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EXPERIMENTAL TESTS OF THE OKUBO–ZWEIG–IZUKA RULE IN HADRON INTERACTIONS

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The Okubo–Zweig–Iizuka (OZI) rule — suppression of the reactions with disconnected quark lines was suggested at the early stage of the development of the quark model of hadrons. It has been tested in a number of experiments in a wide interval of energies. It was found that the OZI rule is fulfilled well, within few per cent accuracy.

So the results of experiments with stopped antiprotons at LEAR (CERN), where unexpected large violation of the OZI rule was found, were quite surprising. In some annihilation channels the ϕ -meson production exceeds the prediction of the OZI rule by a factor of 30–70. It turns out that the deviation from the OZI rule prediction depends drastically on the quantum numbers of the initial state of the nucleon–antinucleon system.

Subsequent experiments found strong violation of the OZI rule not only in the antiproton annihilation, but also in the reactions with protons $pd \rightarrow {}^3\text{He}\phi$, $pp \rightarrow pp\phi$ and pions $\pi p \rightarrow \phi\pi p$. The discrepancy with the OZI rule in these reactions was found by a factor of 10–100.

How is it possible to coincide the nice agreement of the OZI rule predictions with results of some experiments and its complete failure in the others?

To answer this question a model of polarized nucleon strangeness was proposed. It turns out that the polarization of the nucleon strange sea may naturally explain the observed dependence of the degree of the OZI rule violation from the initial state quantum numbers, initial energy and the final state content.

In this review we consider the phenomenology of the OZI rule, the experimental evidences of the large OZI violation, the polarized strangeness model and other theoretical models which provide the explanation of the large OZI rule violation.

Правило Окубо–Цвейга–Иизуки (ОЦИ) — подавление реакций с разрывными кварковыми линиями, было предложено на самой ранней стадии развития кварковой модели адронов. Оно было неоднократно проверено в большом числе экспериментов при разных энергиях. Было показано, что правило ОЦИ выполняется довольно хорошо, с точностью до нескольких процентов.

Поэтому большим сюрпризом стали результаты экспериментов с остановившимися антипротонами на LEAR (ЦЕРН), в которых было найдено неожиданно большое нарушение правила ОЦИ. В некоторых каналах аннигиляции с образованием ϕ -мезона экспериментально найденная вероятность образования превышала предсказания правила ОЦИ в 30–70 раз. Оказалось, что отклонение от правила ОЦИ сильно зависит от квантовых чисел начального состояния системы нуклон–антинуклон.

Последующие эксперименты обнаружили сильное нарушение правила ОЦИ не только в каналах аннигиляции, но и в реакциях с протонами $pd \rightarrow {}^3\text{He}\phi$, $pp \rightarrow pp\phi$ и пионами $\pi p \rightarrow \phi\pi p$. Расхождения с правилом ОЦИ в этих реакциях достигали 10–100 раз.

Как же это возможно, чтобы предсказания правила ОЦИ хорошо подтверждались одними экспериментами и полностью не работали в других экспериментах?

Чтобы ответить на этот вопрос, была предложена модель поляризованной странности нуклона. Оказалось, что если странное море в нуклоне поляризовано, то это может объяснить наблюдаемое нарушение правила ОЦИ и его сильную зависимость от квантовых чисел начального состояния.

В этом обзоре рассмотрена феноменология правила ОЦИ и экспериментальные данные о его большом нарушении, а также модель поляризованной странности нуклона и другие объяснения нарушения правила ОЦИ.

INTRODUCTION

The Okubo–Zweig–Iizuka rule (OZI) [1] was suggested at the early stage of the development of the quark model of hadrons. G. Zweig would like to explain why the $\phi(1020)$ meson, which mass is barely above the mass of $K\bar{K}$ system, decays preferentially into two kaons but not into $\pi\rho$ channel in spite of larger phase space. He proposed that ϕ has an internal structure which is more similar to the kaon than to the pion and assumed that the strange quarks of ϕ prefer to maintain their identity rather than transform to light quarks.

S. Okubo described this tendency of light quarks to keep their identity as a rule which forbids creation of $\bar{s}s$ mesons in the interactions of baryons and mesons consisting of u and d quarks only.

Nowadays a popular formulation of the OZI rule is that the reactions with disconnected quark lines are suppressed. There are also other formulations of the rule, which are nicely reviewed in [2].

Since its appearance, the consequences of the OZI rule have been tested in a number of experiments. Different probes were used in a wide interval of energies. It was found that in practically all of these reactions the OZI rule is fulfilled well, within few per cent accuracy.

The question arises: why? The OZI rule was suggested as a purely phenomenological rule. The reasons why it works well was not understood till the development of the QCD. Though we have not still a full understanding of the success of the OZI rule, it is clear now why it should be fulfilled in some limits. For instance, in the limit of heavy quarks and in the limit of large number of colours N_c . In these cases the OZI rule appears automatically from the QCD general principles.

Now the OZI rule is well tested in many experiments and has solid theoretical background. In this situation it is quite intriguing the results of experiments with stopped antiprotons at LEAR (CERN), where unexpected large violation of the OZI rule was found (for the review, see [3, 4]). In some annihilation channels the ϕ -meson production exceeds the prediction of the OZI rule by a factor of 30–70. It is remarkable that the level of the OZI-rule violation turns out to be different in various annihilation reactions. For instance, in antiproton annihilation at rest, the

observed yield of the reaction $\bar{p}p \rightarrow \phi\pi$ exceeds the OZI rule by a factor of 30, but in the similar reactions $\bar{p}p \rightarrow \phi\rho$ or $\bar{p}p \rightarrow \phi\omega$ no violation has been found.

It turns out that the deviation from the OZI-rule prediction depends drastically on the quantum numbers of the initial state of the nucleon–antinucleon system. Thus, the reaction $\bar{p}p \rightarrow \phi\pi^0$ at rest is allowed from two $\bar{p}p$ initial states, 3S_1 and 1P_1 . It was found a strong violation of the OZI rule from 3S_1 state, but for annihilation from 1P_1 state the ϕ production is at least 15 times less, which is in agreement with the OZI-rule prediction.

Strong violation of the OZI rule was observed not only in the antiproton annihilation, but also in the reactions with protons $pd \rightarrow ^3\text{He}\phi$ [5], $pp \rightarrow pp\phi$ [6, 7] and pions $\pi p \rightarrow \phi\pi p$ [8]. The discrepancy with the OZI rule in these reactions was found by a factor of 10–100.

How is it possible to coincide the nice agreement of the OZI-rule predictions with results of some experiments and its complete failure in the others? The main idea of the explanation is that the OZI rule itself is always valid. Some deviations from this rule are only apparent. They are due to nontrivial dynamics of the process, which cannot be described by a diagram with disconnected quark lines.

For instance, the OZI rule forbids the production of a pure $\bar{s}s$ state in the nucleon–nucleon interaction if there are no strange quarks in the nucleon. Only in this case the production of the $\bar{s}s$ pair is described by a disconnected diagram. But if the strange quarks in the nucleon play a non-negligible role, then the $\bar{s}s$ pair could be produced in the nucleon–nucleon interaction via shake-out or rearrangement of the strange quarks already stored in the nucleon. This process is described by a connected diagram and the OZI-rule suppression is not applicable in this situation. Therefore the observed violation of the OZI rule is only apparent. It reflects that the ϕ mesons may be created from the strange quarks already stored in the nucleon.

However this line of arguments immediately induces new questions. Why does the degree of the OZI-rule violation depend drastically on the quantum numbers of the initial state? Why is the OZI rule violated in the annihilation of antiproton at rest, but not in flight? Why has the strong violation of the OZI rule been observed till now only in some channels but not in all reactions of πp , NN and $\bar{N}N$ interactions?

To answer these questions, a model of polarized nucleon strangeness was proposed [9, 10]. The main idea was suggested by the results of the experiments on lepton deep inelastic scattering on polarized targets [11–14] which may be considered as an indication on the polarization of the strange quarks in the nucleon sea. It turns out that the polarization of the nucleon strange sea may naturally explain the observed dependence of the degree of the OZI-rule violation from the initial state quantum numbers, initial energy and the final state content. A number of tests of the model was proposed [15, 16], a part of them was already successfully confirmed by the experiment.

In this review we consider first the phenomenology of the OZI rule (Sec. 1). The experimental evidences of the large OZI violation are discussed in Sec. 2. Section 3 is devoted to the polarized strangeness model and its explanation of the large OZI violation. In Sec. 4 a review of other theoretical models is given. Concluding section contains a summary and discussion of the future experiments.

1. THE OZI RULE

1.1. Phenomenology of the OZI Rule. There are different formulations of the OZI rule (for review, see [2]). On the phenomenological level it is worthwhile to consider the relevant physics following the approach of Okubo [17].

Let us consider creation of $q\bar{q}$ states in the interaction of hadrons

$$A + B \longrightarrow C + q\bar{q}, \quad \text{for } q = u, d, s, \tag{1}$$

where hadrons A, B , and C consist of only light quarks.

The OZI rule in the formulation of Okubo demands that

$$Z = \frac{\sqrt{2}M(A + B \rightarrow C + s\bar{s})}{M(A + B \rightarrow C + u\bar{u}) + M(A + B \rightarrow C + d\bar{d})} = 0, \tag{2}$$

where $M(A + B \rightarrow C + q\bar{q})$ are the amplitudes of the corresponding processes.

It means that if the ϕ meson is a pure $\bar{s}s$ state, it could not have been produced in the interaction of ordinary hadrons. The OZI rule in Okubo's form strictly forbids creation of strangeonia or charmonia in the interaction of hadrons composed of u and d quarks only.

Sometimes the OZI rule is stated as a suppression of reactions with disconnected quark lines. Let us consider creation of the ϕ meson, assuming that it is a pure $\bar{s}s$ state. If there

are no strange quarks in the nucleon, then the production of the ϕ meson, for instance, in the $\bar{p}p$ annihilation, should be described by the diagram in Fig. 1, *a*. The quark lines of the $\bar{s}s$ pair in the final state are not connected with the quark lines of the initial state and according to the OZI rule this reaction should be suppressed in comparison with the production of the ω meson. The diagram of the ω -meson production is shown in Fig. 1, *b*.

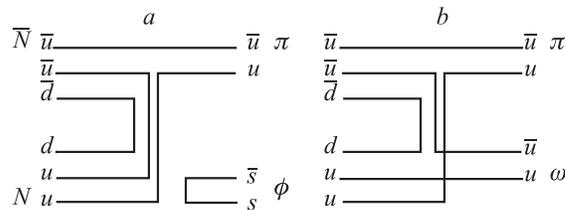


Fig. 1. Quark diagrams for the ϕ - (*a*) and ω -meson (*b*) production in $\bar{N}N$ annihilation

The only way to form ϕ , according to the OZI rule, is through admixture of the light quarks in the ϕ wave function. The corresponding diagram is shown in

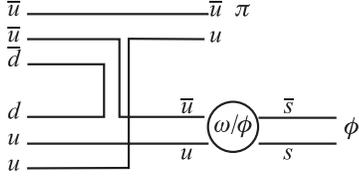


Fig. 2. The admixture of light quarks appears in the ϕ wave function because the ϕ and ω mesons are mixture of $SU(3)$ singlet ω_0 and octet ω_8 states:

$$\phi = \cos \Theta \omega_8 - \sin \Theta \omega_0, \quad (3)$$

$$\omega = \sin \Theta \omega_8 + \cos \Theta \omega_0, \quad (4)$$

Fig. 2. Quark diagram of the OZI-allowed mechanism for the ϕ production in $\bar{N}N$ annihilation

where

$$\omega_8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6}, \quad (5)$$

$$\omega_0 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}. \quad (6)$$

Therefore the ϕ wave function is

$$\phi = (u\bar{u} + d\bar{d}) \left(-\sin \Theta \frac{1}{\sqrt{3}} + \cos \Theta \frac{1}{\sqrt{6}} \right) - s\bar{s} \left(\sin \Theta \frac{1}{\sqrt{3}} + \cos \Theta \frac{2}{\sqrt{6}} \right). \quad (7)$$

Introducing the ideal mixing angle $\Theta_i = 35.3^\circ$, for which

$$\cos \Theta_i = \sqrt{\frac{2}{3}}, \quad \sin \Theta_i = \sqrt{\frac{1}{3}}, \quad (8)$$

one may rewrite (7) as follows:

$$\phi = -\cos(\Theta_i - \Theta) |\bar{s}s\rangle + \sin(\Theta_i - \Theta) |\bar{q}q\rangle, \quad (9)$$

$$\omega = \cos(\Theta_i - \Theta) |\bar{q}q\rangle + \sin(\Theta_i - \Theta) |\bar{s}s\rangle, \quad (10)$$

where $|\bar{q}q\rangle = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)$.

If $\Theta = \Theta_i$, then ϕ is a pure $\bar{s}s$ state.

However the physical mixing angle Θ differs from the ideal one. It is determined by the masses of the mesons in the corresponding nonet. For the vector mesons the physical mixing angle is

$$\tan^2 \Theta = \frac{m_\phi^2 - m_{\omega_8}^2}{m_{\omega_8}^2 - m_\omega^2}, \quad (11)$$

where from the quadratic Gell-Mann–Okubo mass formula

$$m_{\omega_8}^2 = \frac{4m_{K^*}^2 - m_\rho^2}{3}. \quad (12)$$

Substituting the masses of the vector mesons in Eqs. (11)–(12), one obtains $\Theta = 39^\circ$, which is not far from the ideal mixing angle. The difference $\Theta - \Theta_i$ determines the contribution of light quarks in the ϕ wave function. This contribution, according to the OZI rule, determines how large the cross sections of ϕ production are in NN , πN or $\bar{N}N$ interactions. To demonstrate this, let us rewrite Eq. (2) in terms of mixing angles:

$$\frac{M(A + B \rightarrow C + \phi)}{M(A + B \rightarrow C + \omega)} = -\frac{Z + \tan(\Theta - \Theta_i)}{1 - Z \tan(\Theta - \Theta_i)}. \quad (13)$$

If the OZI rule is correct, i. e., the parameter Z is $Z = 0$, then

$$\frac{M(A + B \rightarrow C + \phi)}{M(A + B \rightarrow C + \omega)} = -\tan(\Theta - \Theta_i) \quad (14)$$

and

$$R = \frac{\sigma(A + B \rightarrow \phi X)}{\sigma(A + B \rightarrow \omega X)} = \tan^2(\Theta - \Theta_i) f, \quad (15)$$

where f is the ratio of phase spaces of the reactions. If $f = 1$ and $\Theta = 39^\circ$, then the OZI rule predicts that in all hadron reactions the ratio between the cross sections of ϕ and ω production $R(\phi/\omega)$ should be:

$$R(\phi/\omega) = 4.2 \cdot 10^{-3}. \quad (16)$$

Therefore, using as input only the masses of mesons, the ratio of production cross sections is predicted.

It is remarkable to what extent the experimental data in different interactions and at different energies follow this rule. We will discuss this in detail in the next sections.

The physical mixing angle could be calculated for each meson nonet using the quadratic Gell-Mann–Okubo mass formula of Eqs. (11)–(12). It gives for the tensor mesons $\Theta = 28^\circ$ and for the 3^{--} nonet $\Theta = 29^\circ$ [18]. In both cases the deviation from the ideal mixing angle is not large. It means that the mixing is not large and the production of the corresponding $\bar{s}s$ states will be suppressed in comparison with their light quark counterparts. The small mixing is predicted [19] also for the nonets with $J^{PC} = 1^{++}$, 1^{+-} , and 4^{++} .

Let us consider, for instance, the tensor nonet. The tensor meson $\bar{s}s$ state is $f'_2(1525)$ meson and its partner made of light quarks is $f_2(1270)$. The OZI rule predicts that the ratio $R(f'_2(1525)/f_2(1270))$ is:

$$R = \frac{\sigma(A + B \rightarrow f'_2(1525) + X)}{\sigma(A + B \rightarrow f_2(1270) + X)} = 16 \cdot 10^{-3}. \quad (17)$$

The space factor is assumed to be $f = 1$.

The situation with the mixing of the pseudoscalars is special (see, [20–22]). It reflects a special role of the pseudoscalars as the Goldstone bosons connected with spontaneous breaking of the chiral symmetry. The nonperturbative QCD effects are essential for the mass spectrum of the pseudoscalars, especially for the mass of η' meson. In result, the mass spectrum of pseudoscalars differs from the mass spectrum of «normal» mesons.

Phenomenologically this deviation manifests itself as large deviation from the ideal mixing angle which is $\Theta - \Theta_i \approx -(45 - 55)^\circ$. The values of the mixing angle from $\Theta = -10^\circ$ to $\Theta = -23^\circ$ have been obtained in different analysis. Later we will discuss the situation with the mixing of pseudoscalars in more detail. The only remark here is the following.

Let us take recent result by the KLOE collaboration [23] that the pseudoscalar mixing angle is $\Theta = (-14.7_{-1.5}^{+1.7})^\circ$. Then the ratio between the cross sections of η and η' production is

$$R = \frac{\sigma(A + B \rightarrow \eta X)}{\sigma(A + B \rightarrow \eta' X)} \sim 1.42. \quad (18)$$

Therefore, large mixing induces η dominance over η' in contrast with the ϕ suppression over ω induced by the small mixing of the vector mesons.

Strong mixing is expected [24, 25] for the scalar mesons with $J^{PC} = 0^{++}$. However, the very content of the scalar nonet is still under discussion now (see, e. g., [18]).

Let us consider, how the existing experimental data correspond to the predictions of Eqs. (16)–(18).

1.2. The OZI Rule for the Vector-Meson Production. The production of the ϕ and ω mesons was studied in different experiments in NN , πN , and $\bar{N}N$ interactions. The obtained ratios $R(\phi X/\omega X)$ of the cross sections of ϕ and ω production and the values of the OZI-rule violation parameter Z are shown in Table 1. The parameter Z was calculated for $\delta = \Theta - \Theta_i = 3.7^\circ$, assuming the same phases of the ϕ and ω production amplitudes.

From these results one may obtain that in πN interactions the weighted average ratio of the cross sections of ϕ and ω production at different energies is

$$\bar{R} \left(\frac{\sigma(\pi N \rightarrow \phi X)}{\sigma(\pi N \rightarrow \omega X)} \right) = (3.30 \pm 0.34) \cdot 10^{-3}. \quad (19)$$

It corresponds to the value of the OZI-violation parameter $|Z_{\pi N}| = 0.6 \pm 0.3\%$. Therefore, in πN interaction the agreement with the OZI-rule prediction (16) is practically perfect.

The weighted average ratio of the cross sections of the ϕ and ω production at different energies in nucleon–nucleon interactions is not far from the OZI

Table 1. The ratio $R = \phi X/\omega X$ of the cross sections for production of ϕ and ω mesons in pp , $\bar{p}p$, and $\pi\pi$ interactions

| Initial state | P_L , GeV/c | Final state X | $R = \phi X/\omega X \cdot 10^3$ | $ Z $, % | Refs. |
|---------------|---------------|--------------------------------------|----------------------------------|---------------|----------|
| π^+n | 1.54 – 2.6 | p | 21.0 ± 11.0 | 8 ± 4 | [26, 27] |
| π^+p | 3.54 | π^+p | 19.0 ± 11.0 | 7 ± 4 | [28] |
| π^-p | 5 – 6 | n | 3.5 ± 1.0 | 0.5 ± 0.8 | [29] |
| π^-p | 6 | n | 3.2 ± 0.4 | 0.8 ± 0.4 | [30] |
| π^-p | 10 | π^-p | 6.0 ± 3.0 | 1.3 ± 2.0 | [31] |
| π^-p | 19 | $2\pi^- \pi^+p$ | 5.0^{+5}_{-2} | 0.6 ± 2.5 | [32] |
| π^-p | 32.5 | n | 2.9 ± 0.9 | 1.1 ± 0.8 | [33] |
| π^-p | 360 | X | 14.0 ± 6.0 | 5 ± 3 | [34] |
| pp | 10 | pp | 20.0 ± 5.0 | 8 ± 2 | [31] |
| pp | 24 | pp | 26.5 ± 18.8 | 10 ± 6 | [35] |
| pp | 24 | $\pi^+ \pi^- pp$ | 1.2 ± 0.8 | 3 ± 1 | [35] |
| pp | 24 | $pp m\pi^+ \pi^-$, $m = 0, 1, 2$ | 19.0 ± 7.0 | 7 ± 3 | [35] |
| pp | 70 | pX | 16.4 ± 0.4 | | [36] |
| pp | 360 | X | 4.0 ± 5.0 | 0.1 ± 4 | [37] |
| $\bar{p}p$ | 0.7 | $\pi^+ \pi^-$ | $19.0 \pm 5^*$ | 7 ± 2 | [38] |
| $\bar{p}p$ | 0.7 | ρ^0 | $13.0 \pm 4^*$ | 5 ± 2 | [38] |
| $\bar{p}p$ | 1.2 | $\pi^+ \pi^-$ | 11.0^{+3}_{-4} | 4 ± 1 | [39] |
| $\bar{p}p$ | 2.3 | $\pi^+ \pi^-$ | 17.5 ± 3.4 | 7 ± 1 | [40] |
| $\bar{p}p$ | 3.6 | $\pi^+ \pi^-$ | 9.0^{+4}_{-7} | 3 ± 3 | [39] |

Note. P_L is the momentum of the incoming particle; Z is the parameter of the OZI-rule violation. No corrections on the phase space volume difference were made except the cases marked *.

«magic» value of (16) either:

$$\bar{R} \left(\frac{\sigma(NN \rightarrow \phi X)}{\sigma(NN \rightarrow \omega X)} \right) = (12.78 \pm 0.34) \cdot 10^{-3}. \quad (20)$$

It corresponds to the value of the OZI violation parameter $Z_{NN} = 6.0 \pm 0.2\%$.

Similar values are found for the antiproton annihilation in flight:

$$\bar{R} \left(\frac{\sigma(\bar{p}p \rightarrow \phi X)}{\sigma(\bar{p}p \rightarrow \omega X)} \right) = (14.55 \pm 1.92) \cdot 10^{-3}, \quad (21)$$

$$Z_{\bar{p}p} = 5.8 \pm 0.8\%.$$

The comparison of the above results for πN scattering with those for NN and $\bar{N}N$ put in evidence that:

— The deviation from the OZI-rule prediction in the NN and $\bar{N}N$ scattering is significantly higher than in the πN interaction.

— In general the deviation from the OZI rule for the vector meson production does not exceed 10 %.

One should note that no correction for the phase space difference of the reaction final state was applied. A correct procedure to test the OZI rule needs the comparison of not the cross sections but the amplitudes of the ϕ and ω productions. It was done in [41] for πN and NN scattering. Their conclusions coincide in general with ours: the OZI rule for the vector-meson production is valid within 10 % accuracy.

1.3. The OZI Rule for the Tensor-Meson Production. The experimental data on the tensor-meson production are more scarce, but in general they also confirm the OZI-rule prediction (17).

There are some specific features in the tensor-meson production which should be kept in mind. First, the determination of the tensor-meson mixing angle directly from the masses of the mesons is not a persuading procedure due to the large width of the tensor mesons. Therefore, it is worth checking the numerical prediction of Eq. (17) in another way, by using the data on the decay widths of the $f'_2(1525)$ into $\pi\pi$ and $\bar{K}K$ channels. Taking these data from [18], one may obtain the ratio of the $f'_2(1525)$ decay widths into the OZI-forbidden $\pi\pi$ and OZI-allowed $\bar{K}K$ modes, corrected on the phase space difference:

$$R = \frac{W(f'_2(1525) \rightarrow \pi\pi)}{W(f'_2(1525) \rightarrow \bar{K}K)} = (2.6 \pm 0.5) \cdot 10^{-3}. \quad (22)$$

This value is slightly less than the Eq. (17) one. It indicates that the suppression of the $f'_2(1525)$ on the $f_2(1270)$ should be at the level of

$$R = \frac{\sigma(A + B \rightarrow f'_2(1525) + X)}{\sigma(A + B \rightarrow f_2(1270) + X)} = (3-16) \cdot 10^{-3}. \quad (23)$$

Another complication of the analysis of the tensor-meson production is related to the fact that it is quite hard to select correctly the contribution of the $f_2(1270)$ meson from nearby the $a_2(1320)$ meson. Frequently the total contribution of the $f_2(1270)$ and $a_2(1320)$ mesons is given.

In Table 2 the ratio of the cross sections $R = f'_2(1525)X/f_2(1270)X$ is given for different reactions.

One can see that the general agreement with the OZI-rule prediction (23) is quite well. There are some experiments with large $R = f'_2(1525)X/f_2(1270)X$ ratios, but the errors are also large to be conclusive. Averaging the results for the antiproton annihilation gives

$$\bar{R} \left(\frac{\sigma(\bar{p}p \rightarrow f'_2(1525)X)}{\sigma(\bar{p}p \rightarrow f_2(1270)X)} \right) = (27 \pm 6) \cdot 10^{-3}, \quad (24)$$

$$Z_{\bar{p}p} = 3.9 \pm 1.6 \%.$$

Table 2. **The ratio $R = f'_2(1525)X/f_2(1270)X$ of the cross sections for production of $f_2(1270)$ and $f'_2(1525)$ mesons**

| Initial state | P_L , GeV/c | Final state X | $R(f'_2/f_2) \cdot 10^3$ | Refs. |
|---------------|---------------|-----------------|--------------------------|-------|
| $\pi^- p$ | 100.0 | n | 1.5 ± 0.7 | [42] |
| $\pi^- p$ | 10.0 | n | 44 ± 10 | [43] |
| $\bar{p} p$ | 0 | π^0 | 26 ± 10 | [3] |
| $\bar{p} p$ | 2.32 | $\pi^+ \pi^-$ | $21 \pm 10^*$ | [44] |
| $\bar{p} n$ | 2.3 | π^- | < 15 | [45] |
| $\bar{p} p$ | 1.5–2.0 | $\pi^+ \pi^-$ | $28 \pm 9^*$ | [46] |
| $\bar{p} p$ | 7.02–7.57 | π^0 | $64 \pm 28^*$ | [47] |

Note. P_L is the momentum of the incoming particle. In some cases, marked by *, the cross section of $f_2(1270)$ was not separated from the production of $a_2(1320)$ and the sum of these cross sections is given.

This makes even more interesting the result obtained by the OBELIX collaboration [48]. It was demonstrated that the large violation of the OZI rule occurs in some specific condition: when annihilation takes place from the P wave. We will discuss it in detail in Sec. 2.1.4.

1.4. The OZI Rule for the Pseudoscalar-Meson Production. The mass spectrum of pseudoscalar mesons is not similar to the spectrum of ordinary mesons. The nonperturbative QCD effects are of most importance just in this sector. They lead to the strong upward shift of the η' meson mass. For normal mesons, the pure $SU(3)$ octet state ω_8 from (5) is always heavier than the singlet ω_0 state from (6). It is quite natural because by definition (5), (6) the contribution of strange quarks is larger for ω_8 . However for the pseudoscalars, the state η_8 with more strangeness content is lighter than the corresponding η_0 partner. So, the mixing between $\bar{s}s$ and light $\bar{q}q$ states is large and in this sense the OZI rule for the pseudoscalar sector is strongly violated.

The complications related to a special status of the pseudoscalars is not ended by a large value of the mixing angle. H. Leutwyler [20] has shown that two mixing angles θ_8 and θ_0 are needed for accounting different $SU(3)_f$ violation for the octet and singlet flavor states. The values of the mixing angles are $\theta_8 \sim -20^\circ$, $\theta_0 \sim -4^\circ$. Correspondingly, two different coupling constants f_8 and f_0 are needed.

Feldmann, Kroll, and Stech [21] have introduced a quark flavor basis instead of the octet–singlet one. In this approach η and η' are described as linear combinations of orthogonal states η_q and η_s with the flavor structure $q\bar{q} = (u\bar{u} + d\bar{d})/\sqrt{2}$ and $s\bar{s}$, respectively.

In this scheme it is possible to reduce four constants to the single mixing angle Φ and two coupling constants f_q and f_s . The analysis of a number of decay and scattering processes allows to fix these parameters. The ratio of cross

Table 3. The ratio $R = \eta X / \eta' X$ of the cross sections for production of η and η' mesons. P_L is the momentum of the incoming particle

| Initial state | P_L , GeV/c | X | $R(\eta/\eta')$ | Refs. |
|---------------|---------------|---------------|-----------------|----------|
| $\pi^- C$ | 38.0 | X | 2.0 ± 0.4 | [49] |
| $\pi^- p$ | 8.45 | n | 2.5 ± 0.2 | [50] |
| $\pi^- p$ | 15.0 | n | 1.7 ± 0.2 | [51] |
| $\pi^- p$ | 20.2 | n | 2.0 ± 0.3 | [51] |
| $\pi^- p$ | 25.0 | n | 1.9 ± 0.1 | [51] |
| $\pi^- p$ | 30.0 | n | 1.9 ± 0.1 | [51] |
| $\pi^- p$ | 40.0 | n | 1.9 ± 0.1 | [51] |
| $\pi^- C$ | 39.1 | C^* | 1.7 ± 0.1 | [52] |
| $\pi^- p$ | 39.1 | n | 1.7 ± 0.2 | [52] |
| $\pi^- p$ | 63.0 | n | 1.8 ± 0.6 | [53] |
| $\pi^- p$ | 300 | n | 2.85 ± 1.06 | [54, 55] |
| $\pi^+ p$ | 5.45 | Δ^{++} | 4.5 ± 1.8 | [56] |
| $\pi^+ p$ | 16.0 | Δ^{++} | 5.3 ± 3.4 | [57] |
| pp | 450 | pp | 2.21 ± 0.20 | [55] |
| $\bar{p}p$ | 0 | π^0 | 1.72 ± 0.21 | [3] |
| $\bar{p}p$ | 0 | ω | 1.94 ± 0.25 | [3] |
| $\bar{p}p$ | 0 | ρ | 2.65 ± 0.79 | [58, 59] |
| $\bar{p}p$ | 0 | $\pi^0 \pi^0$ | 2.1 ± 0.5 | [60, 61] |
| $\bar{p}p$ | 0 | $\pi^+ \pi^-$ | 2.2 ± 0.6 | [62, 59] |
| $\bar{n}p$ | x | π^+ | 1.59 ± 0.40 | [63] |

sections for η and η' production at high energies, where phase space corrections assumed to be nonsignificant, is

$$R = \sigma(A + B \rightarrow \eta + X) / \sigma(A + B \rightarrow \eta' + X) = \tan^{-2} \Phi. \quad (25)$$

According to [21] the value of Φ is $\Phi = (39.3 \pm 1)^\circ$. It leads to the following ratio between the cross sections of the η - and η' -meson production

$$R(\eta/\eta') \sim 1.49. \quad (26)$$

It should be compared with the standard, one-mixing-angle scheme prediction of Eq. (18) that $R(\eta/\eta') \sim 1.42$.

The ratios between the cross section of the η and η' mesons in different reactions are collected in Table 3.

In spite of the delicate situation with the mixing of the pseudoscalars, a superficial look at Table 3 provides an impression that the bulk of the data are in agreement with the predictions of Eqs. (18) and (26).

However, there are some marked deviations from the OZI-rule prediction of Eq. (18) found in the measurements of η and η' production in the proton-proton interaction in the vicinity of their thresholds [64, 65]. (For review of the experimental situation, see [66].) It turns out that, for instance, at the proton

energy $Q = 2.9$ MeV above the threshold, the ratio of cross sections is $R(\eta/\eta') = 37.0 \pm 11.3$. At $Q = 4.1$ MeV, the ratio is $R(\eta/\eta') = 26.2 \pm 5.4$.

A standard explanation (see, e. g., [67]) of the reason of this anomaly is increasing of the η production due to the nucleon $S_{11}(1535)$ resonance which strongly couples with the $N\eta$ final state. The excitation of this resonance is essential just near the η production threshold. However, the quantitative results depend on the $S_{11}(1535)$ coupling constants which are not well known. Moreover, to provide large ratio $R(\eta/\eta')$ similar resonances should be absent near the η' production threshold. However, that may be not the case, as recent calculations [68] have shown that the excitation of analogous N^* resonances, such as $S_{11}(1897)$ and $P_{11}(1986)$, could reproduce the η' cross threshold near the threshold.

1.5. Why Does the OZI Rule Work? Quite often the OZI rule is formulated as suppression of the processes described by the disconnected diagrams. Natural explanation of this hierarchy is provided in the large N_c limit of QCD [69, 70]. It has been shown that at large N_c the diagrams with the smallest possible number of quark loops dominate, because the QCD coupling constant tends to zero if N_c is sent to infinity. Therefore the disconnected diagrams are suppressed by higher powers of $1/N_c$ compared with the connected ones.

However in the real world with $N_c = 3$, the degree of the suppression of the OZI violating processes is much stronger than $1/3$. As we discussed in Sects. 1.2 and 1.3 for the vector- and tensor-meson production cross sections this suppression factor is of the order of 10^{-3} .

On a phenomenological level the reasons of applicability of the OZI rule were thoroughly analysed by H. Lipkin and also by P. Geiger and N. Isgur (see [2, 19, 24, 71] and references therein). They pointed out the importance of cancellations between different intermediate states as a reason for the validity of the OZI rule.

Indeed, all OZI-violated reactions could be regarded as two-step processes, for instance:

$$\phi \rightarrow \bar{K}K \rightarrow \rho\pi, \quad (27)$$

$$\bar{p}p \rightarrow \bar{K}K^* \rightarrow \phi\pi, \quad (28)$$

$$\pi^- p \rightarrow K^0 \Lambda \rightarrow \phi n. \quad (29)$$

At each step the process is described by a connected OZI-allowed diagram (see Fig. 3). There is no suppression for each subprocess. Why is then the total process suppressed?

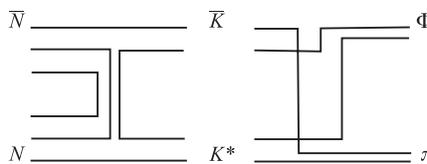


Fig. 3. Annihilation $\bar{p}p \rightarrow \phi\pi$ as a two-step process

H. Lipkin [72] argued that in some sense this suppression could be considered as a reflection of the underlying flavor symmetry which «equalizes» the contributions of different intermediate states. To demonstrate the cancellation between these contributions, he introduced an analog of the G parity in the case of the total flavor symmetry. Under conventional G parity the u quark is transformed into \bar{d} (as well as d into \bar{u}). The corresponding transformation in the case of flavor symmetry transforms light and strange quarks. It interchanges u and \bar{s} (as well as s and \bar{u}). The strong interaction and the T matrix are invariant under this general G parity in the case of flavor symmetry. Then one could classify the meson states into odd or even eigenvalues of the generalized G parity. It was shown in [72] that the contributions from intermediate states having even and odd eigenvalues of the generalized G parity have opposite phases. So the physical reason for the validity of the OZI rule is the cancellation of the contributions from different intermediate states in the transition amplitude of two-step processes.

If this delicate cancellation does not occur for some reasons, e. g., near the thresholds, where some intermediate states are open but others are closed, one may expect to observe the deviation from the OZI-rule predictions. Also if a theoretical analysis considers only a few diagrams, it may easily result in a substantial OZI-rule violation.

This conclusion is very important because a lot of models claimed to reproduce the large violation of the OZI rule, but considering only a very limited set of diagrams of few meson exchanges. So it is not a surprise that the resulting noncompensation allows one to obtain a large OZI-rule violation.

Concrete calculations made by Geiger and Isgur [71] have shown strong cancellations between mesonic loop diagrams consisting of S -wave strange mesons ($\bar{K}K, \bar{K}K^*, \bar{K}^*K^*$) with loops containing K or K^* plus one of the four strange mesons of the $L = 1$ nonet. To maintain the cancellation, a summation of very large set, up to ten thousand (!) channels, is needed [24].

The development of the QCD provides us more understanding of the applicability of the OZI rule. One of the first success of the QCD sum rules approach [73] was the correct calculation of the value of $\phi - \omega$ mixing. It was shown [73] that the reason of the smallness of the mixing is the suppression of contribution of the vacuum intermediate state in the matrix elements $\langle 0 | \bar{q} \Gamma q \bar{q} \Gamma q | 0 \rangle$, where Γ are matrices acting on colour, flavor and spinor indices.

Indeed, let us consider in more detail what are the constituents of the blob in Fig. 2 which describes the ϕ production in $\bar{p}p$ annihilation. According to the OZI rule we should consider this process as a two step process: the first step is the formation of the light quark $\bar{q}q$ pair with effective mass of ϕ meson, the second step is the transition of the $\bar{q}q$ pair to the $\bar{s}s$ pair. This transition schematically depicted by the diagrams of Fig. 4 could be described either via gluon exchange (see Fig. 4, *a*) or via some nonperturbative processes (Fig. 4, *b*).

Studies of the three-gluon exchange diagram of Fig. 4, *a* in the $\phi \rightarrow \rho\pi$ decay have shown [74,75] that its contribution is small and of wrong sign. Nonperturbative effects of Fig. 4, *b* are dominating. This assumption leads to very nontrivial dependence of the OZI-rule violation on the quantum numbers of investigated channel. It was shown in [75] that in the dilute instanton gas approximation the nonperturbative processes of Fig. 4, *b* are suppressed for the vector and tensor channels but nonvanishing for the axial vector, pseudoscalar and scalar channels. Qualitatively it fits with the observed picture that, just in the pseudoscalar and scalar sectors, the meson mass spectra are not similar to the conventional one, obtained with small deviation from the ideal mixing.

Of course, some direct OZI violation is possible. The direct OZI violation means the violation in the amplitude of the ϕ production or decay. Indeed, till now we assume that the ϕ mesons are produced (and decayed) *only* via $\phi-\omega$ or $\phi-\rho$ mixing, i. e., due to light quark components in the ϕ wave function. An example of the mixing is shown in Fig. 5, *a* for the case of the ϕ decay into $\pi^+\pi^-\pi^0$. However the diagram of Fig. 5, *b*, which describes direct transition of ϕ into three-pion system, is also possible. Similar situation exists in the neutral kaon systems, where there is a distinction between the direct CP violation and CP violation due to the mixing of K_S and K_L mesons.

The role of mixing and direct transitions in the ϕ decays was analysed in [77–79]. Recent experiments at VEPP-2M collider have provided some indications of the direct OZI violation [80,81]. The KLOE collaboration at DAΦNE ϕ factory has claimed on the finding direct OZI violation in $\phi \rightarrow \pi^+\pi^-\pi^0$ decay [82]. The amplitude of direct transition turns out to be as large as 10% of the $\rho\pi$ one.

Summarizing, it is possible to say that the OZI rule reflects an important feature of the hadron interactions — suppression of the flavor mixing transitions. It reflects the absence of the processes with pure gluonic intermediate states. One should stress that when the gluonic intermediate states are important, the OZI rule

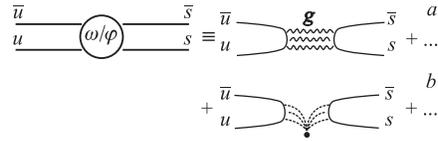


Fig. 4. Quark diagrams of the $\phi-\omega$ mixing: *a*) gluon exchange; *b*) mixing in the instanton field. The instanton is shown by the black point

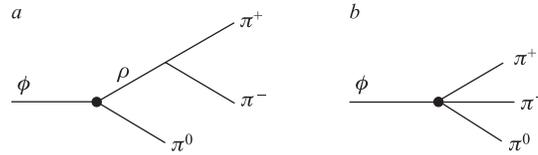


Fig. 5. The diagrams of the $\phi \rightarrow \pi^+\pi^-\pi^0$ decay: *a*) via $\phi-\rho$ mixing; *b*) direct transition to 3π system

in the Okubo's form of Eq. (2) is not valid. In that case the $\bar{s}s$ -pair production is not suppressed as large as the mixing angle prescriptions of Eqs. (16)–(18). A nice example is the decays of $J/\psi \rightarrow \phi + X$ and $J/\psi \rightarrow \omega + X$. Both the decays are OZI-forbidden, however, there is no substantial ϕ meson suppression as predicted by the mixing angle formula (16). Indeed, the ratios of ϕ and ω final states [18] are rather similar and far from the $R(\phi/\omega) = 4.2 \cdot 10^{-3}$ prediction of Eq. (16):

$$R_{\pi\pi} = \frac{W(J/\psi \rightarrow \phi + \pi^+\pi^-)}{W(J/\psi \rightarrow \omega + \pi^+\pi^-)} = (111 \pm 23) \cdot 10^{-3}, \quad (30)$$

$$R_{\eta} = \frac{W(J/\psi \rightarrow \phi + \eta)}{W(J/\psi \rightarrow \omega + \eta)} = (411 \pm 61) \cdot 10^{-3}, \quad (31)$$

$$R_{f_0(980)} = \frac{W(J/\psi \rightarrow \phi + f_0(980))}{W(J/\psi \rightarrow \omega + f_0(980))} = (2290 \pm 1040) \cdot 10^{-3}. \quad (32)$$

The value of the flavor mixing is channel-dependent. It is large for the pseudoscalar and scalar channels. For other channels the OZI rule is a nice approximation. As it was discussed in [76], the OZI limit of QCD is a more accurate approximation than the large N_c limit, or the quenched approximation, or the topological expansion ($N_c \rightarrow \infty$ at fixed N_f/N_c).

2. APPARENT VIOLATION OF THE OZI RULE

The previous Section demonstrates that the OZI-rule predictions have been tested many times in different reactions and the general conclusion is that the rule is working quite well and is valid within 10% accuracy. It is a remarkable agreement, bearing in mind that it is based only on the value of the mixing angle, i. e., on the values of meson masses. It is also impressive that the agreement is valid at different energies from 100 MeV till 100 GeV.

In this situation it was a surprise when, in spite of the solid theoretical background and numerous experimental confirmations, the experiments at LEAR (CERN) with stopped antiprotons showed large violations of the OZI rule (for a review, see [3, 4]). In some annihilation reactions the deviation from the OZI predictions was as large as a factor of 30–70.

Then it was established that this anomaly was not restricted only to the antiproton annihilation at rest but there were similar deviations in πN , pp , and pd interactions. How should we treat these experimental evidences?

We would like to advocate the point of view that the OZI rule itself is always valid. In cases where some deviation from the OZI-rule predictions exists, it should be regarded as a signal on nontrivial physics, as a signal that the dynamics of the processes is more complicated than expected. For instance, let us assume,

following [9], that the nucleon wave function contains $\bar{s}s$ pairs which might take part in the ϕ production in NN or $\bar{N}N$ interactions. Then such processes would be described by connected diagrams and therefore would not be OZI-suppressed. So the violation of the OZI rule observed in these processes is only apparent.

A similar ideology was used to search for exotic mesons and baryons [83]. An exotic 4-quark meson $\bar{q}q\bar{s}s$ should decay more readily into ϕX system demonstrating an apparent violation of the OZI rule. Therefore, the apparent violation of the OZI rule gives us a hint on the exotic nature of these states.

Let us consider the experimental evidences on the large apparent violation of the OZI rule trying to understand what nontrivial physics is behind them.

2.1. Antiproton Annihilation at Rest. The largest violation of the OZI rule was observed in antiproton annihilation at rest. A question arises: why just this process is so distinguished with respect to the OZI violation?

The probable answer may be connected with the specific of the antiproton annihilation in the antiproton–proton atom. The slow antiproton first being captured on an orbit of antiproton–proton atom, preferentially with a large principal quantum number of $n \sim 30$. Its further fate could be either a cascade to lower levels or Stark mixing between the states with various angular momentum. The relative probability of these two scenarios depends on the density of the hydrogen. In gas at low pressure (of few millibars or less) the main process is the cascade to lower levels and annihilation from the P levels with $n = 2$. In liquid hydrogen, Stark mixing dominates and the antiproton annihilates from states with large principal number and orbital angular momentum $L = 0$, i. e., from the S states. The detailed discussion of these processes could be found in [84, 85].

So, in a first approximation, for annihilation in liquid hydrogen the initial states are the S levels. In low density gas the annihilation mainly takes place from the P levels. This circumstance strongly facilitates the analysis of the reaction mechanism because the conservation of C and P parities imposes strong restrictions on the allowed quantum numbers of the initial state.

For instance, the reaction $\bar{p}p \rightarrow \phi\pi^0$ is allowed only from two $\bar{p}p$ initial states, 3S_1 and 1P_1 . The study of this reaction in liquid hydrogen gives us information about the amplitude of this process from the 3S_1 state, whereas in low density hydrogen gas we will obtain the information on the 1P_1 amplitude. To reach the same goal for ordinary NN or $\bar{N}N$ interaction in flight we should use a polarized beam and a polarized target and perform a partial amplitude analysis.

Therefore, the important advantage of the antiproton annihilation at rest is a possibility of obtaining information about the amplitude of a process from the initial state with fixed quantum numbers.

The specific of the antiproton annihilation at rest is that the measured values — annihilation frequencies or annihilation yields — do not reflect directly the dynamics of the strong interaction but also depend on the population of different atomic levels of the $\bar{p}p$ atom.

The annihilation frequency of channel Y is defined as the product of the hadronic branching ratio B by the fraction $W(J^{PC}, \rho)$ of annihilations of the protonium atom from all the levels with given J^{PC} at the given target density ρ .

For instance, the annihilation frequency of the $\phi\pi^0$ channel for the target of density ρ is

$$Y(\bar{p}p \rightarrow \phi\pi^0, \rho) = W(^3S_1, \rho)B(\bar{p}p \rightarrow \phi\pi^0, ^3S_1) + W(^1P_1, \rho)B(\bar{p}p \rightarrow \phi\pi^0, ^1P_1). \quad (33)$$

In order to extract hadronic branching ratios, one has to know the annihilation fraction $W(J^{PC}, \rho)$ for each target density ρ . Usually it was done from the analysis of experimental data on different annihilation reactions with using some information from models of the cascade in $\bar{p}p$ atom (see, cf., [86, 87]). It was assumed that the weights W could be factorized as follows:

$$W(^3S_1, \rho) = 3/4 E(^3S_1, \rho) f_S(\rho), \quad (34)$$

$$W(^1P_1, \rho) = 3/12 E(^1P_1, \rho) (1 - f_S(\rho)). \quad (35)$$

Here $f_S(\rho)$ is the fraction of annihilations from the S states; the numbers $3/4$ and $3/12$ are the statistical weights of the corresponding initial states; and $E(^3S_1, \rho)$ and $E(^1P_1, \rho)$ are the enhancement factors which reflect deviations from the pure statistical population of the levels. The enhancement factors $E(^3S_1)$ and $E(^1P_1)$, determined in [86], turn out to be around 0.9–1 at all densities and $f_S(\rho) = 0.87, 0.42, 0.20$ in liquid, gas target at NTP and 5 mbar, respectively. However, this set of parameters is not unique and should be considered with some warning (see detailed discussion in [88]).

2.1.1. $\bar{p}p \rightarrow \phi\gamma$. The largest OZI-rule violation is observed in the $\bar{p}p \rightarrow \phi\gamma$ channel, where the Crystal Barrel collaboration has found [3, 89] after phase space corrections:

$$R_\gamma = \frac{B(\bar{p}p \rightarrow \phi\gamma)}{B(\bar{p}p \rightarrow \omega\gamma)} = (294 \pm 97) \cdot 10^{-3}, \quad (36)$$

which is about 70 times larger than the OZI prediction $R(\phi/\omega) = 4.2 \cdot 10^{-3}$.

The main experimental problem was the correct selection of the reaction $\bar{p}p \rightarrow K_S K_L \gamma$ among a lot of events of the $\bar{p}p \rightarrow K_S K_L \pi^0$ reaction. If one of two γ from π^0 decay had the energy less than the detection threshold of 10 MeV, then the two channels were indistinguishable. The Monte Carlo simulation has shown that the probability of the feedthrough is small $W(\phi\pi^0 \rightarrow \phi\gamma) = (0.52 \pm 0.02) \%$ [89]. However, the yield of the reaction $\bar{p}p \rightarrow \phi\pi^0$ is so large that it gives 36 ± 2 background events in the $\phi\gamma$ data sample, which after background subtraction comprises 46 ± 9 events. Therefore, the correction for the feedthrough is quite substantial, at the level of 40 %.

However, the study of $\phi\gamma$ was done in two different channels: $\bar{p}p \rightarrow K_S K_L \gamma$ and $\bar{p}p \rightarrow K^+ K^- \gamma$. The branching ratios extracted from both the reactions turned out to be similar.

The reaction $\bar{p}p \rightarrow \phi\gamma$ is possible either from the 1S_0 or from the 3P_J states. The measurements [89] were done in the liquid hydrogen, where the 1S_0 state is much more probable than the 3P_J states. Thus, the apparent OZI-rule violation was detected for the $J^{PC} = 0^{-+}$ initial state.

2.1.2. $\bar{p}p \rightarrow \phi\pi$. Another very large apparent violation of the OZI rule was found by the OBELIX and Crystal Barrel collaborations in the $\bar{p} + p \rightarrow \phi + \pi$ channel.

For the ratio of the phase space corrected branching ratios, the Crystal Barrel measurement [3] in liquid hydrogen gives:

$$R_\pi = \frac{B(\bar{p}p \rightarrow \phi\pi)}{B(\bar{p}p \rightarrow \omega\pi)} = (106 \pm 12) \cdot 10^{-3}. \quad (37)$$

It coincides with the ratio of the annihilation yields measured by the OBELIX collaboration for annihilation in a liquid-hydrogen target [90]:

$$R_\pi = (114 \pm 10) \cdot 10^{-3}. \quad (38)$$

The ratios (37) and (38) are about a factor of 30 higher than the OZI-rule prediction.

The OBELIX collaboration has performed a detailed investigation of the $\phi\pi$ channel in different conditions. First, the reaction

$$\bar{p} + p \rightarrow K^+ + K^- + \pi^0 \quad (39)$$

was studied for annihilation of stopped antiprotons in liquid hydrogen and in hydrogen gas at normal temperature and pressure (NTP) and at 5 mbar pressure [48]. It was accompanied by the measurements of the $\bar{p}p \rightarrow \omega\pi^0$ channel for annihilation in liquid hydrogen and gas at NTP [90].

Second, the annihilation in gaseous deuterium at NTP

$$\bar{p} + d \rightarrow \pi^- + \phi(\omega) + p \quad (40)$$

was measured for two regions of spectator-proton momenta: $p < 200$ MeV/c and $p > 400$ MeV/c [91].

Third, the annihilation of antineutrons

$$\bar{n} + p \rightarrow \pi^+ + \phi(\omega) \quad (41)$$

with momenta of 50–405 MeV/c was investigated [92, 93].

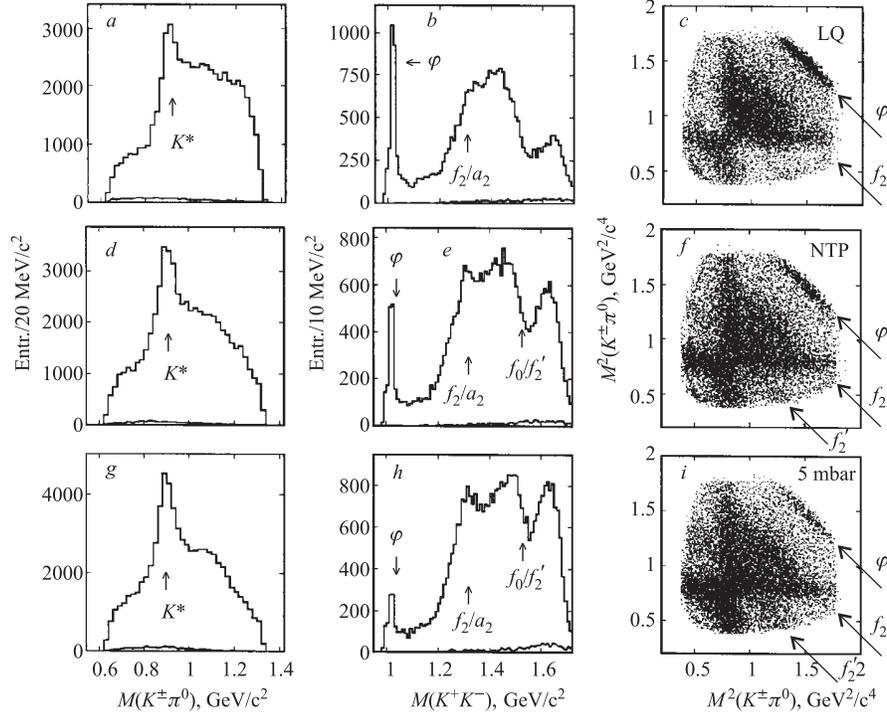


Fig. 6. Invariant mass distributions of the K^+K^- (b, e, h), $K^\pm\pi^0$ (a, d, g) systems and Dalitz plots (c, f, i) for the reaction $\bar{p}p \rightarrow K^+K^-\pi^0$ at three different target densities: for the liquid target (a, b, c), for the gas target at NTP (d, e, f) and for the gas target at 5 mbar (g, h, i) [48]

Table 4. The $\bar{p}p \rightarrow K^+K^-\pi^0$ and $\bar{p}p \rightarrow \phi\pi^0$ annihilation frequencies (in units of 10^{-4}) for three densities of the hydrogen target [48]

| $Y \cdot 10^4$ | LH ₂ | NTP | 5 mbar |
|---|---|--|--------------------------------------|
| $Y(\bar{p}p \rightarrow K^+K^-\pi^0)$ | 23.7 ± 1.6 | 30.3 ± 2.0 | 31.5 ± 2.2 |
| $Y(\bar{p}p \rightarrow \phi\pi^0)$ $Y(\bar{p}p \rightarrow \phi\pi^0, {}^1P_1)$ | 4.88 ± 0.32 | 2.47 ± 0.21 | 0.92 ± 0.10 <0.1 with 95 % CL |
| $Y(\bar{p}p \rightarrow \phi\pi^0)$ Other measurements | 3.3 ± 1.5 [94] 6.5 ± 0.6 [3] | 1.9 ± 0.5 [95] 2.46 ± 0.23 [96] | 0.3 ± 0.3 (LX) [95] |

The measurements of the reaction (39) at different hydrogen target densities allow one to establish an important feature of the apparent OZI-rule violation — its strong dependence on the quantum numbers of the initial state.

As we already mentioned, the fraction of annihilation from the S wave f_S decreases with decreasing of the target density. According to [86], f_S is 87 % for annihilation in liquid hydrogen, 42 and 20 % for gas at NTP and 5 mbar, respectively.

Therefore, if the $\phi\pi$ channel occurs mainly from the 3S_1 initial state, then the yield of the reaction should decrease with decreasing of the hydrogen density. If it is dominated by the 1P_1 initial state, the yield should grow up at a low pressure sample.

The measured invariant mass distributions of the K^+K^- and $K^\pm\pi^0$ systems and the corresponding Dalitz plots for the reaction (39) at different hydrogen pressures are shown in Fig. 6.

One can see immediately three salient features of the spectra in Fig. 6:

— the peak from the ϕ meson reduces with decreasing of the density of the target;

— the peak from K^* does *not* decrease with the density;

— the part of the K^+K^- spectra with high invariant mass ($M > 1.5$ GeV/c²) is more prominent in the low pressure data.

All these features are important for the further analysis. The enhancement in the K^+K^- spectrum around 1.5 GeV/c² at low pressure reflects the strong apparent violation of the OZI rule for the tensor $f_2'(1525)$ meson production. It will be discussed in Sec. 2.1.4. The density dependence of the K^* -meson production is important for discriminating different models of the OZI violation (see, Sec. 4.2). Here we will discuss the ϕ -meson production.

The dependence of the ϕ yield on the density clearly indicates the dominance of the production from the 3S_1 state. The values of the annihilation frequencies of ϕ and K^* production are given in Table 4. Whereas total annihilation frequency of the $\bar{p}p \rightarrow K^+K^-\pi^0$ final state increases by about 50 % from the liquid to the low-pressure hydrogen target, the $\phi\pi^0$ yield in the same conditions decreases by more than 5 times.

In Fig. 7 the dependence of the $\phi\pi^0$ -annihilation frequency on the fraction of S -wave annihilations is shown. One can see that the $\phi\pi^0$ -annihilation frequency linearly decreases with percentage of the S wave. It demonstrates the absence of the contribution from the 1P_1 state.

Using the parameters of the $\bar{p}p$ cascade from [86], the branching ratios of the $\bar{p}p \rightarrow \phi\pi^0$ from definite initial states were determined [48]:

$$B(\bar{p}p \rightarrow \phi\pi^0, ^3S_1) = (7.57 \pm 0.62) \cdot 10^{-4}, \quad (42)$$

$$B(\bar{p}p \rightarrow \phi\pi^0, ^1P_1) < 0.5 \cdot 10^{-4}, \text{ with 95 \% CL.} \quad (43)$$

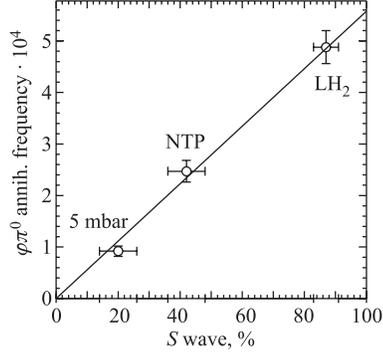


Fig. 7. Dependence of the $\bar{p}p \rightarrow \phi\pi^0$ annihilation frequency on the percentage of annihilation from the S wave [48]. The values of the S -wave percentage at different target densities are from [86]

channel at different hydrogen target densities (the preliminary data is reported in [90]). It turns out that the branching ratio of this reaction for the annihilation from the 1P_1 state is not negligible. The experimental angular distributions were fitted by the sum of the angular distribution from the 3S_1 and 1P_1 initial states:

$$W(\cos \Theta) = \alpha W_{^3S_1}(\cos \Theta) + (1 - \alpha) W_{^1P_1}(\cos \Theta) \quad (44)$$

and the value of the α parameter was determined. This parameter should be equal to 1 if the $\omega\pi$ final state as the $\phi\pi$ channel is dominated from the 3S_1 initial state. However, it turns out that for annihilation in liquid hydrogen $\alpha = 0.88 \pm 0.08$ and $\alpha = 0.69 \pm 0.10$ for annihilation in gas at NTP.

The non-negligible contribution of the 1P_1 state in the $\omega\pi$ channel results in different dependences of the $\phi\pi$ and $\omega\pi$ annihilation frequencies on the target density. Preliminary results [90] for the measurements of the ratio $R_\pi = Y(\phi\pi^0)/Y(\omega\pi^0)$ are:

$$R_\pi = (114 \pm 10) \cdot 10^{-3} \quad \text{for LQ}, \quad (45)$$

$$R_\pi = (83 \pm 10) \cdot 10^{-3} \quad \text{for NTP}. \quad (46)$$

It is also possible to obtain the values of the ϕ/ω ratio from the 3S_1 and 1P_1 initial states. For that one should repeat the same analysis for the $\omega\pi^0$ channel as it was done in [48] for the $\phi\pi^0$. Using $Y(\omega\pi^0) = (42.8 \pm 2.7) \cdot 10^{-4}$ for annihilation in liquid hydrogen and $Y(\omega\pi^0) = (29.6 \pm 2.7) \cdot 10^{-4}$ for

The branching ratio of the $\phi\pi^0$ channel from the 3S_1 initial state is at least 15 times larger than that from the 1P_1 state. This demonstrates strong dependence of the $\phi\pi^0$ production on the quantum numbers of the initial $\bar{p}p$ state.

An indication of this selection rule was reported earlier in [95,96] though on a scarce statistics. Thus in the OBELIX measurements [48], the number of ϕ events for 5 mbar data sample is $N_\phi = 400 \pm 42$, while the ASTERIX collaboration had only $N_\phi = 4 \pm 4$ for the data sample under similar conditions [95].

It is important that the observed tendency exists only for the ϕ -meson production, the ω -meson production from the P wave is quite substantial. That was observed in the measurements of the $\bar{p}p \rightarrow \omega\pi^0$ chan-

annihilation in hydrogen gas at NTP, one may arrive to the following important result:

$$R_\pi(\phi/\omega, {}^3S_1) = (120 \pm 12) \cdot 10^{-3}, \quad (47)$$

$$R_\pi(\phi/\omega, {}^1P_1) < 7.2 \cdot 10^{-3}, \quad \text{with 95 \% CL.} \quad (48)$$

Therefore, a large apparent OZI violation occurs only for annihilation from the spin-triplet S -wave initial state. When we study the *same* reaction channel for spin-singlet P -wave state, the disagreement with the OZI-rule prediction magically disappears.

It turns out that the large apparent OZI violation could be switched off by changing the initial state quantum numbers.

Investigations of the $\phi\pi$ channel for the annihilation in deuterium $\bar{p} + d \rightarrow \pi^- + \phi(\omega) + p$ also confirm the large apparent OZI-rule violation [91]:

$$R_\pi(\phi\pi^-/\omega\pi^-) = (133 \pm 26) \cdot 10^{-3}, \quad p < 200 \text{ MeV}/c, \quad (49)$$

$$R_\pi(\phi\pi^-/\omega\pi^-) = (113 \pm 30) \cdot 10^{-3}, \quad p > 400 \text{ MeV}/c. \quad (50)$$

Here the basic reaction is $\bar{p}n \rightarrow \phi\pi^-$. It was measured for two intervals of proton-spectator momenta: $p < 200 \text{ MeV}/c$ and $p > 400 \text{ MeV}/c$. The ratio R_π is independent of the momentum of the proton-spectator, indicating the relevant dynamics to be connected with the basic $\bar{N}N$ interaction.

From these results one may conclude that if the apparent OZI violation is due to excitation of some resonance, then the resonance should have isospin $I = 1$ and $J^{PC} = 1^{--}$. We will discuss the resonance hypothesis in Sec.4.2.

The experiments with annihilation of antineutrons in flight (41) also have revealed the strong apparent OZI violation and confirmed the difference between the $\phi\pi$ and $\omega\pi$ channels [93]. The phase space corrected ratio of the branching ratios for ϕ and ω production from S wave is:

$$R_\pi(\phi/\omega, {}^3S_1) = (112 \pm 14) \cdot 10^{-3}, \quad (51)$$

that is in agreement with the measurements of Crystal Barrel and OBELIX collaborations for the antiproton annihilation (37) and (47).

The cross sections of the $\bar{n}p \rightarrow \phi(\omega)\pi^+$ channels were measured for antineutron momenta in the interval 50–405 MeV/c. It turns out that the $\phi\pi^+$ cross section drops with energy, strictly following the decreasing of the S wave. The $\omega\pi^+$ cross section decreases with energy not so rapidly. A Dalitz-plot fit of the $\omega\pi^+$ final state demands a significant P -wave contribution. The branching ratio of the $\omega\pi^+$ channel from the 3S_1 final state is $B.R.({}^3S_1) = (8.51 \pm 0.26 \pm 0.68) \cdot 10^{-4}$, whereas that of the 1P_1 final state is only three times less, $B.R.({}^1P_1) = (3.11 \pm 0.10 \pm 0.25) \cdot 10^{-4}$. That is in sharp contrast with the

hierarchy of the same branching ratios for annihilation into $\bar{p}p \rightarrow \phi\pi$ final state (42), (43), which differs by a factor of 15.

It has been also found that the ratio $R_\pi = \sigma(\phi\pi^+)/\sigma(\omega\pi^+)$ decreases with increasing of the incoming antineutron momentum:

$$R_\pi = (100 \pm 17) \cdot 10^{-3}, \quad p = 50-200 \text{ MeV}/c, \quad (52)$$

$$R_\pi = (73.9 \pm 8.9) \cdot 10^{-3}, \quad p = 200-300 \text{ MeV}/c, \quad (53)$$

$$R_\pi = (61.5 \pm 9.4) \cdot 10^{-3}, \quad p = 300-405 \text{ MeV}/c. \quad (54)$$

These results are important because they demonstrate how the large apparent violation of OZI rule in the annihilation at rest smoothly disappears with increasing the energy of the projectile and matches with the results, shown in Table 1 for annihilation in flight.

2.1.3. $\bar{p}p \rightarrow \phi\eta$. This channel was measured by the OBELIX collaboration [97] for the $\bar{p}p$ annihilation at rest in liquid hydrogen, gas at NTP and at low pressure of 5 mbar. The $\phi\eta$ final state has the same J^{PC} as the $\phi\pi^0$ final state. So, one may expect to see the same selection rule as Eqs. (42), (43) and suppose that the ϕ production in the low pressure sample will be suppressed. However, absolutely unexpectedly, the reverse trend is seen: the yield of the $\bar{p}p \rightarrow \phi\eta$ channel grows with decreasing of the target density.

It is demonstrated in Fig. 8 where the invariant mass distribution of two kaons $M_{K^+K^-}$ from the reaction $\bar{p}p \rightarrow K^+K^-X$ is shown. On Fig. 8, *b, e, h*, the events with the missing mass $0.26 < M_{\text{miss}}^2 < 0.34 \text{ GeV}^2/c^4$ (centered around the mass of η meson, $m_\eta^2 = 0.3 \text{ GeV}^2/c^4$) are selected. Figure 8 *a, d, g* and *c, f, i*, correspond to the $M_{K^+K^-}$ distributions for the missing mass intervals below and above the η mass: $0.15 < M_{\text{miss}}^2 < 0.23$ (*a, d, g*) and $0.37 < M_{\text{miss}}^2 < 0.45 \text{ GeV}^2/c^4$ (*c, f, i*).

One can see that the ϕ peak in the η missing mass interval is growing up with the decreasing of the density. Using the same parameters of the $\bar{p}p$ atom cascade for the evaluation of the branching ratios as in [48], it is obtained [97] that

$$B(\bar{p}p \rightarrow \phi\eta, {}^3S_1) = (0.76 \pm 0.31) \cdot 10^{-4}, \quad (55)$$

$$B(\bar{p}p \rightarrow \phi\eta, {}^1P_1) = (7.72 \pm 1.65) \cdot 10^{-4}. \quad (56)$$

Therefore some dynamical selection rule is observed with a trend opposite to that for the $\phi\pi$ channel.

The question arises: what about the OZI rule for the $\phi\eta$ production?

The Crystal Barrel measurements of annihilation in liquid give for the ratio of the phase space corrected branching ratios [3]

$$R_\eta = \frac{B(\bar{p}p \rightarrow \phi\eta)}{B(\bar{p}p \rightarrow \omega\eta)} = (4.6 \pm 1.3) \cdot 10^{-3} \quad (57)$$

in a perfect agreement with the OZI-rule prediction for the *vector* mesons (16).

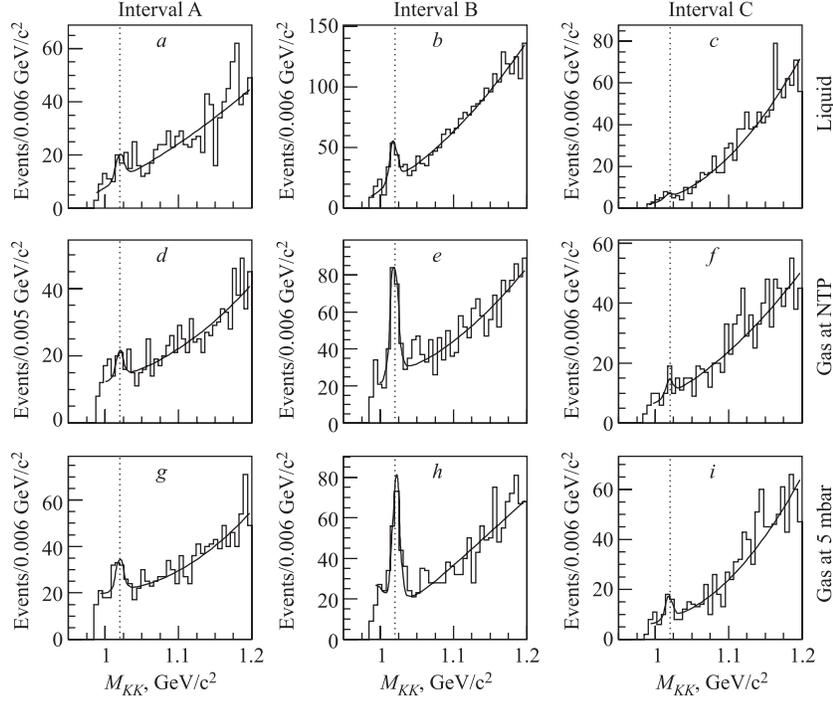


Fig. 8. The distributions on $M_{K^+K^-}$ for events of the reaction $\bar{p}p \rightarrow K^+K^-X$ at three target densities: a, b, c) for the liquid target; d, e, f) for the gas target at NTP; g, h, i) for the gas target at the 5 mbar pressure [97]. The column a, d, g corresponds to the interval of missing mass below and column c, f, i — above the η mass. Dashed lines show the ϕ meson mass

It will be interesting to measure the density dependence of the $\bar{p}p \rightarrow \omega\eta$ channel. The reasons for that are discussed in Sec. 4.5.

2.1.4. $\bar{p}p \rightarrow f'_2(1525)\pi^0$. The OBELIX measurements of the $\bar{p} + p \rightarrow K^+ + K^- + \pi^0$ channel for annihilation of stopped antiprotons in hydrogen targets of different density [48] provide for the first time the indication of the apparent OZI-rule violation for the tensor mesons.

Discussing the Dalitz plots of this reaction at different target densities shown in Fig. 6 we have already mentioned that at the low pressure the part of the K^+K^- spectra with invariant masses $M \sim 1.5 \text{ GeV}/c^2$ is more prominent than in the annihilation in liquid. The partial-wave analysis of the Dalitz plots [48] determines the yields of the tensor $\bar{s}s$ state — the $f'_2(1525)$ meson and allows one

to compare them with the S - and P -wave yields of the $f_2(1270)$ meson, which consists of light quarks only.

To avoid the problem of poor separation between the $f_2(1270)$ and $a_2(1320)$ mesons, the high statistics $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ channel was analysed to determine the $\bar{p}p \rightarrow f_2(1270)\pi^0$ annihilation frequencies. In the $K^+K^-\pi^0$ final state there is strong interference between the $f_2(1270)$ and $a_2(1320)$ states, whereas in the $\pi^+\pi^-\pi^0$ final state the $a_2(1320)$ contribution is absent.

Using the f'_2 yield from the analysis of the $K^+K^-\pi^0$ channel and f_2 from the $\pi^+\pi^-\pi^0$ one, it was obtained [48] that

$$\begin{aligned} R(f'_2(1525)\pi^0/f_2(1270)\pi^0) &= (47 \pm 14) \cdot 10^{-3}, & S \text{ wave}, & (58) \\ &= (149 \pm 20) \cdot 10^{-3}, & P \text{ wave}. & (59) \end{aligned}$$

Remind the reader that the OZI-rule prediction for the tensor mesons (17) is $R(f'_2/f_2) = (3-16) \cdot 10^{-3}$.

The result of (58) for the S wave agrees with the Crystal Barrel measurement [3]

$$R(f'_2(1525)\pi^0/f_2(1270)\pi^0) = (26 \pm 10) \cdot 10^{-3} \quad (60)$$

for annihilation in liquid hydrogen, where the S wave is dominant. The excess of the $f'_2(1525)$ production (58) observed in the S wave is marginal within the experimental errors. However, the strong apparent violation of the OZI rule is seen in the P -wave annihilation. It means that for annihilation in flight this effect should increase with the energy of the incoming antiproton.

2.1.5. $\bar{p}p \rightarrow \phi\pi\pi$. The OBELIX collaboration has measured the reaction of the ϕ and ω production with two pions

$$\bar{p} + p \rightarrow \phi(\omega) + \pi^+ + \pi^- \quad (61)$$

for annihilation of stopped antiprotons in a gaseous and a liquid hydrogen target [98].

The ratio $R_{\pi\pi} = Y(\phi\pi^+\pi^-)/Y(\omega\pi^+\pi^-)$ was determined for different invariant masses of the dipion system. It turns out that without selection on the dipion mass, the ratio $R_{\pi\pi}$ is at the level of $(5-6) \cdot 10^{-3}$, i. e., in agreement with the prediction of the OZI rule. However, at small dipion masses $300 < M_{\pi\pi} < 500$ MeV the degree of the OZI-rule violation increases up to $R_{\pi\pi} = (16-30) \cdot 10^{-3}$. That should be compared with the ratio $R_{\pi} = (106 \pm 12) \cdot 10^{-3}$ for the $\phi\pi^0/\omega\pi^0$ channels for annihilation in liquid [3], which also proceeds from the same 3S_1 initial state.

In Fig. 9 the values of the $R_{\pi\pi}$ corrected for the phase space difference are compared with the results of other measurements of binary reactions of antiproton annihilation at rest. The clear dependence of the degree of the OZI-rule violation

on the mass of the system created with ϕ is seen. Namely, the degree of the OZI-rule violation increases with decreasing of the mass of the system created with ϕ . For annihilation at rest $\bar{N}N \rightarrow \phi X$, the decreasing of the mass of X means an increase of the momentum transferred to the ϕ .

The same effect was found in ϕ production in $\pi^\pm N \rightarrow \phi N$ interaction [30] where the $d\sigma/dt$ distribution of ϕ production at large t differs significantly from the one for ω meson, leading to the increase of ϕ/ω ratio at large t . The direct measurements of the t dependence of the differential cross sections of $\phi\pi$ and $\omega\pi$ channels in $\bar{p}p$ annihilation in flight should clarify the problem.

It would be interesting to perform a systematic investigation to what extent the degree of the apparent OZI-rule violation depends on the momentum transfer.

2.1.6. $\bar{p}d \rightarrow \phi n$. The largest momentum transfer in the ϕ production by stopped antiproton annihilation is available in the so-called Pontecorvo reaction



This is an example of a specific reaction of antiproton annihilation with only one meson in the final state



where $M = \pi, \rho, \omega, \phi, \dots$ is a meson and $N = p, n, \Delta, \Lambda, \dots$ is a baryon. They were first considered by B. Pontecorvo [99] in 1956. These processes are forbidden for antiproton annihilation in hydrogen but allowed for annihilation in deuterium.

The momentum transferred to the ϕ in the Pontecorvo reaction (62) with a stopped antiproton is $q^2 = -0.762 \text{ GeV}^2/c^2$, compared to $q^2 = -0.360 \text{ GeV}^2/c^2$ for the $\bar{p}p \rightarrow \phi\pi^0$ reaction.

The OBELIX collaboration [100] has measured reaction (62) in a deuterium gas target at NTP and the Crystal Barrel collaboration has measured the Pontecorvo reaction with ωn in the final state [101].

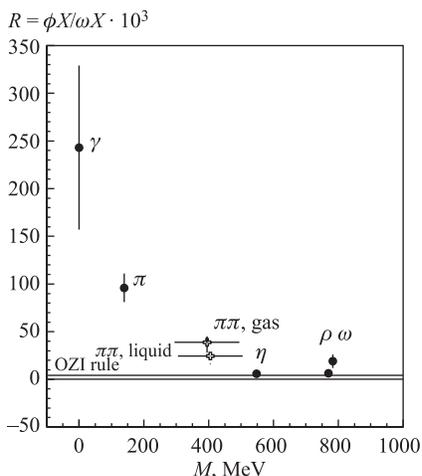


Fig. 9. The ratio $R = \phi X/\omega X$ corrected on phase space for different reactions of $\bar{p}p$ annihilation at rest as a function of the mass M of the system X (from [98]). Solid line shows the prediction of the OZI rule

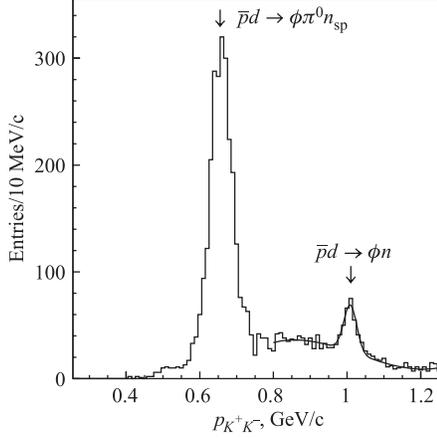


Fig. 10. The total momentum distribution of K^+K^- system for the events obeying the cut $|M_{K^+K^-} - M_\phi| < 10 \text{ MeV}/c^2$ (from [100])

shown. To provide that these two kaons are coming from ϕ decay, the events with invariant mass around the mass of ϕ at $|M_{K^+K^-} - M_\phi| < 10 \text{ MeV}/c^2$ were chosen. A clear peak from the Pontecorvo reaction is seen at $p_{K^+K^-} = 1 \text{ GeV}/c$. A more prominent peak at $p_{K^+K^-} = 650 \text{ MeV}/c$ is mainly from the reaction $\bar{p}d \rightarrow \phi\pi^0n$.

The measurement of the yield of (62) provides that $Y(\bar{p}d \rightarrow \phi n) = (3.56 \pm 0.20_{-0.1}^{+0.2}) \cdot 10^{-6}$. That should be compared with the yield of the Pontecorvo reaction for the ω production $Y(\bar{p}d \rightarrow \omega n) = (22.8 \pm 4.1) \cdot 10^{-6}$ [101]. It turns out that the ratio ϕ/ω is rather large:

$$R = Y(\bar{p}d \rightarrow \phi n)/Y(\bar{p}d \rightarrow \omega n) = (156 \pm 29) \cdot 10^{-3}. \quad (64)$$

It is even greater than the corresponding ratio R_π from Eq.(37) for the annihilation on a free nucleon $\bar{p}p \rightarrow \phi\pi^0$ in liquid hydrogen and twice as large as the ratio R_π measured in hydrogen gas at NTP (46).

Therefore, there is a serious expectation that the degree of the OZI-rule violation depends on the momentum transfer.

2.1.7. Summary of $\bar{p}p$ Annihilation Results. The experiments at LEAR with antiproton annihilation have demonstrated the following distinctive features:

1) Unusually strong deviation from the OZI-rule predictions. In some reactions it exceed the OZI estimation by a factor of 30–70.

2) This effect is nonuniversal for all annihilation channels of the ϕ production but mystically occurs only in some of them. For instance, no enhancement

The kinematics of the Pontecorvo reaction $\bar{p}d \rightarrow \phi n$ facilitates its selection because it is the only two-body reaction of the $\bar{p}d \rightarrow \phi X$ annihilation. The momentum of ϕ in reaction (62) should be equal to $1.01 \text{ GeV}/c$ for annihilation of antiproton at rest. Another quasi-two-body reaction is $\bar{p}d \rightarrow \phi\pi^0n$. The yield of this process is dominated by the two-body annihilation on the proton $\bar{p}p \rightarrow \phi\pi^0$, whereas the neutron behaves as a spectator with typical momenta $p \leq 200 \text{ MeV}/c$. The momentum of ϕ from this reaction is $650 \text{ MeV}/c$. It should be spread by the Fermi motion of proton in deuteron and experimental resolution.

In Fig.10 the distribution of the events on the total momentum of K^+K^- system measured in [100] is

of the ϕ production is observed for the $\phi\omega$ or $\phi\rho$ channels ($R(\phi\omega/\omega\omega) = (19 \pm 7) \cdot 10^{-3}$, $R(\phi\rho/\omega\rho) = (6.3 \pm 1.6) \cdot 10^{-3}$ [4]).

3) There is a strong dependence of the OZI-rule violation on the quantum numbers of the initial $\bar{p}p$ state. It was clearly demonstrated by the OBELIX collaborations results:

$$R_\pi(\phi/\omega, {}^3S_1) = (120 \pm 12) \cdot 10^{-3}, \quad (65)$$

$$R_\pi(\phi/\omega, {}^1P_1) < 7.2 \cdot 10^{-3}, \quad \text{with 95 \% CL.} \quad (66)$$

4) There is a serious indications that the degree of the OZI-rule violation depends on the momentum transfer.

5) The apparent OZI violation was found not only for the ϕ meson production but also for the tensor $\bar{s}s$ state — $f_2'(1525)$ meson. As in the case of ϕ meson the apparent OZI violation for tensor mesons turns out to be extremely sensitive to the quantum numbers of the initial state.

2.2. Proton-Proton and Proton-Deuteron Interactions. The large apparent OZI violation was observed not only in experiments with stopped antiprotons. Recent experiments with ϕ production in pp and pd interactions have also revealed significant deviation from the OZI predictions.

2.2.1. $pp \rightarrow pp\phi$. The DISTO collaboration [6, 7] has performed the measurement of the ϕ and ω production

$$p + p \rightarrow p + p + \phi(\omega) \quad (67)$$

at the same proton energy of 2.85 GeV.

It was found [7] that

$$R = \frac{\sigma(pp \rightarrow pp\phi)}{\sigma(pp \rightarrow pp\omega)} = (3.8 \pm 0.2_{-0.9}^{+1.2}) \cdot 10^{-3}. \quad (68)$$

At first glance this value seems to be in agreement with the OZI-rule prediction (16). However, a correction on a different phase space volume of the ϕpp and ωpp final states is needed. The incoming proton energy of 2.85 GeV corresponds to 83 MeV above the ϕ production threshold and 320 MeV above the threshold for the ω production. The corresponding phase spaces differ by a factor of 14, on which one should multiply the ratio (68).

Therefore, a substantial OZI violation has been observed also in the proton-proton interaction. One should mention that besides the DISTO measurement, the ϕ production in pp interaction was investigated only in two other experiments, at 10 and 24 GeV/c [31, 35]. The new experimental information on the ϕ and ω production near the threshold is badly needed.

It is interesting that the DISTO collaboration has observed also the differences between the angular distributions of the ϕ and ω mesons produced in (67). The

ϕ meson angular distribution is flat, whereas to fit the ω angular distribution, the first three even Legendre polynomials are needed [6].

In general, the difference in the angular distributions of the ϕ and ω mesons is an indication of different production mechanisms. It contradicts the OZI-rule postulate that the ϕ could be formed in pp interactions only via ω - ϕ mixing.

To demonstrate that, one should compare the ϕ - and ω -meson distributions at the same energy above the corresponding thresholds. However, this condition was not fulfilled in the DISTO measurements. So, in principle, it is possible that the ω angular distribution is more asymmetric simply because it was measured at larger energy above the threshold. Recently the ω production was measured at lower energy of 173 MeV above the threshold [102]. The measurement again reveals strong angular anisotropy. That indicates that the difference in the ϕ - and ω -meson production is not due to kinematics but due to the difference in the production mechanisms.

Clearly future measurements should avoid this disadvantage and take data at different incoming proton energies but at the same energy above the threshold of the ϕ and ω production.

2.2.2. $pp \rightarrow pp\phi$ Diffractive Production. Interesting results were obtained at the SPHINX spectrometer at the Protvino U-70 accelerator [103] in the study of diffractive production of the ϕ and ω mesons

$$p + p \rightarrow p + [pV], \quad V = \phi, \omega \quad (69)$$

at 70 GeV proton energy.

To fulfill the «elasticity» condition, to ensure the diffractive character of the process, the events were selected in such a way that the total energy of the proton and the vector meson decay products was within the 65–75 GeV interval.

The simple ratio of the total cross sections of diffractively produced ϕ and ω does not largely deviate from the OZI prediction of (16):

$$R = \frac{\sigma(pp \rightarrow p[p\phi])}{\sigma(pp \rightarrow p[p\omega])} = (15.5 \pm 0.5 \pm 3) \cdot 10^{-3}. \quad (70)$$

However, the *shape* of the invariant mass spectra of the $p\phi$ and $p\omega$ systems is absolutely different.

The authors [103] argue that the simple ratio of the total cross sections (70) has little physical sense because a significant contribution to the total cross section of the $p\omega$ production comes from the kinematical region below the threshold of the $p\phi$ production. They prefer to compare either the differential cross sections of the vector-meson production with the same invariant mass of the pV system, or the differential cross sections in the same vector meson momentum interval. In both cases the (ϕ/ω) ratios increase significantly till $R(\phi/\omega) = (40-73) \cdot 10^{-3}$.

It is interesting that this ratio of the differential cross sections is practically independent of the squared transverse momentum p_T^2 of the pV system.

2.2.3. $pd \rightarrow {}^3\text{He}\phi$. The measurements of the ϕ - and ω -mesons production yields in the reaction



were performed at SATURNE II accelerator [5]. The yield of ${}^3\text{He}$ was measured as a function of the proton beam energy just near the thresholds of the ϕ - and ω -mesons production. The method exploits the fact that only near the threshold the ${}^3\text{He}$ is formed at rest in the centre-of-mass frame and flies in a very small cone around the beam direction covered by the spectrometer.

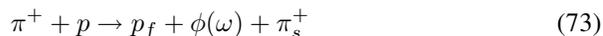
A large deviation from the OZI-rule prediction $R(\phi/\omega) = 4.2 \cdot 10^{-3}$ was found:

$$R(\phi/\omega) = (80 \pm 3_{-4}^{+10}) \cdot 10^{-3}. \quad (72)$$

After corrections due to the ω - ${}^3\text{He}$ final state interactions and different ϕ and ω thresholds, the apparent OZI violation is still large [5]: $R(\phi/\omega) = (63 \pm 5_{-8}^{+27}) \cdot 10^{-3}$.

2.3. Pion-Proton Interactions. In general, the agreement with the OZI-rule predictions is the best just for πN scattering (see discussion in Sec.1.2). However, even in this case there is an experiment [8] which claims finding a large OZI violation (on factor 100).

The authors of [8] have analysed the data of CERN WA 56 experiment on the ϕ and ω production in a special kinematic regime:



at the beam momentum of 20 GeV/c (similar reactions for $\pi^- p$ interaction were studied at 12 GeV/c).

Here p_f stands for fast proton with lab momentum more than 10 GeV/c and π_s means slow pion, which was undetectable. Physically these conditions correspond to the baryon exchange processes.

The measured ϕ/ω ratios in the reactions (73) are enormous, ranging from $R(\phi/\omega) = (430 \pm 140) \cdot 10^{-3}$ for $\phi\pi$ invariant masses below 1.75 GeV till $R(\phi/\omega) = (75 \pm 34) \cdot 10^{-3}$ for $\phi\pi$ invariant masses in the 2.75–3.25 GeV interval.

However, from the experimental point of view, there are some questions concerning the measurement [8]. The overall statistics is scarce, comprises 345 ± 22 events of ω production and 247 ± 22 of ϕ production. In case of the ω production there are two unseen pions in the reaction (73). In general, in such cases it is not possible to select the reaction by the kinematical fit. The authors used additional experimental information, but of course could not cure the situation completely. In result, for instance, the invariant mass resolution in the ω peak is as large as 60 MeV.

So, these results need confirmation from the high statistics experiments with reliable final state selection.

2.4. Production of the $\phi\phi$ System. Production of the $\phi\phi$ pair in the interactions of nonstrange hadrons is a well-known process which does not follow the prescriptions of the OZI rule. Thus in [104] it was found that the yield of the reaction $\pi^- p \rightarrow \phi\phi n$ at 22 GeV/c is significant. It was not precisely compared with the corresponding yield of the $\omega\omega$ channel but simply stated that the 100 observed events were too much for the OZI-forbidden reaction. The effective mass of the $\phi\phi$ system exhibits a large enhancement around the 2.2–2.4 GeV region. The partial wave analysis has shown that the largest contribution comes from the state with quantum numbers of $J^P SL = 2^+ 20$, where S is the total spin of two ϕ , and L is their orbital angular momentum. The other significant contribution comes from $J^P SL = 2^+ 22$ state, again with $S = 2$.

The JETSET collaboration at LEAR has reported an unusually high apparent violation of the OZI rule in the $\phi\phi$ final state [105] of the antiproton annihilation:

$$\bar{p} + p \rightarrow \phi + \phi. \quad (74)$$

The measured cross section of this reaction turns out to be 2–4 μb for the antiproton momenta interval from 1.1 to 2.0 GeV/c. One should compare it with the cross section of the reaction $\bar{p} + p \rightarrow \omega + \omega$, but this channel has not been measured directly. The authors of [105] considered as a reference point the cross section for the reaction $\bar{p} + p \rightarrow 2\pi^+ 2\pi^- 2\pi^0$, which is about 5 mb. For the $\omega\omega$ final state they put 10% of this value and assuming standard mixing angle value obtained

$$\sigma(\phi\phi) = \sigma(\omega\omega) \tan^4(\Theta - \Theta_i) \sim 10 \text{ nb}. \quad (75)$$

It is by two orders of the magnitude less than the experimental value.

The spin-parity analysis of the JETSET data [106] also shows dominance of the 2^{++} states. It turns out that near the $\phi\phi$ threshold the largest contributions are from 2^+ states with the total spin of the $\phi\phi$ system $S = 2$.

The same trend was seen in the central production of the $\phi\phi$ system in pp interactions [55] at 450 GeV/c. A broad enhancement was observed in the $\phi\phi$ effective mass spectrum around 2.35 GeV. The angular analysis provides the best fit for the 2^+ state with $S = 2$ and $L = 0$.

The comparison between the $\phi\phi$ production in $\pi^- p$ and $K^- p$ interaction was done in [107]. The cross section of the OZI-forbidden reaction

$$\pi^- p \rightarrow \phi\phi n \quad (76)$$

for pion momentum of 8 GeV/c was compared with the cross section of the OZI-allowed reaction

$$\pi^- p \rightarrow \phi K^+ K^- n \quad (77)$$

for the same kaon beam momentum.

It turns out that the ratio of these cross sections is

$$R_1 = \frac{\sigma(\pi^- p \rightarrow \phi K^+ K^- n)}{\sigma(\pi^- p \rightarrow \phi \phi n)} = 10.3 \pm 3.3. \quad (78)$$

Analogous processes for the $K^- p$ interaction are

$$K^- p \rightarrow \phi \phi \Lambda \quad (79)$$

and

$$K^- p \rightarrow \phi K^+ K^- \Lambda. \quad (80)$$

These reactions are OZI-allowed and it was expected that the ratio R_2 of their cross sections

$$R_2 = \frac{\sigma(K^- p \rightarrow \phi K^+ K^- \Lambda)}{\sigma(K^- p \rightarrow \phi \phi \Lambda)} \quad (81)$$

will be significantly different from the R_1 . Namely, one expects that $R_1 \gg R_2$. However, the experiment [107] found that $R_1 \simeq R_2$.

The violation of the OZI rule in the production of $\phi\phi$ system is so drastic and clear that the question of the explanation of these and other experimental results discussed in this section is mandatory. The proposal how to solve these problems is discussed below.

3. POLARIZED NUCLEON STRANGENESS

The role of the nucleon sea quarks is under extensive investigation now. There are experimental indications that the $\bar{s}s$ pairs in the proton wave function are responsible for the number of nontrivial effects.

It was found that the magnitude of the strange quarks contribution varies for different nucleon matrix elements. In [108] an explanation is giving, why the strange quarks contribution in the nucleon could be at the same time small or large, depending on the considered matrix element. The authors of [108] connect the size of the nucleon strange matrix elements with the contribution from the QCD nonperturbative effects. These nonperturbative effects should increase the nucleon matrix elements $\langle p | \bar{s} O_n s | p \rangle$ for operators $O_n = \gamma_\mu \gamma_5, \gamma_5, I$. Whereas for $O_n = \gamma_\mu, \theta_{\mu\nu} = \gamma_\mu \partial_\nu + \gamma_\nu \partial_\mu$ the nonperturbative effects are small and an enhancement of the nucleon strange matrix elements is not expected.

Indeed, the fraction of the nucleon momentum carried by the strange quarks is not large [109, 110]:

$$P_s = 4\% \text{ at } Q^2 = 20 \text{ GeV}^2. \quad (82)$$

The contribution of the strange quarks to the proton electric form factor is also quite small. The HAPPEX collaboration measurements allow one to extract the combinations of strange electric and magnetic form factors at $Q^2 = 0.48 \text{ (GeV/c)}^2$ [111]

$$G_E^s + 0.39G_M^s = 0.025 \pm 0.020 \pm 0.014 \quad (83)$$

(the last error is related to uncertainties in electromagnetic form factors).

The strange-quark contribution to the nucleon magnetic moment, measured by the SAMPLE collaboration [120], is also small. The contribution of strange quarks to the proton magnetic moment is $-0.1 \pm 5.1 \%$.

However the contribution of the strange quarks in the nucleon mass may be substantial. Usually the strangeness content of the nucleon is parametrized as the following ratio:

$$y = \frac{2\langle p|\bar{s}s|p\rangle}{\langle p|\bar{u}u + \bar{d}d|p\rangle}. \quad (84)$$

The classical analysis of the πN phase shifts [112] gives $y = 0.2$ though with large uncertainties. The lattice calculations give quite a large value of y : $y = 0.36 \pm 0.03$ [113] and $y = 0.59 \pm 0.13$ [114]. The prediction of heavy baryon chiral perturbation theory is $y = 0.20 \pm 0.12$ [115]. The calculation in the framework of the perturbative chiral model [116] gives somewhat small value $y = 0.076 \pm 0.012$. Also the cloudy bag model predicts a small value of $y \sim 0.05$ [117].

The summary of recent analysis of the πN experimental data for evaluation of the nucleon σ -term was done in [118]. Main conclusion is quite unexpected, the $\bar{s}s$ content of the proton turns out to be as large as $y = 0.36-0.48$ (see, also [119]).

Moreover, during the past decade the EMC [11] and successor experiments [12–14] with polarized lepton beams and nucleon targets gave indication that the $\bar{s}s$ pairs in the nucleon are polarized:

$$\Delta s \equiv \int_0^1 dx [s_\uparrow(x) - s_\downarrow(x) + \bar{s}_\uparrow(x) - \bar{s}_\downarrow(x)] = -0.10 \pm 0.02. \quad (85)$$

The minus sign means that the strange quarks and antiquarks are polarized negatively with respect to the direction of the nucleon spin.

Experiments on elastic neutrino scattering [121] have also provided an indication that the intrinsic nucleon strangeness is negatively polarized though within large uncertainties. It was obtained [121] that $\Delta s = -0.15 \pm 0.07$.

The analysis [122] of the baryon magnetic moments also leads to the conclusion that, in the proton, the strange quarks are polarized and $\Delta s = -0.19 \pm 0.05$.

The lattice QCD calculations also indicate the negative polarization of strange quarks in the proton. The calculations in the quenched approximation give $\Delta s =$

-0.12 ± 0.01 [123] and $\Delta s = -0.109 \pm 0.030$ [124], whereas the calculation in full lattice QCD [125] gives $\Delta s = -0.12 \pm 0.07$.

The negative polarization of the nucleon strange sea was calculated within the framework of the $SU(3)$ flavor chiral quark model [126]. This model couples light quarks with octet of pseudoscalar mesons by the requirement of the chiral symmetry. The values of the polarization within $\Delta s = -(0.11-0.22)$ interval were predicted for different model parameters.

To explain the huge violation of the OZI rule in the annihilation of stopped antiprotons and its strong dependence on the spin of the initial state, which was discussed in Sec. 2.1, the model based on a nucleon wave function containing negatively polarized $s\bar{s}$ pairs was proposed [9, 10].

The model claims that the observed OZI violation is only apparent because in these processes the $\bar{s}s$ meson is created via *connected* diagrams with participation of intrinsic nucleon strange quarks. The strong dependence on the initial quantum numbers is due to polarization of the strange sea. Let us discuss these assumptions in more detail.

3.1. Formation of $\bar{s}s$ Mesons. Let us consider the production of $\bar{s}s$ strangeonia in NN or $\bar{N}N$ interactions assuming that the nucleon wave function contains an admixture of $\bar{s}s$ pairs which are polarized negatively with respect to the direction of the nucleon spin.

Due to the interaction it is possible that these pairs could be either shaken-out from the nucleon, or strange quarks from different nucleons could participate in some rearrangement process similar to the one shown in Fig. 11. Let us assume further that the quantum numbers of the $\bar{s}s$ pair are $J^{PC} = 0^{++}$ (later we will explain this choice).

Then the shake-out of such pairs will not create ϕ or tensor $f'_2(1525)$ meson, but a scalar strangeonium. The $\bar{s}s$ systems with other quantum numbers (like ϕ or $f'_2(1525)$) should be produced due to a process where strange quarks from *both* nucleons are participating.

The examples of these rearrangement diagrams are shown in Fig. 11. If the nucleon spins are parallel (Fig. 11, *a*), then the spins of the \bar{s} and s quarks in both nucleons are also parallel. If the polarization of the strange quarks does not change during the interaction, then the \bar{s} and s quarks could keep parallel spins in the final state. The total spin of $\bar{s}s$ quarks will be $S = 1$ and if their relative orbital momentum is $L = 0$, it means that the strangeonium has the ϕ quantum numbers, if $L = 1$, it will correspond to the creation of tensor strangeonium, $f'_2(1525)$.

If the initial NN state is a spin-singlet, the spins of strange quarks in different nucleons are antiparallel and the rearrangement diagrams like that in Fig. 11, *b* may lead to the preferential formation of the $\bar{s}s$ system with total spin $S = 0$. It means that for $L = 0$ one should expect additional production of strangeonia with the pseudoscalar quantum numbers 0^{-+} .

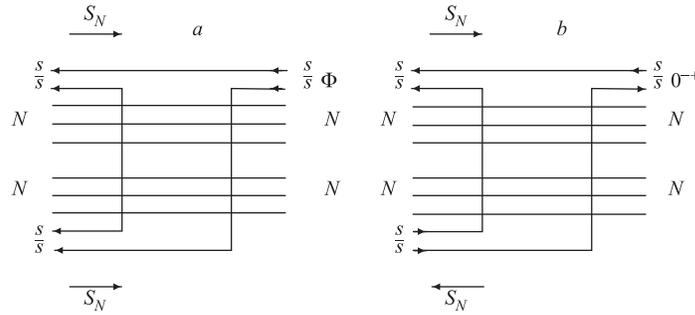


Fig. 11. Production of the $\bar{s}s$ mesons in NN interaction from the spin-triplet (a) and spin-singlet (b) states. The arrows show the direction of spins of the nucleons and strange quarks

Therefore, the rearrangement of the $\bar{s}s$ pairs always takes place, but it does not mean that always the $\bar{s}s$ pairs are produced as a ϕ meson. The predictions of the polarized strangeness model for antiproton annihilation are quite definite:

- the ϕ should be produced mainly from the 3S_1 state;
- the $f'_2(1525)$ should be produced mainly from the 3P_J states;
- the spin-singlet initial states favour the formation of pseudoscalar strangeonia.

It explains why the ϕ/ω ratio is not the same in different channels of antiproton annihilation at rest. It is simply due to different initial states.

The polarized strangeness model postulates that the OZI rule itself is valid and its observed violation is only apparent. It means that one could not describe the ϕ production only via disconnected diagrams. The ϕ meson may be produced also in the processes described by the connected quark diagrams if the nucleon structure is complicated and allows the presence of the polarized strange sea.

It is important to note that these rules should be preserved for antiproton–proton annihilation, as well as for nucleon–nucleon interaction. The natural question is why the especially large OZI violation was observed in the antiproton annihilation at rest whereas the same reaction in flight exhibits no deviation from the OZI predictions.

The answer is clear from the general feature of the antiproton annihilation at rest which was discussed in Sec. 2.1. The conservation of C and P parities selects only few initial states with definite values of total spin and angular momentum. In this sense annihilation in the $\bar{p}p$ atom is an analog of polarized antinucleon interaction with polarized nucleon target. In these conditions, when the initial state quantum numbers are fixed (or strongly limited), we could obtain more detailed information about the interaction amplitude.

3.2. Quantum Numbers of the Nucleon $\bar{s}s$ Pairs. There are different possibilities for the quantum numbers of the $\bar{s}s$ component in the nucleon wave function. It may have, for instance, pseudoscalar quantum numbers $J^{PC} = 0^{-+}$ or vector $J^{PC} = 1^{--}$ ones. Then the relative angular momentum j between the $\bar{s}s$ and uud clusters with $J^P = 1/2^+$ should be $j = 1$. However, it is also possible that the $\bar{s}s$ pair has quantum numbers of the vacuum $J^{PC} = 0^{++}$, then $j = 0$ to provide quantum numbers of proton. It is up to the experiment to determine which of these possibilities are realized in nature.

One could see that the $\bar{s}s$ could be stored in the nucleon with the quantum numbers of η and ϕ if the relative angular momentum between the $\bar{s}s$ and the uud clusters is $j = 1$. But if $j = 0$, then the quantum numbers of $\bar{s}s$ pair may be different, including the vacuum quantum numbers $J^{PC} = 0^{++}$. Predictions of the model will depend drastically on the assumption about the $\bar{s}s$ quantum numbers. Thus, the assumption that the $\bar{s}s$ pair has quantum numbers of ϕ meson leads to serious problems. In this case one might expect some additional ϕ production due to the strangeness, stored in the nucleon. This quasi- ϕ pair could be easily shaken-out from the nucleon. Then it is not clear how to explain the strong dependence of the ϕ yield on quantum numbers of *both* nucleons, discussed in Sec. 2.1.2.

Moreover, the shake-out of the ϕ stored in the nucleon should lead to an apparent violation of the OZI rule in *all* reactions of the ϕ production.

This is ruled out by the experiment, which showed that the OZI-rule violation is not a universal trend of all channels of ϕ production in $\bar{p}p$ annihilation. In general the OZI rule is fulfilled within 10 % accuracy, but there are few cases of the strong (on factor 30–70) violation of the OZI rule.

Similar arguments were provided in [127], where it was demonstrated that the experimental data on the production of η and η' mesons exclude the 0^{-+} quantum numbers for the $\bar{s}s$ admixture in the nucleon wave function.

In [15] it was argued that the strange nucleon sea may be negatively polarized due to the interaction of the light valence quarks with the QCD vacuum. Due to the chiral dynamics the interaction between quarks and antiquarks is most strong in the pseudoscalar $J^{PC} = 0^{-+}$ sector. This strong attraction in the spin–singlet pseudoscalar channel between light valence quark from the proton wave function and a strange antiquark from the QCD vacuum will result in the spin of the strange antiquark which will be aligned opposite to the spin of the light quark (and, finally, opposite to the proton spin). As strange antiquark comes from the vacuum, the corresponding strange quark to preserve the vacuum quantum numbers $J^{PC} = 0^{++}$ should also be aligned opposite to the nucleon spin.

From the QCD sum rules analysis [128, 129], it is known that the condensate of the strange quarks in the vacuum is not small and comparable with the

condensate of the light quarks:

$$\langle 0 | \bar{s}s | 0 \rangle = (0.8 \pm 0.1) \langle 0 | \bar{q}q | 0 \rangle, \quad q = (u, d). \quad (86)$$

Thus, the density of $\bar{s}s$ pairs in the QCD vacuum is quite high and one may expect that the effects of the polarized strange quarks in the nucleon will be also non-negligible.

Therefore, we arrive to the picture of the negatively polarized $\bar{s}s$ pair with the vacuum quantum numbers 3P_0 . These strange quarks should not be considered like constituent quarks formed some five quarks configuration of the nucleon. Rather they are included in the components of a constituent quark. It is important to stress that the $\bar{s}s$ pair with the 3P_0 quantum numbers itself is not polarized being a scalar. That is a chiral nonperturbative interaction which selects only one projection of the total spin of the $\bar{s}s$ pair on the direction of the nucleon spin.

3.3. Shake-Out of the Intrinsic $\bar{s}s$ Pairs. Since the quantum numbers of the $\bar{s}s$ pair in nucleon are fixed to be 3P_0 , the straightforward prediction is that one should see the shake-out of this state in the nucleon-nucleon or antiproton-proton interactions. If the strange scalar strangeonium is $f_0(980)$ meson [18], then the shake-out of the intrinsic strangeness should lead to some enhancement of the $f_0(980)$ production. The rearrangement diagrams like those in Fig. 11 should in general lead to increasing of the $f_0(980)$ yield for annihilation from the P wave. This effect is the same as observed for the production of tensor strangeonium. However one should observe increasing of the ratio of $f_0(980)$ yield to the yield of light quark state $\sigma(400-1200)$ for annihilation from the P wave. It is hard to determine this ratio due to a large width of the σ meson.

However the shake-out of 3P_0 state with its subsequent decay into kaons should lead to some quite peculiar effects. In [10] it was stressed that shake-out of the negatively-polarized $\bar{s}s$ pair from the 3S_1 initial state should lead to the enrichment of charged K^+K^- pairs over the $K^0\bar{K}^0$ ones and neutral $K^{*0}\bar{K}^{*0}$ over $K^{*+}K^{*-}$.

The reason of these effects is easy to comprehend from Figs. 12 and 13.

If the spins of the nucleon and antinucleon are oriented in the same direction, as, e. g., in the 3S_1 initial state, the shake-out of *negatively* polarized $\bar{s}s$ will form preferentially the *charged* pseudoscalar K^+K^- mesons from s and u quarks — which have opposite polarization — and *neutral* vector $K^{*0}\bar{K}^{*0}$ mesons, from s and d quarks — which have the same polarization. The corresponding quark diagrams are shown in Fig. 12, *a* and 13, *a*. On the other hand, if the $\bar{s}s$ quarks are polarized *positively*, i. e., along the direction of the nucleon spin, then s and u quarks will have the same polarization and they will form preferentially the *neutral* pseudoscalar K mesons and *charged* vector mesons as seen in Figs. 12, *b* and 13, *b*, respectively.

It is important to note that these effects should be absent for annihilation from the spin-singlet initial state 1S_0 .

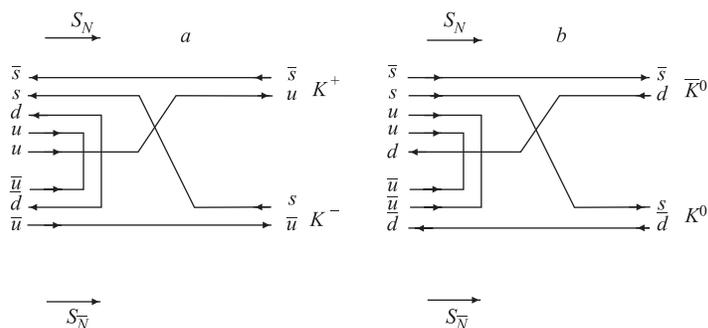


Fig. 12. Production of $K\bar{K}$ due to shake-out of a polarized $\bar{s}s$ pair in the proton wave function in $\bar{p}p$ annihilation from the initial 3S_1 state, for negative (a) and positive (b) polarization of the $\bar{s}s$ pair. The arrows show the directions of the spins of the nucleons and quarks

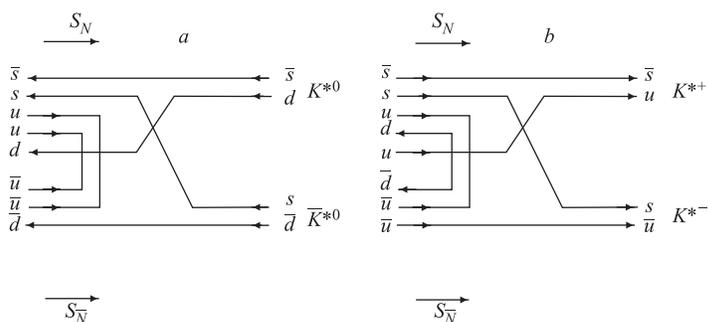


Fig. 13. Production of $K^*\bar{K}^{*0}$ due to shake-out of a polarized $\bar{s}s$ pair from the proton wave function in $\bar{p}p$ interaction from the initial 3S_1 state, for negative (a) and positive (b) polarization of the $\bar{s}s$ pair. The arrows show the directions of the spins of the nucleons and quarks

This phenomenon has indeed been observed in bubble-chamber experiments [130, 131], where it was found that annihilation into two neutral K^* dominates over charged K^* formation. For instance, according to [130], $Y(\bar{p}p \rightarrow K^{*0}\bar{K}^{*0}) = (30 \pm 7) \cdot 10^{-4}$, whereas $Y(\bar{p}p \rightarrow K^{*+}\bar{K}^{*-}) = (15 \pm 6) \cdot 10^{-4}$. However, a word of caution is needed: these data are quite old and evaluation of the yield of two broad resonances in the presence of other open channels was done in a too simplified way.

However, the tendency has recently been confirmed by the Crystal Barrel collaboration [132] in measurements of the channel $\bar{p}p \rightarrow K_L^0 K^\pm \pi^\mp \pi^0$ in anni-

hilation at rest. It was found that, for annihilation from the 3S_1 state, the ratio between neutral and charged K^* production is

$$\frac{K^*(\text{neutral})\bar{K}^*(\text{neutral})}{K^*(\text{charged})\bar{K}^*(\text{charged})} \approx 3. \quad (87)$$

We are not aware of other theoretical arguments that explain this unexpected selection rule. On the other hand, the polarized-strangeness model provides a natural explanation of this effect, making essential use of the sign of the polarized pair. In remarkable consistency with this hypothesis, this effect is absent for annihilation from the 1S_0 initial state, again as it should be for the shake-out of the polarized $\bar{s}s$ pair.

Till recent time it was believed [3,133] that in the production of $K\bar{K}$ system there is a suppression of the isospin $I = 0$ amplitude on factor 5–10 in comparison with the $I = 1$ one. This hierarchy nicely agrees with the prediction of the polarized strangeness model [10]. However it was shown [134] that this conclusion was followed from the error in the data analysis, and the magnitude of the $I = 0$ and $I = 1$ amplitudes is approximately the same.

4. THEORETICAL VIEWS ON LARGE OZI VIOLATION PROCESSES

Let us consider how different theoretical models treat concrete experimental facts of a large OZI violation discussed in Sec. 2.

4.1. $\bar{p}p \rightarrow \phi\gamma$. The largest apparent OZI violation was observed in this channel (see (36)). However this reaction was measured for the spin-singlet 1S_0 initial state. It does not quite match the prediction of the polarized strangeness model that ϕ should be produced mainly from the spin-triplet initial states.

In [9] it was argued that if really ϕ production from the spin-triplets dominates, then one would expect that the ratio $\phi\gamma/\omega\gamma$ will increase for annihilation from low pressure hydrogen gas, where the P wave annihilation is dominant. Till now these measurements have not been performed and the puzzle remains unsolved.

Recently A. Kotzinian [135] brings attention to the fact that polarization of the vacuum strange quarks by a valence quark may result in formation of the $\bar{s}s$ pair with $J^{PC} = 0^{++}$ but spins of the strange and antistrange quarks are oriented in opposite directions. Indeed, in Sec. 3.2 we discuss that the main idea of [15] for polarization of the strange sea is the assumption that a proton valence quark interacts strongly with a vacuum *antistrange* quark when the quantum numbers of the $u\bar{s}$ system are pseudoscalars. So, the spins of the proton valence u -quark and vacuum \bar{s} quark should be oriented in opposite directions:

$$u \begin{array}{c} \uparrow \\ \bullet \end{array} \downarrow \begin{array}{c} \circ \\ \bar{s} \end{array}. \quad (88)$$

The quantum numbers of the $\bar{s}s$ pair should have the vacuum quantum numbers, i. e., the total spin $S = 1$, the orbital angular momentum $L = 1$, and the total angular momentum $J = 0$. To provide that it was assumed [15] that the spin of the s quark should follow the direction of the spin of \bar{s} quark:

$$u \uparrow \bullet \downarrow \overset{\circ}{\bar{s}} \downarrow \overset{\circ}{s}. \quad (89)$$

However the direction of the s -quark spin may also be opposite to the \bar{s} ones, preserving the total $\bar{s}s$ spin $S = 1$ and the demand of $J^{PC} = 0^{++}$. Choosing an axis z in the direction of the spin of the u quark, there must be configuration with $S_z = 0$:

$$u \uparrow \bullet \downarrow \overset{\circ}{\bar{s}} \uparrow \overset{\circ}{s} \quad (90)$$

along with the configuration of (89) with the projection on $S_z = -1$.

Then the ϕ production due to the rearrangement diagrams will be modified. If both nucleon and antinucleon have $\bar{s}s$ pairs with $S_z = 0$, then as in the case with $S_z = -1$, the rearrangement will create ϕ preferentially from the spin-triplet states. However, if in the nucleon there is the $\bar{s}s$ pair with $S_z = -1$, and in the antinucleon the $\bar{s}s$ pair is in $S_z = 0$ state, then the rearrangement could produce the ϕ also from the spin-singlet initial state. Then the ϕ production in $\bar{p}p$ annihilation could be symbolically depicted as follows:

$$u \uparrow \bullet \downarrow \overset{\circ}{\bar{s}} \downarrow \overset{\circ}{s} + \bar{u} \downarrow \bullet \uparrow \overset{\circ}{s} \downarrow \overset{\circ}{\bar{s}} \implies \downarrow \overset{\circ}{\bar{s}} \downarrow \overset{\circ}{s}, \quad (91)$$

here only the valence u and \bar{u} quarks of proton and antiproton are shown, the arrows indicate the direction of quarks spin.

To what extent this possibility could describe the violation of the OZI rule in the $\phi\gamma$ channel depends on the relative probability of $S_z = -1$ and $S_z = 0$ components of $\bar{s}s$ pair in the proton wave function. We will come back to the discussion of this question in the next section.

There are other explanations of the $\phi\gamma$ paradox. The reaction

$$\bar{p} + p \rightarrow \phi + \gamma \quad (92)$$

is quite specific — in this process all valence quarks from the initial state should annihilate. So gluons are dominating in the intermediate state. In such processes, as we discussed in Sec. 1.5, the applicability of the OZI rule for prediction of ϕ/ω ratio is questionable. It is interesting that a similar strong OZI violation was seen in $\bar{p}p \rightarrow \phi\phi$ reaction (see, (75)), where also all the valence quarks of the initial state annihilate completely.

Another possible explanation comes from the fact that the amplitude of the reaction (92) is connected with the amplitude of ϕ photoproduction $\gamma + p \rightarrow \phi + p$. In ϕ photoproduction, it is well known that the ϕ/ω ratio does not follow

the mixing angle prediction (16). Thus in the diffractive photoproduction of ϕ mesons [136] a large value of the ϕ/ω ratio was found:

$$\frac{\gamma A \rightarrow \phi \pi^+ \pi^- A}{\gamma A \rightarrow \omega \pi^+ \pi^- A} = (97 \pm 19) \cdot 10^{-3}. \quad (93)$$

The photon could interact strongly as a $\bar{q}q$ state and in the photoproduction the contribution of $\bar{s}s$ pair in the initial state is non-negligible. So the diffractive photoproduction of ϕ is not described by the disconnecting quark diagram and one could not expect validity of the OZI-rule prediction (16) for this process as well as for the reaction (92).

Concrete calculations along these lines were performed in [137, 138]. The vector dominance model (VDM) was applied. The reaction was treated in two steps: annihilation $\bar{p}p \rightarrow \phi + V$ into ϕ and some vector meson V , and conversion of the produced vector meson into a real photon via VDM. In [137] it was claimed that it was possible to reproduce successfully experimental branching ratio of the $\phi\gamma$ channel using as an input branching ratios of $\phi\rho$ and $\phi\omega$ channel and assuming destructive interference between the amplitudes of these reactions. However the analysis of [138] confirms this conclusion only if the phase space factor is chosen in a standard two-body form $f = k^{2l+1}$. If the phase space factor is taken from parametrization of Vandermeulen [139] as $f = k \exp(-A\sqrt{s - m_X^2})$, where k is the final state c.m. momentum, \sqrt{s} is the total energy, m_X is the sum of mass of the particles in the final state, and value of parameter $A = 1.2 \text{ GeV}^{-1}$ is obtained from the fit of momentum dependence of the cross section of various annihilation channels, then the corresponding branching ratio drops down by a factor of 10 and turns out to be $BR(\phi\gamma) = 1.5 \cdot 10^{-6}$. This is to be compared with the experimental result $BR(\phi\gamma) = (2.0 \pm 0.4) \cdot 10^{-5}$ [3]. The question of the phase space factor for annihilation reactions has been discussed many times (see, e. g., [3, 95] and references therein). It was agreed that the Vandermeulen factor better reflects the many-channel nature of the annihilation at rest, where a number of channels are open and the phase space does not follow the simple two-body prescription. The authors of [138] conclude that «large observed branching ratio for $\phi\gamma$ remains unexplained in the framework of VDM» and we would like to join this statement.

4.2. $\bar{p}p \rightarrow \phi\pi$. The experimental facts for this reaction seem to match perfectly with the polarized strangeness model. The opulent ϕ production is seen for annihilation from the spin-triplet 3S_1 wave

$$R_\pi(\phi/\omega, {}^3S_1) = (120 \pm 12) \cdot 10^{-3}, \quad (94)$$

$$R_\pi(\phi/\omega, {}^1P_1) < 7.2 \cdot 10^{-3}, \quad \text{with 95 \% CL}, \quad (95)$$

whereas the ratio from the spin-singlet 1P_1 initial state is comparable with the mixing angle prediction (16).

However, it was noted [140] that the explanation [9] of the $\phi\pi$ reaction as a rearrangement process meets with a problem. It was assumed [9] that there is no spin-flip of strange quarks due to the rearrangement diagram, shown in Fig. 11. However it is not possible to meet this condition in $\bar{p}p \rightarrow \phi\pi$ reaction assuming that both strange and antistrange quarks in nucleon are *negatively* polarized, i. e., that the projection of the total spin of $\bar{s}s$ pair is $S_z = -1$.

Indeed, this reaction is going from the 3S_1 initial state, the orbital momentum $L = 0$, and the projection on axis z of total angular momentum J coincides with the projection of the total spin $m_J = m_{S_i} = \pm 1, 0$, where S_i is the total spin of nucleons in the initial state. Let us assume that $m_{S_i} = m_J = +1$. Then the projection of the spin of the strange quarks will be $m_s = m_{\bar{s}} = -1/2$ and the projection of the spin of ϕ should be $m_{S_\phi} = -1$ assuming that there is no spin-flip of the strange quarks during the annihilation. The total angular momentum of the final state J_f is the sum $J_f = S_\phi + L_f$, where S_ϕ is the spin of ϕ meson and L_f is the orbital angular momentum between the ϕ and π mesons. The P -parity conservation dictates that $L_f = 1$ for annihilation from 3S_1 . Then it is clear that it is impossible to add $|S_\phi, m_{S_\phi}\rangle = |1, -1\rangle$ with $|L_f, m_{L_f}\rangle = |1, m_{L_f}\rangle$ to obtain $|J_f, m_{J_f}\rangle = |1, +1\rangle$ for any allowed values of m_{L_f} . Schematically this situation is depicted as follows:

$$N \begin{array}{c} \uparrow \\ \bullet \end{array} \begin{array}{c} \circ \\ \downarrow \end{array} \bar{s} \begin{array}{c} \circ \\ \downarrow \end{array} s + \bar{N} \begin{array}{c} \uparrow \\ \bullet \end{array} \begin{array}{c} \circ \\ \downarrow \end{array} s \begin{array}{c} \circ \\ \downarrow \end{array} \bar{s} \neq \phi \begin{array}{c} \uparrow \\ \bullet \end{array} + \pi \bullet. \quad (96)$$

It is clear that to solve this problem one should introduce either spin-flip of the s quarks during the annihilation or give up the assumption about the negative polarization of the strange quarks in the nucleon. The spin-flip explanation is physically less motivated and to avoid this problem in [140] it is assumed that the strange quarks are polarized *positively* with respect to the nucleon spin.

However, the suggestion of [135] to take into account the $\bar{s}s$ pair with vacuum quantum numbers and $S_z = 0$ could easily solve the problem. In that case the $\bar{p}p \rightarrow \phi\pi$ reaction could be considered as the rearrangement of two $\bar{s}s$ pairs with the $S_z = 0$. And no spin-flip of strange quarks is needed to provide correct orientation of the ϕ spin, as it is seen from the following schematic diagram:

$$N \begin{array}{c} \uparrow \\ \bullet \end{array} \begin{array}{c} \circ \\ \downarrow \end{array} \bar{s} \begin{array}{c} \circ \\ \uparrow \end{array} s + \bar{N} \begin{array}{c} \uparrow \\ \bullet \end{array} \begin{array}{c} \circ \\ \downarrow \end{array} s \begin{array}{c} \circ \\ \uparrow \end{array} \bar{s} = \phi \begin{array}{c} \uparrow \\ \bullet \end{array} + \pi \bullet. \quad (97)$$

In [137, 141–143] it has been suggested that the anomalously high yield of the $\bar{p}p \rightarrow \phi\pi^0$ channel could be explained by rescattering diagrams with OZI-allowed transitions in the intermediate state, e. g., $\bar{p}p \rightarrow K^*\bar{K} \rightarrow \phi\pi^0$. Calculations are capable [137, 142, 143] to provide a reasonable agreement with the experimental data on the $\phi\pi$ yield for annihilation from the S wave. However, what is not yet explained in this approach is the strong dependence of the ϕ yield on the spin of the initial state. Why the $\phi\pi$ yield from the spin-singlet state is 15 times less than from the spin-triplet state is absolutely unclear in these models.

In [144] it was assumed that a possible reason may be that the total decay width of the $\bar{p}p$ atom for the 1P_1 state with isospin $I = 1$ may be anomalously suppressed. This suppression was predicted in some optical potential models as a consequence of the isospin-mixing in the protonium wave function. However this suppression should be effective not only on the $\phi\pi$ but also on the $\omega\pi$ channel and [144] predicted that the ϕ/ω ratio for annihilation from the P state may be as large as from the spin-triplet S state. That is at variance with the experimental data of (47), (48). These data show that the ratio ϕ/ω for annihilation from the P wave is 15 times less than the corresponding ratio for annihilation from the S state. It is due to the absence of any suppression of the $\omega\pi$ channel from the P state.

Moreover, the experimental results on K^*K branching ratios from the S and P states do not quite fit with the predictions of the two-step model [137,141–143]. If the anomalously high yield of the $\bar{p}p \rightarrow \phi\pi^0$ is due to rescattering diagrams with $K^*\bar{K}$ in the intermediate state $\bar{p}p \rightarrow K^*\bar{K} \rightarrow \phi\pi^0$, then to explain the suppression of the $\phi\pi$ yield for annihilation from the P wave, one should infer that it is due to unusually small frequency of the $K^*\bar{K}$ amplitude from the 1P_1 channel [144].

To verify this conclusion, the spin-parity analysis of annihilation frequencies of the $K^*\bar{K}$ final state at different target densities was performed [48]. The results are shown in Table 5.

The yields correspond to the case of the best fit (Solution I); to demonstrate the robustness of the results, the yields for another set of isobars (Solution II) are also shown.

One can see that the 1P_1 fraction of the $K^*\bar{K}$ annihilation frequency is not negligible. It is comparable with the 3S_1 fraction and increases with the decrease of the target density. This dependence is opposite to that of the $\phi\pi$ yield which decreases with the target density.

However, these results could not completely exclude the rescattering mecha-

Table 5. The $K^*\bar{K}$ annihilation frequency (in units of 10^{-4}) at three densities of the hydrogen target [48]

| Amplit. set vs $f(K^*\bar{K}) \cdot f(K^*\bar{K} \rightarrow K^+K^-\pi^0)$ | LH ₂ | NTP | LP (5 mbar) |
|--|-----------------|-----------|-------------|
| Solution I | 5.20±0.89 | 7.01±0.84 | 7.45±0.95 |
| 3S_1 fraction | 3.27±0.81 | 1.75±0.44 | 0.78±0.20 |
| 1P_1 fraction | 0.89±0.16 | 3.44±0.53 | 4.52±0.70 |
| Solution II | 4.82±0.44 | 8.09±1.04 | 9.34±1.37 |
| 3S_1 fraction | 2.47±0.24 | 1.29±0.13 | 0.57±0.08 |
| 1P_1 fraction | 0.57±0.18 | 2.30±0.72 | 3.03±0.95 |

nism of [137, 141–143]. The reason is due to the impossibility of distinguishing between the isospin $I = 0$ and $I = 1$ components of the $K^*\bar{K}$ amplitude. In principle, it may occur that the observed increase of the $K^*\bar{K}$ yield in the P wave is due to the $I = 0$ part of the amplitude. Whereas the $I = 1$ $K^*\bar{K}$ state, allowed for rescattering into $\phi\pi^0$, could be suppressed for some unknown reasons. The final answer to this question should be given by the coupled channels analysis of the $K^+K^-\pi^0$, $K^0K^\pm\pi^\mp$, and $\pi^+\pi^-\pi^0$ final states.

It has been suggested [146] that the enhancement of the ϕ -meson production in certain $\bar{N}N$ annihilation channels might be due to resonances. Specifically, if there existed a vector ($J^{PC} = 1^{--}$) $\phi\pi$ resonance close to the $\bar{N}N$ threshold, it might be possible to explain the selective enhancement of the $\phi\pi$ yield in S -wave annihilation, and the relative lack of ϕ 's in the P -wave annihilation. The best candidate for such a state is one with mass $M = 1480 \pm 40$ MeV, width $\Gamma = 130 \pm 60$ MeV and quantum numbers $I = 1$, $J^{PC} = 1^{--}$, which was observed [147] in the $\phi\pi^0$ mass spectrum in the reaction $\pi^-p \rightarrow K^+K^-\pi^0n$ at 32.5 GeV/c, and dubbed the C meson.

However, this resonance cannot explain the OZI-rule violation observed in the $\phi\gamma$ channel, which is a final state with different quantum numbers. The experimental status of the C meson is unconfirmed. Although some experiments have found indications for its existence (for a review, see [148]), but others have not. It was not seen in pp central production [149], in antiproton annihilation at rest [3] and in recent measurements of the E852 collaboration [150]. The latter investigated the same reaction $\pi^-p \rightarrow K^+K^-\pi^0n$ at 18 GeV. The partial wave analysis shows that the intensity of $\phi\pi$ wave is quite smooth in the $KK\pi$ mass interval of 1.2–1.5 GeV. Indication on some enhancement is seen around 1.6 GeV. However the statistics is too scarce and the authors concluded that no resonance was seen in the $\phi\pi$ system, at least, in the C -meson region.

The predicted [146] isoscalar partner of the C meson, which should couple to the $\phi\eta$ channel, also was not observed, and no deviation from the OZI rule has been detected in this mode. Therefore the resonance interpretation of the apparent violation of the OZI rule is not accepted due to the absence of the corresponding states.

4.3. $\bar{p}p \rightarrow f'_2(1525)\pi^0$. The discovery of the OBELIX collaboration [48] of the strong OZI-rule violation for the tensor $f'_2(1525)$ meson was predicted in the framework of polarized strangeness model [9]. It was predicted that the violation should occur just for annihilation from the P wave and the experiment has confirmed that. It was found that

$$R(f'_2(1525)\pi^0/f_2(1270)\pi^0) = (47 \pm 14) \cdot 10^{-3}, \quad S \text{ wave}, \quad (98)$$

$$= (149 \pm 20) \cdot 10^{-3}, \quad P \text{ wave}. \quad (99)$$

That should be compared with the OZI-rule prediction (17)

$$R = \frac{\sigma(A + B \rightarrow f'_2(1525) + X)}{\sigma(A + B \rightarrow f_2(1270) + X)} = 16 \cdot 10^{-3}. \quad (100)$$

The production of f'_2 in the $\bar{p}p \rightarrow f'_2\pi^0$ reaction was calculated in the rescattering model assuming OZI-allowed transitions to the K^*K and $\rho\pi$ intermediate states [145]. The obtained production rates of f'_2 are rather small, about 10^{-6} . That is about two orders of magnitude less than the experimental values measured by the OBELIX collaboration [48].

Therefore, it turns out impossible to accommodate the large yield of the tensor $\bar{s}s$ state just from the P wave within the framework of the rescattering model which used the meson loops in the intermediate state.

4.4. $\bar{p}d \rightarrow \phi n$. One of the largest violation of the OZI rule occurs in the Pontecorvo reaction of $\bar{p}d$ annihilation.

$$R = Y(\bar{p}d \rightarrow \phi n)/Y(\bar{p}d \rightarrow \omega n) = (156 \pm 29) \cdot 10^{-3}. \quad (101)$$

This fact had been predicted in the polarized strangeness model [9] a few years before the corresponding experiment was started.

The other approach to treat the Pontecorvo reactions was suggested in [151, 152]. These reactions were considered as two-step processes. First, two mesons are created in the \bar{p} annihilation on a single nucleon of the deuteron and then one of them is absorbed by the spectator nucleon. In this approach, the OZI violation in the Pontecorvo reaction $\bar{p}d \rightarrow \phi n$ is simply a reflection of its violation in the elementary act $\bar{p}p \rightarrow \phi\pi^0$.

The model provides a possibility of accounting for the large ratio between the ϕ and ω production [152]:

$$R_{\text{th}} = \frac{Y(\bar{p}d \rightarrow \phi n)}{Y(\bar{p}d \rightarrow \omega n)} = (192 \pm 27) \cdot 10^{-3}. \quad (102)$$

However the two-step model is in serious doubts after measurements by the Crystal Barrel collaboration of the Pontecorvo reactions with the open strangeness [153]:

$$\bar{p} + d \rightarrow \Lambda + K^0, \quad (103)$$

$$\bar{p} + d \rightarrow \Sigma^0 + K^0. \quad (104)$$

It is found [153] that the yields of these reactions are practically equal, $R_{\Sigma,\Lambda} = Y(\Sigma K)/Y(\Lambda K) = 0.92 \pm 0.15$, in a sheer discrepancy with the two-step model prediction [151] that the Σ production should be about 100 times less than the Λ production. It was predicted [152] that $R_{\Sigma,\Lambda} = 0.012$. This hierarchy

appears naturally in the two-step model due to the fact that the $\bar{K}N \rightarrow \Lambda X$ cross section is larger than the $\bar{K}N \rightarrow \Sigma X$ one.

The measured yields of the reactions (103), (104) are also at least by a factor of 10 over the two-step model prediction [151].

Therefore, experiments on Pontecorvo reactions clearly indicate the opulent production of additional strangeness either in the form of ϕ mesons or of the ΛK and ΣK pairs.

4.5. $\bar{p}p \rightarrow \phi\eta, \phi\rho, \phi\omega\dots$ One of the main puzzles in the complicated picture of ϕ production in antiproton annihilation at rest is to understand why the increasing of the ϕ yield is observed only in some channels, like $\phi\gamma$ and $\phi\pi$ whereas no deviation from the OZI predictions exists in the other channels, like $\phi\eta, \phi\omega, \phi\rho$.

A possible key for solving this problem is in the dependence on the momentum transfer. In Fig. 14 the compilation of the data on the ratio $R = (\phi X/\omega X) \cdot 10^3$ of yields for different reactions of $\bar{p}p \rightarrow \phi(\omega)X$ annihilation at rest is shown as a function of the momentum transfer to ϕ . The solid line corresponds to the prediction of the OZI rule (16).

One could see that the largest OZI violation has been observed for the reactions with the largest momentum transfer to ϕ , that is, Pontecorvo reaction $\bar{p}d \rightarrow \phi n$ and $\bar{p}p \rightarrow \phi\gamma, \phi\pi$ processes. The degree of the violation smoothly decreases with mass of system X created with the ϕ , i. e., with decreasing of the momentum transfer. Thus for the $\phi\pi\pi$ final state with light effective masses of the two-pions system around 300–400 MeV the deviation from the OZI rule is significant. Whereas for the $\phi\eta$ final state there is no problem with the OZI rule.

The polarized strangeness model explained this trend due to the rearrangement nature of the ϕ production. The rearrangement mechanism implies that two nucleons should participate in the ϕ production. This means a dependence on quantum numbers of both nucleons as well as appearance of some minimal momentum transfer from which this additional mechanism becomes important.

The rearrangement nature of additional ϕ production allows one to make some interesting prediction concerning annihilation into the $\phi\eta$ final state. As

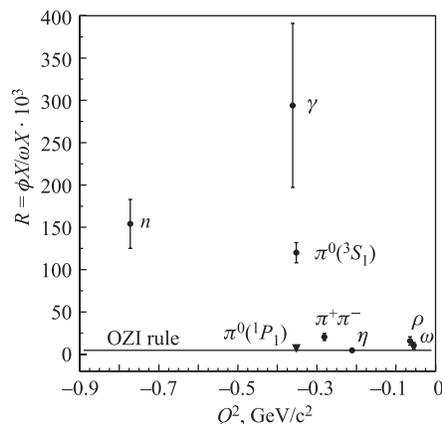


Fig. 14. The ratio $R = \phi X/\omega X \cdot 10^3$ of yields for different reactions of $\bar{p}p \rightarrow \phi(\omega)X$ annihilation at rest as a function of the momentum transfer to ϕ . The solid line shows the prediction of the OZI rule (16)

we discussed in Sec. 2.1.3 it was found [97] that the yield of the $\bar{p}p \rightarrow \phi\eta$ channel grows with decreasing of the target density. The branching ratio for annihilation from the 1P_1 state turns out to be 10 times higher than that of the 3S_1 state:

$$B(\bar{p}p \rightarrow \phi\eta, ^3S_1) = (0.76 \pm 0.31) \cdot 10^{-4}, \quad (105)$$

$$B(\bar{p}p \rightarrow \phi\eta, ^1P_1) = (7.72 \pm 1.65) \cdot 10^{-4}. \quad (106)$$

The polarized strangeness model suggests the following explanation of these facts: the momentum transfer in the $\phi\eta$ reaction is too small for the rearrangement diagrams starting relevant. Increasing of the $\phi\eta$ yield in the P wave is not connected with proton intrinsic strangeness. Therefore no OZI-rule violation should be found neither for annihilation from the S wave nor from the P wave. It means that the ratio $Y(\phi\eta)/Y(\omega\eta)$ should remain small in the P wave. Therefore ten times increasing of the $\omega\eta$ yield for annihilation from the P wave is predicted.

Unfortunately, the kinematics of antiproton annihilation at rest restricts the variation of the momentum transfer. It is important to study the dependence of the violation of the OZI rule on the momentum transfer directly for annihilation in flight.

4.6. $pp \rightarrow pp\phi$. The production of ϕ in nucleon–nucleon interaction will provide a crucial test for the polarized intrinsic strangeness model as an explanation of the strong OZI violation seen in antiproton annihilation at rest. First, an enhancement of the ϕ production over OZI prediction should be seen. Second, a specific dependence of the ϕ production on the spin of the initial NN state should be observed. The ϕ should be produced mainly from the spin triplet states.

In Sec. 2.2.1 we have discussed that the DISTO collaboration [6, 7] indeed saw in the proton–proton collisions an enhancement of the ϕ/ω ratio on factor 10 over the OZI-rule prediction. However, in this experiment the ϕ and ω cross sections were evaluated at the same proton energy, it means at different c. m. energies above the corresponding thresholds. If one takes for the ω cross section the value, obtained from the extrapolation of the energy dependence of all existing experimental data, then the ratio ϕ/ω is still large, but it enhanced over the OZI prediction by a factor of 5 only [7]. That should be compared with enhancement factors 30–70 seen in some reactions of antiproton annihilation at rest.

The theoretical analysis of the ϕ - and ω -meson production was done in [154–157]. The diagrams of ϕ production via mesonic current $\pi\rho \rightarrow \phi$ as well as ϕ production via direct coupling with nucleon were considered. It was found that the mesonic current dominates. The contribution from the direct ϕNN coupling is small. Precise size of this contribution, evaluated in [154], differs by a factor 4 for different sets of parameters, nevertheless the authors conclude that no violation

of OZI rule is needed to invoke. However, a violation of OZI rule is needed in the mesonic current, where the corresponding coupling constants $\phi\rho\pi$ and $\omega\rho\pi$ turn out to be connected in a different way than the OZI rule predicts. In other words, it is not possible to explain both the ω and ϕ total and angular cross sections assuming exact $SU(3)$ relations between the coupling constants $g_{\omega\rho\pi}$ and $g_{\phi\rho\pi}$.

Recent experiment on the ω production cross sections [102] in pp collisions at 92 and 173 MeV excess energies has also confirmed inconsistencies arising in the theory [158] trying to consider both the ϕ - and ω -mesons production within the same approach. It turns out that the parameters of the mesonic current chosen to fit the DISTO data on the ϕ cross section and angular distribution overestimate the ω total cross sections and completely fail to reproduce strong angular anisotropy of the ω angular distribution.

However, the scarcity of the experimental data prevents from any final conclusions. It is interesting to verify the polarized strangeness model by using more clear tests. In [10], it was pointed out that it is possible to verify the spin dependence of the ϕ production amplitude using unpolarized nucleons, comparing ϕ production in np and pp collisions. If ϕ is not produced from the spin-singlet states, then the ratio of the np and pp cross sections at threshold is

$$R_\phi = \frac{\sigma(np \rightarrow np\phi)}{\sigma(pp \rightarrow pp\phi)} = \frac{1}{2} \left(1 + \frac{|f_0|^2}{|f_1|^2} \right) \approx \frac{1}{2}. \quad (107)$$

In the framework of the one-boson exchange model, i. e., without any assumption about the nucleon's intrinsic strangeness, this ratio was calculated [157] to be $R_\phi = 5$. Definitely, the experimental measurements of this ratio near threshold could discriminate the predictions of these theoretical models.

4.7. $\bar{p}p \rightarrow \phi\phi$. As we discussed in Sec. 2.4 the opulent production of the $\phi\phi$ system was seen in a number of experiments. Thus the JETSET collaboration has seen an unusually high apparent violation of the OZI rule in the $\bar{p} + p \rightarrow \phi + \phi$ channel [105]. The measured cross section of this reaction turns out to be two orders of the magnitude higher than the value expected from the OZI rule. The polarized strangeness model predicted [9] that the $\phi\phi$ system should be produced mainly from the initial spin-triplet state. Indeed, the data of the JETSET collaboration [106] have demonstrated that the initial spin-triplet state with 2^{++} dominates.

Moreover, it turns out that the final states with the total spin S of $\phi\phi$ system $S = 2$ are enhanced. This fact could be naturally explained in the polarized strangeness model as a consequence of the rearrangement of the $\bar{s}s$ pairs from proton and antiproton.

Of course, the polarized nucleon strangeness model is not the only possible explanation of the facts. In a model of [159] the $\bar{p}p$ annihilation in $\phi\phi$ was

considered assuming hyperon–antihyperon intermediate states, like $\Lambda\bar{\Lambda}$, $\Sigma\bar{\Sigma}$. It turns out that the calculated total cross section of $\phi\phi$ production agrees with preliminary data of the JETSET collaboration but missed their final values [105] by a factor of 4.

In the model of [160] the reactions $\bar{p}p \rightarrow \phi\phi$ and $\bar{p}p \rightarrow \phi\gamma$ were considered in framework of the instanton induced interaction between quarks. It was conjectured that the specific spin-flavour properties of the instanton interaction could explain the experimental trends in the apparent OZI-rule violation in $\bar{p}p$ annihilation. Main prediction of the model [160] is that the largest OZI-rule violation should take place in the 1S_0 initial state. It agrees with the experimental results for the $\bar{p}p \rightarrow \phi\gamma$ reaction but fails to explain the large OZI violation for the tensor $\bar{s}s$ -mesons production, which exists for annihilation just from the P -wave annihilation. This prediction seems also not fulfilled in $\bar{p}p \rightarrow \phi\phi$ reaction, where the 2^{++} state is dominating.

The «simplest» explanation of the strong OZI violation in the $\phi\phi$ production is that the 2^{++} state dominance is a signal of a tensor glueball [55, 104]. So the coupling with the tensor glueball of the proper mass increases the $\phi\phi$ cross section significantly above the prescription based on the mixing angle value (75).

This possibility is remarkable in its general application to all cases of the OZI violation. Everywhere the strange particle production is enhanced, one could argue that it is due to the gluon degrees of freedom. In hadron interactions at intermediate energies there are not so many reactions where the effects of gluons appeared explicitly, not hidden in the form of meson and baryon exchanges. In this sense the OZI violation provides the clear signal of importance of the gluon degrees of freedom.

CONCLUSIONS

This review has considered the theoretical and experimental situation with the fulfillment of the OZI rule — one of the oldest phenomenological prescription of the hadron physics. It turns out that the rule is working quite well in different hadronic reactions at large energy interval. So, the general rule, which states that the processes described by the disconnecting quark lines is suppressed, is valid.

However there are a number of experimental results demonstrating a significant deviation from the predictions (16)–(18), (75) based on the OZI rule. Especially large violation (on factor 30–70) was found in the ϕ production in the antiproton annihilation at rest. The ϕ -meson production in the low energy proton–proton interaction also exceeds the OZI rule expectation by a factor of 10–13.

An important feature is the dependence of the degree of the OZI violation on the spin of the initial state as well as on the sort of the meson, created with the ϕ .

It induces the idea that the observed violation of the OZI rule is only apparent: the rule itself is valid but the dynamics of the considered processes is not described by the disconnecting quark diagrams. In particular, it is suggested [9, 10] that the physical reason for the strong OZI violation in the strange particle production is the polarization of the strange sea-quarks inside the nucleon.

In Sec. 3 we collect the experimental and theoretical results on the value of possible strange quark polarization Δs . However this value was deduced from the *inclusive* DIS data with some debatable assumptions. In few experiments the sign of the charged hadrons in DIS was also measured [161, 162]. The semi-inclusive DIS data on charged hadrons disagree with the inclusive DIS results and claimed for quite small polarization of the strange quarks. For instance, the HERMES result [162] is $\Delta s = -0.01 \pm 0.03 \pm 0.04$. However, an ad hoc assumption has been made in this data analysis that the polarization of all sea quarks should be equal. So, it is up to a new generation of the semi-inclusive DIS experiments, which could provide a good particle identification to separate pions and kaons, to measure the Δs . At present, the best experimental possibilities exist for the HERMES (DESY) and COMPASS (CERN) [163] experiments, where the corresponding programmes to measure the polarization of different quark flavours are under way. Precise determination of the strange and antistrange quarks polarized structure functions could be done in future neutrino factories [164].

However even in the case of observation of nonzero polarization of intrinsic nucleon strangeness it is absolutely nontrivial that the antiproton annihilation at rest or proton-proton interaction at threshold will be affected by this effect. Therefore corresponding measurements, confirming the OZI violation and investigating its characteristics, are needed.

The polarization strangeness model [9, 10] could qualitatively explain practically all experimental facts on strange particle production in hadron interactions at low energies. However some caveats still exist.

Thus, the strong OZI violation was seen in the $\bar{p}p \rightarrow \phi\gamma$ channel from the initial spin-singlet 1S_0 state. It does not fit with the polarized strangeness model postulate that ϕ should mostly be created from the spin-triplet initial states. To cure the situation one should observe in this reaction even a larger OZI violation from the initial spin-triplet 3P_J states. This experiment should be done.

Another problem appears to explain the spin transfer measurements in the reaction $\bar{p} + \vec{p} \rightarrow \Lambda + \bar{\Lambda}$ [165]. The polarized strangeness model assumes an anticorrelation between spins of the proton and the s quark. Then it is natural to predict a negative value for depolarization D_{nn} measured in the Λ production in polarized proton interactions $\vec{p}p \rightarrow \Lambda K^+p$. The measurements of DISTO collaboration [166] indeed have confirmed this prediction. The same effect is expected for the depolarization of Λ produced in antiproton interactions with polarized protons $\bar{p} + \vec{p} \rightarrow \Lambda + \bar{\Lambda}$. However preliminary results of the PS 185

experiment [165] have shown that D_{nn} is quite small but the spin transfer to $\bar{\Lambda}$ K_{nn} is unusually high and positive.

There are versions of the polarized strangeness model where the spin of proton is indeed mainly transferred to $\bar{\Lambda}$ rather than to Λ [135]. But in these modifications the K_{nn} should be still negative. So, it is for the future to resolve this paradox.

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REFERENCES

1. Okubo S. // Phys. Lett. B. 1963. V. 5. P. 165;
Zweig G. CERN Report No. 8419/TH412. 1964;
Iizuka I. // Prog. Theor. Phys. Suppl. 1966. V. 37. P. 38; 21.
2. Lipkin H.J. // Int. J. Mod. Phys. E. 1992. V. 1. P. 603.
Lipkin H.J. Preprint WIS-91/79. Rehovot, 1991.
3. Amsler C. // Rev. Mod. Phys. 1998. V. 70. P. 1293.
4. Sapozhnikov M.G. JINR Preprint E1-98-341. Dubna, 1998;
Proc. of LEAP'98 Conf., Villasimius, Italy, 1998; Nucl. Phys. A. 1999. V. 655. P. 151c.
5. Wurzinger R. et al. // Phys. Rev. C. 1995. V. 51. P. R443.
Wurzinger R. et al. // Phys. Lett. B. 1996. V. 374. P. 283.
6. Balestra F. et al. // Phys. Rev. Lett. 1998. V. 81. P. 4572.
7. Balestra F. et al. // Phys. Rev. C. 2001. V. 63. P. 024004.
8. Ferrer A. et al. // Phys. Lett. B. 1997. V. 394. P. 395.
9. Ellis J. et al. // Phys. Lett. B. 1995. V. 353. P. 319.
10. Ellis J. et al. // Nucl. Phys. A. 2000. V. 673. P. 256.
11. Ashman J. et al. (EMC Collaboration) // Phys. Lett. B. 1988. V. 206. P. 364; Nucl. Phys. B. 1989. V. 328. P. 1.
12. Adeva B. et al. (SMC Collaboration) // Phys. Lett. B. 1997. V. 412. P. 414;
Adams D. et al. // Phys. Rev. D. 1997. V. 56. P. 5330.
13. Abe K. et al. (E143 Collaboration) // Phys. Rev. D. 1998. V. 58. P. 112003.
14. Anthony P. L. et al. (E155 Collaboration) // Phys. Lett. B. 1999. V. 458. P. 529.
15. Alberg M., Ellis J., Kharzeev D. // Phys. Lett. B. 1995. V. 356. P. 113.
16. Ellis J., Kharzeev D., Kotzinian A. // Z. Phys. C. 1995. V. 65. P. 189.
17. Okubo S. // Phys. Rev. 1977. V. 16. P. 2336.
18. Review of Particle Properties. // Eur. Phys. J. C. 2000. V. 15. P. 1.

19. Geiger P., Isgur N. // Phys. Rev. Lett. 1991. V. 67 . P. 1066;
Geiger P., Isgur N. // Phys. Rev. D. 1991. V. 44. P. 799.
20. Leutwyler H. // Nucl. Phys. B (Proc. Suppl.) 1998. V. 64. P. 223;
Kaiser R., Leutwyler H. hep-ph/9806336.
21. Feldmann Th., Kroll P., Stech B. // Phys. Rev. D. 1998. V. 58. P. 114006; Phys. Lett. B. 1999. V. 449. P. 339.
22. Feldmann Th., Kroll P. hep-ph/0201044. 2002.
23. KLOE Collaboration hep-ex/0107022. 2001.
24. Isgur N., Thacker H.B. hep-lat/0005006. 2000.
25. Anisovitch A. V., Anisovitch V. V., Sarantsev A. V. // Z. Phys. A. 1997. V. 359. P. 173.
26. Davies D. et al. // Phys. Rev. D. 1970. V. 2. P. 506.
27. Danburg J. et al. // Phys. Rev. D. 1970. V. 2. P. 2564.
28. Abolins M. et al. // Phys. Rev. Lett. 1963. V. 11. P. 381.
29. Ayres D. et al. // Phys. Rev. Lett. 1974. V. 32. P. 1463.
30. Cohen D. et al. // Phys. Rev. Lett. 1977. V. 38. P. 269.
31. Baldi R. et al. // Phys. Lett. B. 1977. V. 68. P. 381.
32. Woodworth P. et al. // Phys. Lett. B. 1976. V. 65. P. 89.
33. Dorofeev V. et al. (Lepton-F Collaboration) // Proc. NAN'95 Conf., Moscow, 1995.
34. Aguilar-Benitez M. et al. (LEBC-EHS Collaboration) // Z. Phys. C. 1989. V. 44. P. 531.
35. Blobel V. et al. // Phys. Lett. B. 1975. V. 59. P. 88.
36. Golovkin S. et al. (SPHINX Collaboration) // Proc. NAN'95 Conf., Moscow, 1995.
37. Aguilar-Benitez M. et al. (LEBC-EHS Collaboration) // Z. Phys. C. 1991. V. 50. P. 405.
38. Cooper A. et al. // Nucl. Phys. B. 1978. V. 146. P. 1.
39. Donald R. et al. // Phys. Lett. B. 1976. V. 61. P. 210.
40. Chen C. et al. // Nucl. Phys. B. 1977. V. 130. P. 269.
41. Sibirtsev A., Cassing W. // Eur. Phys. J. A. 2000. V. 7. P. 407.
42. Alde D. et al. // Nucl. Phys. B. 1986. V. 269. P. 485.
43. Costa G. et al. // Nucl. Phys. B. 1980. V. 175. P. 402.
44. Chen C. et al. // Nucl. Phys. B. 1977. V. 130. P. 269.
45. Gray G. et al. // Phys. Rev. D. 1983. V. 27. P. 307; Ph.D. Syracuse University, 1969 (unpublished).
46. Vuillemin V. et al. // Nuovo Cimento A. 1976. V. 33. P. 133.
47. Gagnuli S. et al. // Nucl. Phys. B. 1981. V. 183. P. 295.
48. Alberico A. et al. (OBELIX Collaboration) // Phys. Lett. B. 1998. V. 438. P. 430.
49. Bannikov A. et al. JINR Preprint E1-89-486, Dubna, 1989.
50. Stanton F. et al. // Phys. Lett. B. 1980. V. 92. P. 353.
51. Apel W. et al. // Phys. Lett. B. 1979. V. 83. P. 131.
52. Apokin V. IFVE-86-240. 1986.
53. Daum C. et al. // Z. Phys. C. 1981. V. 8. P. 95.

54. Alde D. *et al.* // *Z. Phys. C.* 1989. V. 43. P. 541.
55. Barberis D. *et al.* (*WA102 Collaboration*) // *Phys. Lett. B.* 1998. V. 432. P. 436.
56. Bloodworth I. *et al.* // *Nucl. Phys. B.* 1972. V. 39. P. 525.
57. Honecker H. *et al.* // *Nucl. Phys. B.* 1977. V. 131. P. 189.
58. Abele A. *et al.* // *Phys. Lett. B.* 1997. V. 411. P. 354.
59. Urner D. // Ph.D. thesis (Univ. of Zurich), 1995.
60. Amsler C. *et al.* // *Phys. Lett. B.* 1994. V. 333. P. 277.
61. Abele A. *et al.* // *Phys. Lett. B.* 1997. V. 404. P. 179.
62. Abele A. *et al.* // *Phys. Lett. B.* 1997. V. 411. P. 354.
63. Filippi A. *et al.* // *Phys. Lett. B.* 1999. V. 471. P. 263.
64. Calen H. *et al.* // *Phys. Lett. B.* 1996. V. 366. P. 39.
65. Moskal P. *et al.* // *Phys. Rev. Lett.* 1998. V. 80. P. 3202.
66. Moskal P. *et al.* // *Proc. of STORI-99 Conf., AIP Conf. Proc.* 2000. V. 512. P. 65; nucl-ex/0007002. 2000.
67. Germond J. P., Wilkin C. // *Nucl. Phys. A.* 1990. V. 518. P. 308.
68. Nakayama K. *et al.* // *Phys. Rev. C.* 2000. V. 61. P. 024001.
69. Witten E. // *Nucl. Phys. B.* 1979. V. 160. P. 57;
t'Hooft G. // *Nucl. Phys. B.* 1974. V. 72. P. 461.
70. Montanet L., Rossi G., Veneziano G. // *Phys. Rep.* 1980. V. 63. V. 149.
71. Geiger P., Isgur N. // *Phys. Rev. D.* 1997. V. 55. P. 299.
72. Lipkin H. J. // *Nucl. Phys. B.* 1987. V. 291. P. 720.
73. Shifman M. A., Vainstein A. I., Zakharov V. I. // *Nucl. Phys. B.* 1979. V. 147. P. 385; 448; 519.
74. Arafune J., Fukugita M., Oyanagy Y. // *Phys. Lett. B.* 1977. V. 70. P. 221.
75. Geshkenbein B. V., Ioffe B. L. // *Nucl. Phys. B.* 1980. V. 166. P. 340.
76. Veneziano G. // *Proc. «From Symmetries to Strings: Forty Years of Rochester Conferences», / Ed. A. Das. Singapore, 1990; Preprint CERN-TH.5840/90.*
77. Achasov N. N., Kozhevnikov A. A. // *Int. J. Mod. Phys.* 1992. V. 7. P. 4825.
78. Achasov N. N., Kozhevnikov A. A. // *Yad. Fiz.* 1996. V. 59. P. 153.
79. Achasov N. N., Kozhevnikov A. A. hep-ph/9906520. 1999.
80. Achasov M. N. *et al.* // *Phys. Lett. B.* 1999. V. 449. P. 122.
81. Achasov M. N. *et al.* // *Phys. Lett. B.* 2000. V. 474. P. 188.
82. *KLOE Collaboration* hep-ex/0006036. 2000.
83. Landsberg L. G. // *Physics-Uspkhi.* 1999. V. 42. P. 871.
84. Batty C. J. // *Rep. Prog. Phys.* 1989. 52. 1989. P. 1165.
85. Gastaldi U. *et al.* // *Phys. Lett. B.* 1994. V. 320. P. 193.
86. Batty C. J. // *Nucl. Phys. A.* 1996. V. 601. P. 425.
87. Zoccoli A. // *Proc. of Hadron Spectroscopy. AIP Conf. Proc.* 1998. V. 432. P. 347.
88. Bendiscioli G. *et al.* // *Nucl. Phys. A.* 2000. V. 686. P. 317.
89. Amsler C. *et al.* // *Phys. Lett. B.* 1995. V. 346. P. 363.

90. Doná R. (*OBELIX Collaboration*) // Proc. of LEAP'98 Conf., Villasimius, 1998; Nucl. Phys. A. 1999. V. 655. P. 213c.
91. Ableev V. G. et al. (*OBELIX Collaboration*) // Nucl. Phys. A. 1995. V. 585. P. 577.
92. Ableev V. G. et al. (*OBELIX Collaboration*) // Phys. Lett. B. 1994. V. 334. P. 237.
93. Filippi A. et al. (*OBELIX Collaboration*) // Nucl. Phys. A. 1999. V. 655. P. 453.
94. Chiba M. et al. // Phys. Lett. B. 1988. V. 202. P. 447.
95. Reifenrother J. et al. // Phys. Lett. B. 1991. V. 267. P. 299.
96. Ableev V. G. et al. (*OBELIX Collaboration*) // Nucl. Phys. A. 1995. V. 594. P. 375.
97. Alberico A. et al. (*OBELIX Collaboration*) // Phys. Lett. B. 1998. V. 432. P. 427.
98. Bertin A. et al. (*OBELIX Collaboration*) // Phys. Lett. B. 1996. V. 388. P. 450.
99. Pontecorvo B. M. // Sov. Phys. JETP. 1956. V. 3. P. 966.
100. Gorchakov O. E. et al. (*OBELIX Collaboration*) // Phys. Lett. B. 2002. V. 528. P. 34.
101. Amsler C. et al. // Z. Phys. A. 1995. V. 351. P. 325.
102. Abd El-Samad S. et al. (*COSY-TOF Collaboration*) // Phys. Lett. B. 2001. V. 522. P. 16.
103. Golovkin S. V. et al. // Z. Phys. A. 1997. V. 359. P. 435.
104. Etkin A. et al. // Phys. Rev. Lett. 1982. V. 49. P. 1620.
105. Evangelista C. et al. (*JETSET Collaboration*) // Phys. Rev. D. 1998. V. 57. P. 5370.
106. Bertolotto L. et al. (*JETSET Collaboration*) // Yad. Fiz. 1996. V. 59. P. 1501.
107. Landberg C. et al. // Phys. Rev. D. 1996. V. 53. P. 2839.
108. Ioffe B. L., Karliner M. // Phys. Lett. B. 1990. V. 247. P. 387.
109. CCFR Collaboration // Z. Phys. C. 1995. V. 65. P. 189.
110. Martin A. D. et al. hep-ph/9803445. 1998.
111. Aniol K. A. et al. (*HAPPEX Collaboration*) // Phys. Lett. B. 2001. V. 509. P. 211.
112. Gasser J., Leutwyler H., Sanio M. // Phys. Lett. B. 1991. V. 253. P. 252; 260.
113. Dong S. J. et al. // Phys. Rev. D. 1996. V. 54. P. 5496.
114. Gusken S. et al. // Phys. Rev. D. 1999. V. 59. P. 054504.
115. Borasoy B. // Eur. Phys. J. C. 1999. V. 8. P. 121.
116. Lyubovitskij V. E. et al. hep-ph/0009341.
117. Stuckey R., Birse M. // J. Phys. G. 1997. V. 23. P. 29.
118. Meissner U.-G., Smith G. hep-ph/0011277. 2000.
119. Pavan M. M. et al. hep-ph/0111066. 2001.
120. Hasty R. et al. (*SAMPLE Collaboration*) // Science. 2000. V. 290. P. 2117.
121. Garvey G. T. et al. // Phys. Rev. C. 1993. V. 48. P. 761.
122. Gerasimov S. B. hep-ph/9906386. 1999;
Gerasimov S. B. // Phys. Lett. B. 1995. V. 357. P. 666.
123. Dong S. J. et al. // Phys. Rev. Lett. 1995. V. 75. P. 2096.
124. Fukugita M. et al. // Phys. Rev. Lett. 1995. V. 75. P. 2092.
125. Gusken S. et al. // Phys. Rev. D. 1999. V. 59. P. 114502.

126. *Chen X. B., Chen X. S., Wang F.* // Phys. Rev. Lett. 2001. V. 87. P. 012001.
127. *Dover C., Fishbane P.* // Phys. Rev. Lett. 1990. V. 64. P. 3115.
128. *Ioffe B. L.* // Nucl. Phys. B. 1981. V. 188. P. 317, Erratum. 1981. V. 191. P. 591.
129. *Reinders L. J., Rubinstein H. R.* // Phys. Lett. B. 1984. V. 145. P. 108.
130. *Barash N. et al.* // Phys. Rev. B. 1965. V. 139. P. 1659.
131. *Baltay C. et al.* // Phys. Rev. Lett. 1965. V. 15. P. 532.
132. *Abele A. et al. (Crystal Barrel Collaboration)* // Phys. Lett. B. 1997. V. 415. P. 289.
133. *Rotondi A.* // Nucl. Phys. A. 1993. V. 558. P. 235c.
134. *Kudryavtsev A. E.* // Phys. At. Nuclei. 2000. V. 63. P. 1969.
135. *Kotzinian A.* // Proc. of the Second Workshop on Physics with a Polarized-Electron Light-Ion Collider (EPIC), Sept. 14–16, 2000, MIT, Cambridge, MA USA (to be published).
136. *Goodman M. G. et al.* // Phys. Rev. D. 1980. V. 22. P. 537.
137. *Locher M. P., Lu Y., Zou B. S.* // Z. Phys. A. 1994. V. 347. P. 281.
138. *Gutsche T. et al.* // Phys. Rev. C. 1999. V. 59. P. 630.
139. *Vandermeulen J.* // Z. Phys. C. 1988. V. 37. P. 1988.
140. *Rekaló M., Arvieux J., Tomasi-Gustafsson E.* // Z. Phys. A. 1997. V. 357. P. 133.
141. *Locher M. P., Lu Y.* // Z. Phys. A. 1995. V. 351. P. 83.
142. *Buzatu D., Lev F.* // Phys. Lett. B. 1994. V. 329. P. 143.
143. *Gortchakov O. et al.* // Z. Phys. A. 1996. V. 353. P. 447.
144. *Zou B. S.* // Phys. Rev. C. 1996. V. 53. P. 1452; Proc. of NAN'95 Conf., Moscow, 1995; Yad. Fiz. 1996. V. 59. P. 1485.
145. *Buzatu D. and Lev F.* // Phys. Lett. B. 1995. V. 359. P. 393.
146. *Dover C., Fishbane P.* // Phys. Rev. Lett. 1989. V. 62. P. 2917.
147. *Bitukov S. I. et al. (Lepton-F Collaboration)* // Phys. Lett. B. 1987. V. 188. P. 383.
148. *Landsberg L. G.* // Sov. J. Part. Nucl. 1990. V. 21. P. 446; Preprint IHEP 88-143. Protvino, 1988.
149. *Armstrong T. et al.* // Z. Phys. C. 1992. V. 56. P. 29.
150. *Adams G. et al. (E852 Collaboration)* hep-ex/0107042. 2001.
151. *Kondratyuk L. A., Sapozhnikov M. G.* // Phys. Lett. B. 1989. V. 220. P. 333.
152. *Kondratyuk L. A. et al.* // Yad. Fiz. 1998. V. 61. P. 1670.
153. *Abele A. et al.* // Phys. Lett. B. 1999. V. 469. P. 276.
154. *Nakayama K. et al.* // Phys. Rev. C. 1998. V. 57. P. 1580.
155. *Nakayama K., Haidenbauer J., Speth J.* // Phys. Rev. C. 2000. V. 63. P. 015201.
156. *Titov A., Kampfer B., Shklyar V. V.* // Phys. Rev. C. 1999. V. 59. P. 999.
157. *Titov A., Kampfer B., Reznik B. L.* // Eur. Phys. J. A. 2000. V. 7. P. 543.
158. *Nakayama K. et al.* // Phys. Rev. C. 1999. V. 60. P. 055209.
159. *Mull V.* // Phys. Lett. B. 1994. V. 334. P. 295.
160. *Kochelev N. I.* // Yad. Fiz. 1996. V. 59. P. 1698; hep-ph/9503249, 1995.
161. *Adeva B. et al. (SMC Collaboration)* // Phys. Lett. B. 1998. V. 420. P. 180.
162. *Ackerstaff K. et al. (HERMES Collaboration)* // Phys. Lett. B. 1999. V. 464. P. 123.
163. COMPASS Proposal. CERN/SPSLC 96-14. SPSC/P297. 1996.
164. *Mangano M. L. et al.* hep-ph/0105155. 2001.
165. *Paschke K. et al.* // Proc. of LEAP-2000 Conf., Venice; Nucl. Phys. A. 2001. V. 692. P. 55c.
166. *Balestra F. et al.* // Phys. Rev. Lett. 1999. V. 83. P. 1534.