeV$< E_p + E_{K^+} + E_{K^-} <$75 GeV.

The K^+K^- effective-mass spectrum for reaction (29) selected in this way is illustrated in Fig.6a. This spectrum exhibits a distinct peak associated with ϕ production and which permits isolation of reaction (26). The observed ϕ mass agrees well with the tabular value [38], while the shape of the ϕ peak is consistent with that predicted by a Monte Carlo simulation taking detector resolution into account. The simulation was based on the GEANT package [42]. The detector responses to generated events with required kinematics were recorded on a tape in the real-event format. These simulated events were then subjected to the same selections as real events. In plotting distributions for reaction (26), we used the standard integral technique of background subtraction. According to this technique, the half-sum of the distributions for the ϕ-mass sidebands (0.995-1.005 annd 1.035-1.045 GeV) was subtracted from that for the central ϕ region 1.010-1.030 GeV. The above mass intervals are indicated in Fig.6a.

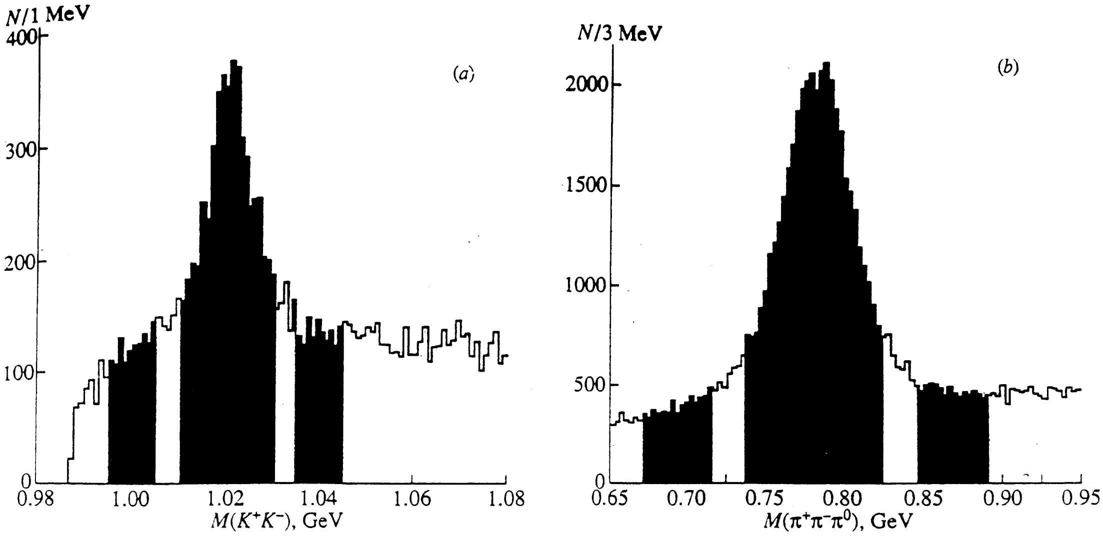

Fig. 6. Selection of the reactions $p + N \to [p\phi] + N$ (26) and $p + N \to [p\omega] + N$ (27) and illustration of sideband method for background subtraction to separate these processes: a) effective mass spectrum $M(K^+K^-)$ in $p + N \to [pK^+K^-] + N$ (29); b) effective mass spectrum $M(\pi^+\pi^-\pi^o)$ in $p+N \to [p\pi^+\pi^-\pi^o]+N$ (30). The regions of the ϕ and ω peaks and sideband regions for background subtraction to obtain all distributions in (26) and (27) are shown on these spectra.

Reaction (23) was isolated throught the following selection criteria:

(1) the presence of three charged secondaries that are identified as p, π^+ and π^- in the RICH and in the threshold Cherenkov counters and which originate from a common vertex within the target;

(2) the presence of two photons above the energy threshold (E_γ > 0.65 GeV) in the γ detector with an effective mass compatible with a π^o mass (0.11 GeV< $M(\gamma\gamma)$ <0.16 GeV);

(3) fulfillment of the "elasticity" condition 65 GeV< $E_p + E_{\pi^+} + E_{\pi^-} + E_{\pi^o}$ <75 GeV.

The $\pi^+\pi^-\pi^o$ effective mass in reaction (30) is plotted in Fig.6b. The spectrum shows an ω peak permitting the extraction of reaction (27). The observed position and shape of the peak are in good agreement with the tabular ω mass value and with mass resolution simulated by the Monte Carlo method. As before, the integral technique was used for backrground subtraction involving the mass intervals 0.737-0.825, 0.671-0.715, and 0.847-0.891 GeV, as illustrated in Fig.6b.

The distributions in the squared transverse momentum P_T^2 for reactions (26) and (27) are shown in Figs.7 and 8, respectively. Each of them is adequately described by the sum of two exponentials with nearly equal weights. The slope of the first exponential cannot be determined precisely because of a finite experimental resolution, and its visible value [$b \geqslant 50$ (GeV)$^{-2}$] suggests a coherent transition on a carbon nucleus. Since the character of these distributions is identical for reactions (26) and (27), we usually present the results for the entire P_T^2 region (except the data on Fig.13, see below).

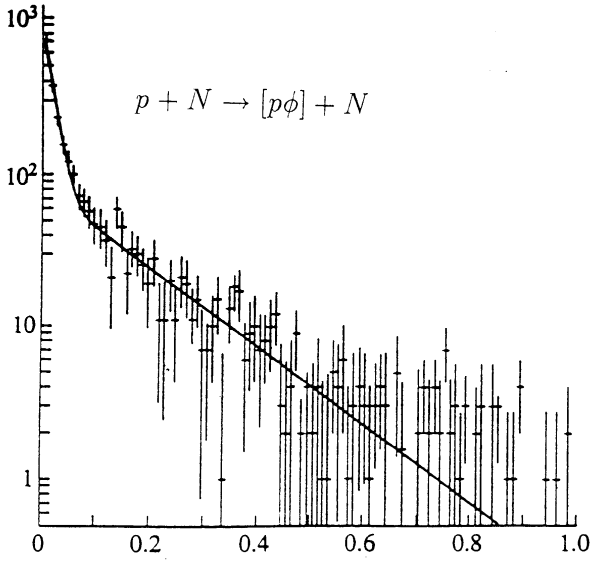

Fig. 7. Distribution of the $p\phi$ system in the square of the transverse momentum P_T^2 for reaction (26).

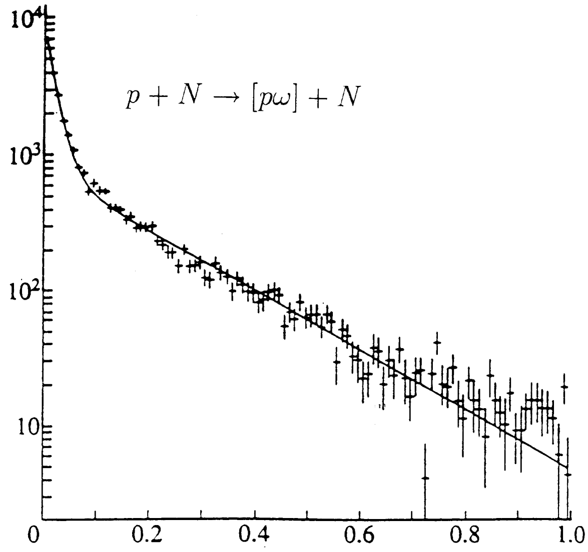

Fig. 8. Distribution of the $p\omega$ system in the square of the transverse momentum P_T^2 for reaction (27).

The distributions of events from reactions (26) and (27) in $M(p\phi)$ and $M(p\omega)$ were corrected for detection efficiencies and for the $\phi \to K^+K^-$ and $\omega \to \pi^+\pi^-\pi^o$ branching ratios. The results are illustrated in Fig.9. For convenience, the distribution in $M(p\phi)$ is scaled up by a factor of 100. The quoted errors are purely statistical. Detection efficiencies for transitions (26) and (27) were estimated by using samples of simulated events with uniform distributions in $M(p\phi)$ and $M(p\omega)$ and P_T^2 distributions similar to those observed experimentally. The angular distributions for the systems $p\phi$ and $p\omega$ and for the decay $\phi \to K^+K^-$ were assumed to be isotropic. The normal vector to the $\omega \to \pi^+\pi^-\pi^o$ decay plane was also assumed to be isotropically distributed. On the whole, the above assumptions lead to an adequate description of experimental data, except for some limited inconsistencies (in particular, the observed distribution in the cosine of the polar-angle in the Gottfried-Jackson frame depends on the mass of the $p\omega$ system and is not uniform). Many systematic errors are expected to be canceled out in the ratio of cross sections $R(\phi/\omega)$, since events from reactions (29) and (30) were detected simultaneously under similar experimental conditions. The above assumptions lead to an estimated systematic uncertainty in $R(\phi/\omega)$ smaller than 20% (due to the different final states in these reactions).

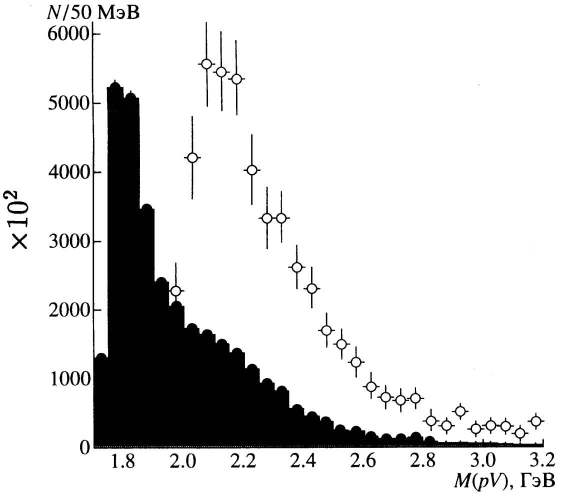

Fig. 9. Weighted distributions of events in the mass $M(pV)$ (here and in other figures of this subsection all distributions are weighted with efficiency of the setup). Closed and open circles represent, respectively, the distribution on $p\omega$ and the scale distribution of $p\phi$ (scale factor is 100).

Derivation of the ratio $R(\phi/\omega)$ for pN collisions and the OZI rule testing in these processes are not as straightforward as in charge exchange pion reactions (Section 2), meson decays (Section 3) or in nucleon-antinucleon annihilation [19-21]. The problem is that a significant contribution to the cross section for reaction (27) comes from the kinematical region below the threshold of $p\phi$ production. Thus, the simple ratio of the cross section for reactions (26) and (30)

$$R(\phi/\omega) = \sigma(26)/\sigma(30) = (1.55 \pm 0.05 \pm 0.31) \cdot 10^{-2} \tag{31}$$

is not very meaningful for the OZI rule testing.

Bearing in mind this difficulty we used two approaches to the OZI rule test in proton reactions.

A. On Fig.10 we present the data for the distributions dN/dP_V for reactions (26) and (27) as a function of vector meson momentum P_V in the rest frame for pV system with the invariant mass $M(pV)$

$$P_V = \frac{\{[M(pV)^2 - (m_V + m_p)^2][M(pV)^2 - (m_V - m_p)^2]\}^{1/2}}{2M(pV)} \tag{32}$$

(here and everywhere V denotes vector ϕ or ω mesons).

For testing the OZI rule we obtain the ratio of the cross sections for reactions (26) and (27) as a function of some minimal value of momentum $P_{V min} = P_o$ (see Fig.11)

$$R_1(\phi/\omega)|_{P_V > P_o} = \frac{\int_{P_o}^{P_{max}} (d\sigma/dP)_\phi \cdot dP_\phi}{\int_{P_o}^{P_{\max}} (d\sigma/dP)_\omega \cdot dP_\omega} \simeq \frac{\sum_{P_\phi > P_o} N_\phi(P_\varphi)}{\sum_{P_\omega > P_o} N_\omega(P_\omega)}. \tag{33}$$

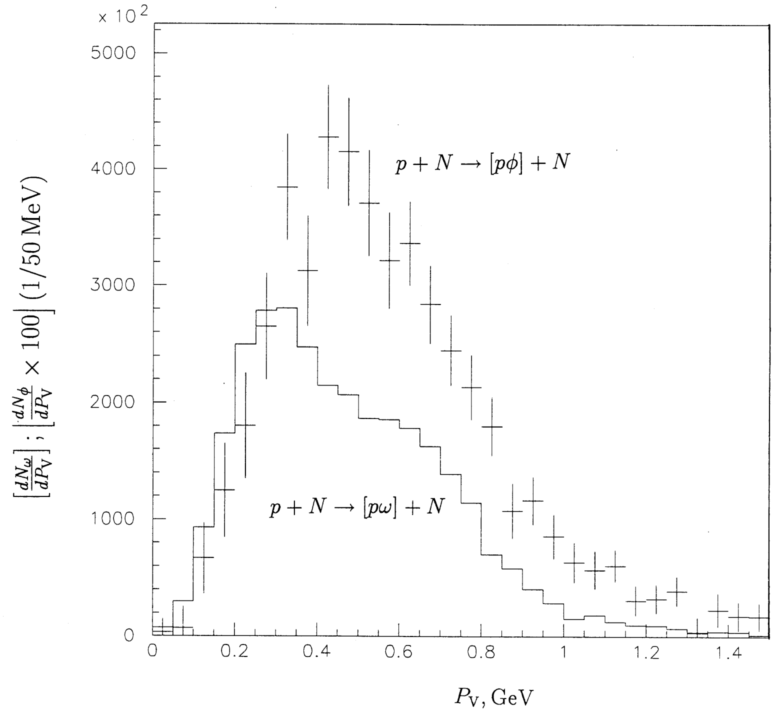

Fig. 10. The weighted distributions dN/dP_v for reactions (26) and (27) as functions of momentum P_v in the rest frame of pV system. The distribution for $p\phi$ is scale by a factor of 100.

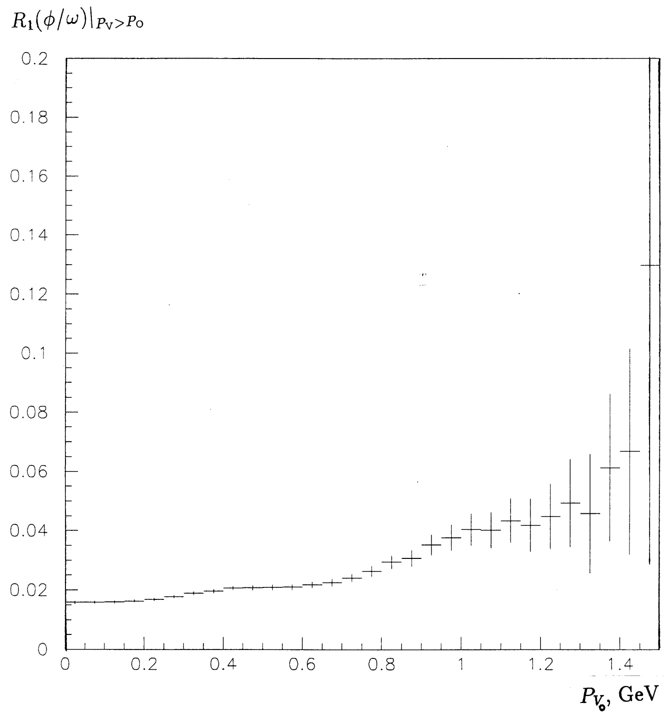

Fig. 11. Integrated ratio $R_1(\phi/\omega)$ (see(33)) as a function of minimal momentum $P_{\rm vmin} = P_0$.

To avoid the influence of possible resonances or resonance-like threshold structure effects which can be different for reactions (26) and (27) we use the value P_o >1 GeV ("asymptotic region" for $R_1(\phi/\omega)$, see Fig.11). For this value of P_o

$$R_1(\phi/\omega)|_{P_v>1 \text{ GeV}} = (4.0 \pm 0.04 \pm 0.08) \cdot 10^{-2}. \tag{34}$$

This approach is justified if the cross sections of (26) and (27) are functions of P_V only.

B. Another approach can be used if these cross sections are functions of invariant mass $M(pV)$ and phase space. For this case we can obtain the values of $\rho_2(\phi/\omega)$ as a function of mass $M(pV)$ at $M > M_p + M_\phi$ with correction for phase space

$$\rho_2(\phi/\omega) = \frac{d\sigma/dM)_\phi}{d\sigma/dM)_\omega} \cdot \frac{P_\omega}{P_\phi} = \rho_2(\phi/\omega; M). \tag{35}$$

The data on $\rho_2(\phi/\omega)$ are presented on Fig.12.[2]

For a more precise testing of the OZI rule in proton reactions (26) abd (27) in this approach we use weighted average values of the ratio $\rho_2(\phi/\omega)$ in different regions of masses $M(pV) > M_o$. The mass threshold M_o is introduced to avoid the influence of some near threshold peculiarities or resonance effects in the invariant mass spectra $M(p\phi)$ and $M(p\omega)$ (see Fig.9). Thus we define

$$< \rho_2(\phi/\omega) > |_{M(pV)>M_o} = \frac{1}{\xi} \sum_{M_i>M_o}^{M_{max}} \rho_2(\phi/\omega; M_i)\xi_i. \tag{36}$$

Here $\xi_i = 1/\sigma_i^2$ are statistical weights; σ_i^2 — variance of $\rho_2(\phi/\omega; M_i)$; $\xi = \sum \xi_i$. Variance of $< \rho_2(\phi/\omega >$ is $1/\xi$. Weighted average values $< \rho_2(\phi/\omega) > |_{M(pV)>M_o}$ were obtained from the data of Fig.12 for different values of M_o. We give here several numbers for this ratio (for different M_o):

$$< \rho_2(\phi/\omega) > |_{M(pV)>M_o} = \begin{cases} (7.3 \pm 0.5 \pm 1.5) \cdot 10^{-2} & (M_o = 2.5 \text{ GeV}); \\ (6.5 \pm 0.3 \pm 1.3) \cdot 10^{-2} & (M_o = 2.3 \text{ GeV}); \\ (5.8 \pm 0.2 \pm 1.2) \cdot 10^{-2} & (M_o = M_p + M\phi = 1.96 \text{ GeV}). \end{cases} \tag{37}$$

The values $R_1(\phi/\omega)$ (34) and $< \rho_2(\phi/\omega) >$ (37) must be compared with the OZI rule prediction $R_{OZI} = 0.4 \cdot 10^{-2}$ (28). Thus, we see that in proton-nucleon reactions the OZI rule is significantly violated — by more than an order of magnitude for $< \rho_2(\phi/\omega) >$, in a strong contradiction with data on pion reactions. This violation is practically independent of transverse momenta, as is demonstrated for $< \rho_2(\phi/\omega) > |_{M >_{m_p+m_\phi}}$ in Fig.13. From (5) and (37) it is possible to estimate the value of the parameter Z for the OZI rule violation in proton reaction (26)

$$0.2 \lesssim |Z| \lesssim 0.3. \tag{38}$$

[2]We use designation $\rho(\phi/\omega)$ for the ratio of differential cross sections and $R(\phi/\omega)$ – for the ratio of integrated cross sections.

The ϕ/ω ratio had also been measured in pp collisions at low energies of 10 and 11.75 GeV. The reported values exceed the OZI prediction by a factor varying between 2 and 5 [43, 44].

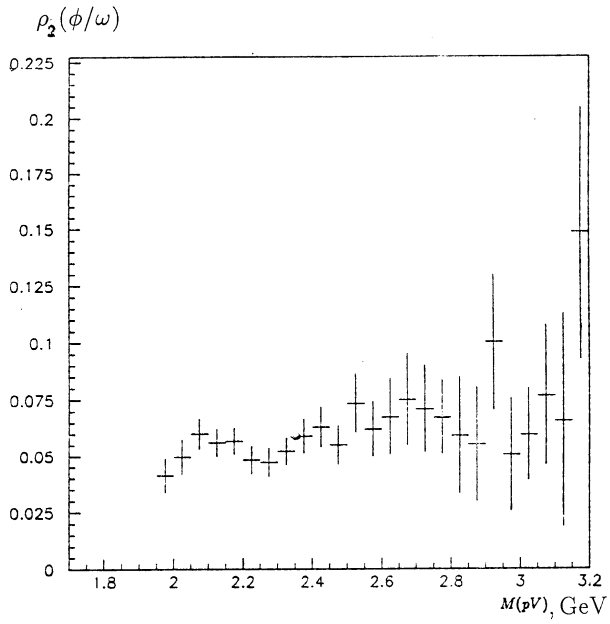

Fig. 12. Differential ratio $\rho_2(\phi/\omega; M)$ (see (35)) as a function of effective mass $M(pV)$.

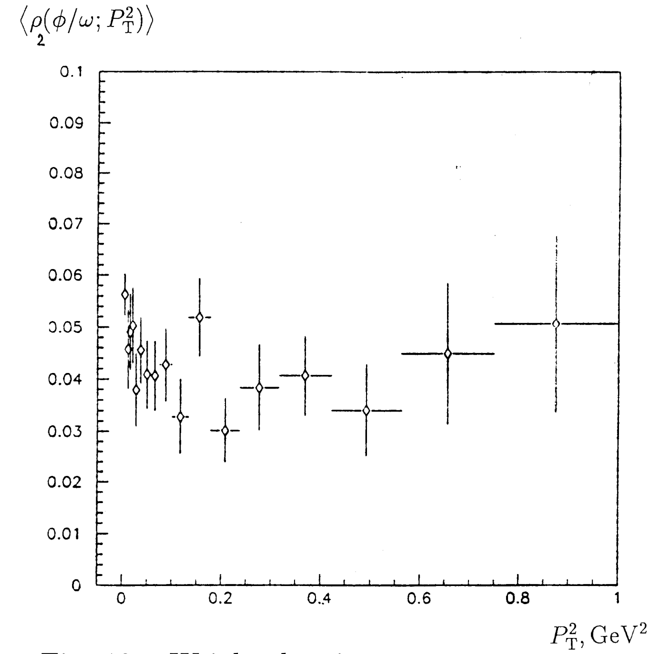

Fig. 13. Weighted ratio $< \rho_2(\phi/\omega) > |_{M>M_p+M_\phi}$ as a function of squared transverse momentum P_T^2 of the pV system.

5. Aparent violation of the OZI rule and hidden intrinsic strangeness in nucleons

Summing up the main results of studying the ϕ and ω meson production processes we must stress that there is a significant violation of the OZI rule in proton-induced reactions and in particular, in high energy diffractive production processes. At the same time the data on pion charge exchange reactions are in a good agreement with this selection rule and with the value of mixing angle in the vector meson nonet. True enough, from (17) we must bear in mind that even in pion reactions it is impossible to exclude a perceptible OZI rule violation with an accidental compensation between this amplitude and mixing effects. But such interpretation seems to be unlikely because of a good agreement between the value of $|\alpha_V|$ obtained from (15) (in the assumption of $Z = 0$ in expression (4) for processes under study) and other independent data on this mixing angle. Thus, it seems that pion-induced charge-exchange reactions are in a good agreement with the OZI rule, but in proton-induced data this rule is strongly violated. Very large OZI-violation effects (with $|Z| \sim 0.2 \div 0.4$) were also observed in a number of antiproton annihilation reactions [17-21].

A large apparent violation of the OZI selection rule in proton and antiproton reactions can significantly change our concept of quark structure of these particles. According to the naive quark model the valence quark constituents (uud for proton) give a good general description of hadron structure at large distances (small momenta transfer region) and hadron quantum numbers. Hadronic probes of shorter distances (large momentum transfers) reveal more consistuents which form the "sea" of quark-antiquark pairs and gluons. This "sea" and its evolution with momentum transfer is in qualitative agreement with QCD. However, the data on strong OZI-violation in nucleons may be considered as possible manifestation of additional $s\bar{s}$ pairs in nucleon wave function even at large distances. Another experimental indications of possible hidden strangeness component in nucleons come from the data on $\pi^- N$ sigma term and from "spin crisis" effects in polarized μp scattering. The interpretation of all these data in terms of direct intrinsic $s\bar{s}$ component in the nucleon wave function (higher Fock-space component) was discussed in Refs. [17-20].

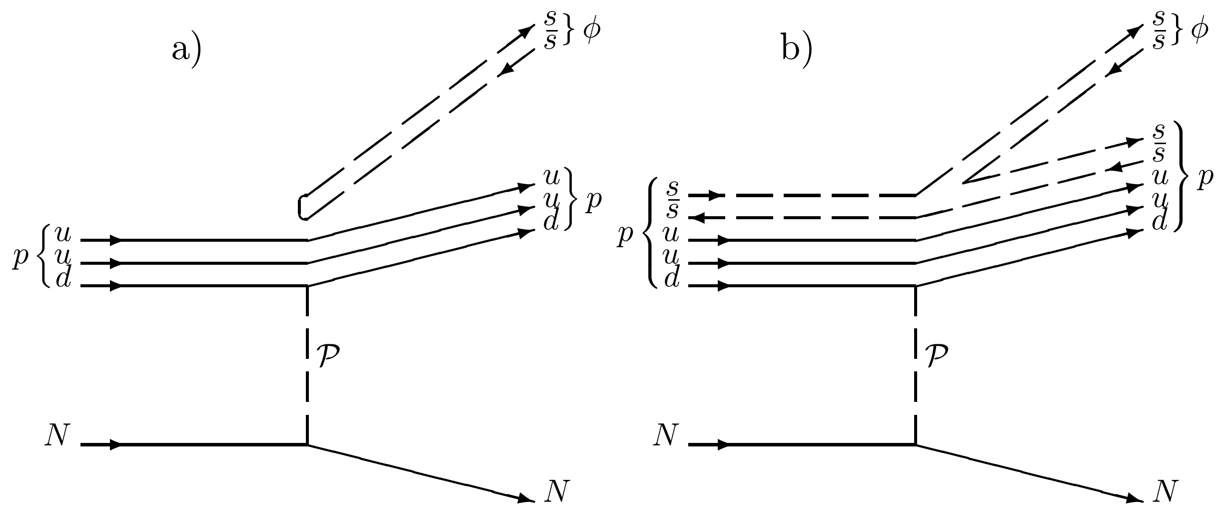

Fig. 14. ϕ production in proton-nucleon or proton-nucleus diffractive reactions: a) disconnected quark diagram for ordinary proton wave function (OZI-suppressed process); b) connected quark diagram for the model in which proton wave function has small exotic component with hidden strangeness (see (39)). This process can explain apparent violation of the OZI rule in proton reactions.

In the intrinsic hidden strangeness model the wave function of proton can be presented as follows [20]:

$$|p> = \alpha \sum_X |uudX> + \beta \sum_X |uuds\bar{s}X>, \quad (39)$$

where X stands for any numbers of $q\bar{q}$ pairs and gluons (nucleon "sea") and $|\alpha|^2 + |\beta|^2 = 1$. The possible way for unsuppressed ϕ meson production by this small exotic component of the proton $|uuds\bar{s}X>$ is presented on Fig.14. This connected quark diagram (not suppressed by the OZI rule) can explain an apparent OZI-violation effect in the reaction $p + N \to [p\phi] + N$, which was observed in the SPHINX experiment, if $|\beta/\alpha|$ is of an order of 0.1-0.2. This value of $|\beta/\alpha|$ is compatible with annihilation data.

Possible existence of small exotic component with hidden strangeness in parton wave function is very exciting and it must be thoroughly investigated in other processes, some of which were considered in Ref. [20].

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142284, Протвино Московской обл.

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