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PRODUCTION OF ϕ-MESONS IN $\overline{N}N$ ANNIHILATION AND POLARIZED STRANGENESS IN THE NUCLEON

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1 Introduction

According to standard views, a nucleon at small momentum transfer consists of three constituent quarks. Probing the nucleon at high momentum transfer reveals a sea of $u\bar{u}$, $d\bar{d}$ and $s\bar{s}$ quark pairs as well as gluons. The admixture of strange quarks in the nucleon sea is non–negligible and reaches few percent. The perturbative QCD is successfully applied for describing the processes in this regime.

However recent experimental results induce an idea that the effects of intrinsic nucleon strangeness are not negligible even at small momentum transfers. Here the non–perturbative QCD effects may create an admixture of $\bar{s}s$ pairs to the nucleon wave function already at large distances. It is these effects that will be discussed in this lecture.

The story begins with the work of J.Ellis, E.Gabathuler and M.Karliner (EGK) [1], who pointed out in 1989 that the idea of intrinsic nucleon strangeness at small momentum transfer naturally followed from some theoretical models and could provide an explanation for a number of experimental puzzles that existed at that time. It is instructive today to look retrospectively at these experimental facts.

The first was the problem with the πN sigma term

$$\Sigma = \frac{1}{2}(m_u + m_d) < p\left|\bar{u}u + \bar{d}d\right|p > \qquad (1)$$

which was a factor of 2 higher than the value expected on the assumption that $< p|\bar{s}s|p >= 0$. It led to an unusually high admixture of strangeness, cited in the EGK paper as

$$W(\bar{s}s) = \frac{< p|\bar{s}s|p >}{< p\left|\bar{u}u + \bar{d}d + \bar{s}s\right|p >} \simeq 0.21 \qquad (2)$$

Since that time a lot of work has been done for clarification of this problem (for a review, see [2], [3]). It was realized how correctly connects the information from πN scattering with the data obtained from the baryon masses. As a result, it was found that the effect of nucleon strange quarks is neither too dramatic nor negligible. They contribute about 130 MeV to the nucleon mass (see, e.g. [4],[5]). Recent lattice QCD calculations [6] give

$$W(\bar{s}s) = 0.14 \pm 0.05 \qquad (3)$$

Another problem, discussed in the EGK paper, was the famous result of EMC measurement of deep inelastic polarized μp scattering [7], which indicated that

$$\Delta s \equiv \int_0^1 dx[q_\uparrow(x) - q_\downarrow(x) + \bar{q}_\uparrow(x) - \bar{q}_\downarrow(x)] = -0.24 \pm 0.07, \qquad (4)$$

where Δs is the fraction of the proton spin carried by strange quarks and antiquarks. The minus sign means that the strange q and $\bar{q}$ are polarized opposite to the direction of the nucleon spin.

A number of dedicated experiments [8] were done to verify the EMC results. Now the world average value of Δs is

$$\Delta s = -0.10 \pm 0.03, \qquad (5)$$

The third experimental puzzle, discussed in the EGK paper, was the observation [9] of the backward peak in $\bar{p}p \to K^+K^-$ annihilation at 0.5 GeV/c. No such peak was seen for annihilation into two pions $\bar{p}p \to \pi^+\pi^-$. Recent experiments at LEAR and KEK confirm existence of the strong backward peak at $\bar{\mathrm{p}}$ momenta $p < 1$ GeV/c [10],[11].

Important part of the EGK paper was dedicated to the apparent violation of the Okubo-Zweig-Iizuka (OZI) rule seen in proton-proton and antiproton-proton interactions. Thus the cross sections of ϕ production in pp scattering were 4-5 times larger than the predictions from the OZI-rule. The same situation was in $\bar{p}p$ annihilation. Now recent results from the LEAR experiments on ϕ-meson production in annihilation of stopped antiprotons have demonstrated much stronger violation of the OZI rule predictions (by a factor of 30-50).

So, all experimental facts cited in the EGK paper [1] as the reasons for introducing intrinsic nucleon strangeness survived the tests performed within these 6 years. All the problems that existed at that time are still unsolved today. Moreover, new puzzles have appeared: thus, it occurs that ϕ production in $\bar{p}p$ annihilation at rest strongly depends on quantum numbers of the initial state. Not all channels of ϕ production in $\bar{p}p$ annihilation at rest exhibit strong OZI-rule violation. It seems that ϕ production is enhanced from spin triplet states and suppressed from the spin singlet ones.

To explain these experimental features an idea of polarized nucleon strangeness was considered [12]. In fact, the results from deep inelastic lepton scattering (4)-(5) indicate that strange quarks are polarized. However the extension of this idea to the processes with small momentum transfer is non-trivial. An important step was done by M.Alberg, J.Ellis and D.Kharzeev [13] who suggested the mechanism for polarization of strange quarks in the non-perturbative regime.

It is important to note that the nucleon intrinsic strangeness was demonstrated not to contradict the known information about nucleon formfactors or magnetic moments (see discussion in [14], [15]).

So, at present the very notion of intrinsic nucleon strangeness in a small momentum transfer region looks sound. It seems that polarization of strange quarks can play a decisive role in providing the experimental confirmation of these effects. But before discussing challenging perspectives of different experiments which should demonstrate intrinsic nucleon strangeness, I would like to return to more mundane things and discuss first what we know about the OZI-rule and why violation of this semi-empirical rule is connected with nucleon strangeness.

2 The OZI rule in hadron interactions

The OZI rule was proposed [16] at an early stage of QCD history and there are different formulations of this rule. It is often said that the OZI rule suppressed the processes with disconnected quark lines (see Fig.1). Production of the ϕ meson is a particularly sensitive test of the OZI rule because the ϕ is almost a pure $\bar{s}s$ state, containing just a small admixture of light quarks associated with a small deviation of the vector mesons mixing angle from the ideal one.

If there are no strange quarks in the nucleon, then production of the ϕ meson, for instance in $\bar{p}p$ annihilation, should look like in Fig.1 a). The $\bar{s}s$ pair should be created in the final state, it is absent in the initial state, so ϕ production is described by the disconnected diagram and should be suppressed. On the contrary, production of the ω meson, which contains only light quarks, could be described by the diagram of Fig. 1b), where quark lines of the initial state are connected with the final state ones. Therefore, no suppression is expected for ω meson production.

To obtain the degree of the ϕ suppression it is worthwhile to formulate

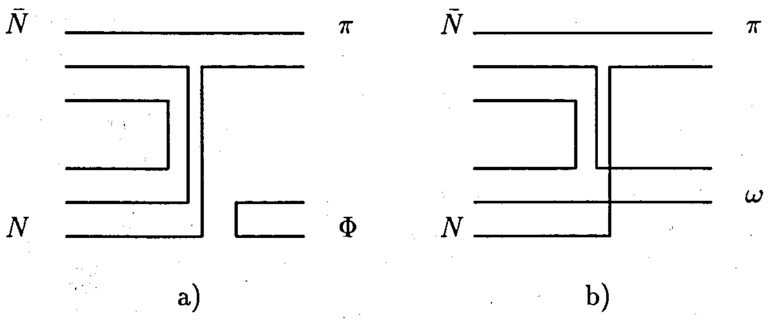

Figure 1: Disconnected quark diagram of ϕ meson production in $\bar{N}N$ interaction (a). Diagram of ω production in the same process (b).

the OZI rule following Okubo [17]. Let us consider creation of $q\bar{q}$ states in the interaction of hadrons

$$A + B \longrightarrow C + q\bar{q} \quad \text{for q=u,d,s} \tag{6}$$

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

The OZI rule demands that

$$Z = \frac{\sqrt{2}M(A+B \to C+s\bar{s})}{M(A+B \to C+u\bar{u}) + M(A+B \to C+d\bar{d})} = 0 \tag{7}$$

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

It means that if the ϕ meson was a pure $\bar{s}s$ state, it could not be produced in the interaction of ordinary hadrons. The OZI rule in Okubo's form strictly forbids creation of new flavors confined in only one particle. They (quarks with new flavors) must be shared among different particles.

However, the ϕ and ω are mixtures

$$\phi = \cos\Theta\ \omega_8 - \sin\Theta\ \omega_1 \tag{8}$$
$$\omega = \sin\Theta\ \omega_8 + \cos\Theta\ \omega_1 \tag{9}$$

of the SU(3) singlet ω_1 and octet ω_8

$$\omega_8 = (u\bar{u} + d\bar{d} - 2s\bar{s})/\sqrt{6} \tag{10}$$
$$\omega_1 = (u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3} \tag{11}$$

and the ϕ could be created in the hadron interaction due to small admixture of light quarks in its wave function.

Then OZI rule Eq. (7) could be re-written in terms of physical ϕ and ω

$$\frac{M(A+B \to C+\phi)}{M(A+B \to C+\omega)} = -\frac{Z + \tan(\Theta - \Theta_i)}{1 - Z\tan(\Theta - \Theta_i)} \tag{12}$$

here Θ and Θ_i are physical and ideal mixing angles, $\Theta_i = 35.3^0$.

From this equation one can immediately see that if OZI rule Eq. (7) is fulfilled and the parameter Z is equal to zero , then

$$R = \frac{\sigma(A+B \to \phi X)}{\sigma(A+B \to \omega X)} = \tan^2(\Theta - \Theta_i) \cdot f \tag{13}$$

here f is a kinematical phase space factor.

Since the vector mesons are practically ideally mixed, the difference $\delta = \Theta - \Theta_i$ is small: the mixing angle from the quadratic Gell-Mann-Okubo mass formula is $\Theta = 39^0$ and from the linear one it is $\Theta = 36^0$. Substituting these values in Eq. (13) one could obtain for $f = 1$:

$$R = 4.2 \cdot 10^{-3} \quad \text{for quadratic mass formula} \tag{14}$$
$$R = 0.15 \cdot 10^{-3} \quad \text{for linear mass formula} \tag{15}$$

As is clear from Eq. (12), the smallness of the ϕ/ω ratio is due to the OZI rule demand $Z = 0$ and perfect mixing of vector mesons $\delta = \Theta - \Theta_i \approx 1-3^0$. Another situation exists, for instance, for the pseudoscalar mesons, where mixing is not so perfect and the difference δ is large. In principle, under violation of the OZI rule one could imply the physical reasons which provide the deviation of the corresponding physical angle from the ideal mixing one. Or, more precisely, the reasons for different mixing in pseudoscalar and vector meson nonets. However here we will consider the violation of the OZI rule at a pure phenomenological level as a deviation of the measured ϕ/ω ratios from the prediction of Eq. (14).

According to the OZI-rule the ratio of ϕ to ω-meson production in the hadron interactions should be rather small, at a level of few times 10^{-3}. That prediction has been nicely confirmed in a number of experiments with proton-proton, pion-proton and antiproton-proton annihilation at different energies of the projectiles. In Table 1 we collected the experimental data on the ratio $R = \phi X/\omega X$ for different hadronic interactions.

Table 1. The ratios $R = \phi X/\omega X$ for production of the ϕ and ω - mesons in pp, $\bar{p}p$ and πp interactions at P_L different from zero. The parameter Z of the OZI-rule violation is calculated for $\delta = \Theta - \Theta_i = 3.7^0$, assuming identical phases of the ϕ and ω production amplitudes.

Initial state	P_L (GeV/c)	Final state X	$R = \phi X/\omega X \cdot 10^3$	$\lvert Z \rvert$ (%)	Refs.
$\pi^+ n$	1.54-2.6	p	21.0 ± 11.0	8 ± 4	[18],[19]
$\pi^+ p$	3.54	$\pi^+ p$	19.0 ± 11.0	7 ± 4	[20]
$\pi^- p$	5-6	n	3.5 ± 1.0	0.5 ± 0.8	[21]
$\pi^- p$	6	n	3.2 ± 0.4	0.8 ± 0.4	[22]
$\pi^- p$	10	$\pi^- p$	6.0 ± 3.0	1.3 ± 2.0	[23]
$\pi^- p$	19	$2\pi^-\pi^+ p$	5.0^{+5}_{-2}	0.6 ± 2.5	[24]
$\pi^- p$	32.5	n	2.9 ± 0.9	1.1 ± 0.8	[25]
$\pi^- p$	360	X	14.0 ± 6.0	5 ± 3	[26]
pp	10	pp	20.0 ± 5.0	8 ± 2	[23]
pp	24	pp	26.5 ± 18.8	10 ± 6	[27]
pp	24	$\pi^+\pi^- pp$	1.2 ± 0.8	3 ± 1	[27]
pp	24	pp $m\pi^+\pi^-$, m=0,1,2	19.0 ± 7.0	7 ± 3	[27]
pp	70	pX	16.4 ± 0.4		[28]
pp	360	X	4.0 ± 5.0	0.1 ± 4	[29]
$\bar{p}p$	0.7	$\pi^+\pi^-$	$19.0 \pm 5^{*)}$	7 ± 2	[30]
$\bar{p}p$	0.7	ρ^0	$13.0 \pm 4^{*)}$	5 ± 2	[30]
$\bar{p}p$	1.2	$\pi^+\pi^-$	11.0^{+3}_{-4}	4 ± 1	[31]
$\bar{p}p$	2.3	$\pi^+\pi^-$	17.5 ± 3.4	7 ± 1	[32]
$\bar{p}p$	3.6	$\pi^+\pi^-$	9.0^{+4}_{-7}	3 ± 3	[31]

*) corrected for phase space.

As we see in Table 1, many past experiments found an apparent excess of R above the OZI prediction, though it was not very dramatic: $R \leq (10 - 20) \cdot 10^{-3}$.

It was speculated in [30] that the OZI rule is violated more strongly in pp or $\bar{p}p$ interactions than in πp one, suggesting existence of "a dynamical mechanism" of the OZI rule violation in the case of a system of two baryons. However, one can see that there is no big difference between ϕ/ω ratios in the πp and pp or $\bar{p}p$ data.

So one may conclude that the OZI-rule predictions (14) are fullfiled in the hadronic interactions at a level of about 10 % . But what is the reason for this perfect agreement with the experimental data?

2.1 Why the OZI rule is valid?

In some sense the OZI rule should be regarded as a phenomenological rule, because it is not clear how in general to derive it from the first principles of QCD. It was demonstrated that, indeed, in some limits of QCD it is fullfilled.

For instance, suppression of the processes described by the disconnected diagrams (like the one in Fig.1 a)) was proved for the large N_c limit [33], [34]. The disconnected diagrams are suppressed by higher powers of $1/N_c$ compared with the connected ones.

The OZI rule is also natural in the heavy-quark limit when the mixing between, for instance, the $\bar{c}c$ state with 1^{--} and a light $\bar{q}q$ pair is suppressed by α_s^3.

But the reasons why the OZI rule is valid in the light hadron interactions is still a subject of investigations [35],[36]. The puzzle of the OZI-rule for ordinary hadron interaction is to understand why it is so perfectly fullfiled in spite of its apparent inapplicability. Indeed, all OZI–violated reactions could be regarded as two-step processes, for instance:

$$\phi \to \bar{K}K \to \rho\pi \tag{16}$$

$$\bar{p}p \to \bar{K}K^* \to \phi\pi \tag{17}$$

$$\pi^- p \to K^0\Lambda \to \phi n \tag{18}$$

At each step the process is described by a connected diagram, like that in Fig.2 . There is no suppression for each sub-process. Why then the total process is suppressed?

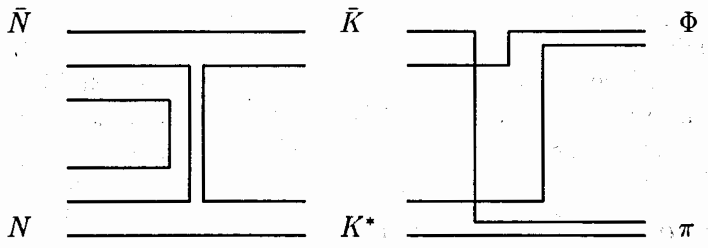

Figure 2: Annihilation $\bar{p}p \to \phi\pi$ as a two-step process.

An answer to this question was found by H.Lipkin (see [35],[36] and references therein), who pointed out the importance of the cancellations between different intermediate states as a reason for validity of the OZI rule.

He argued that in some sense the OZI rule is a reflection of the underlying flavor symmetry which "equalized" the contributions of different intermediate states. To demonstrate the cancellation between these contributions he introduced an analog of G-parity in the case of the total flavor symmetry [37]. 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 interactions and the T matrix are invariant under this general G-parity in the case of flavor symmetry. Then one could classify the meson states having odd or even eigenvalues of the generalized G-parity. It was shown in [37] 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 cancellation of the contributions

from different intermediate states in the transition amplitude of two-step processes like (16)- (18).

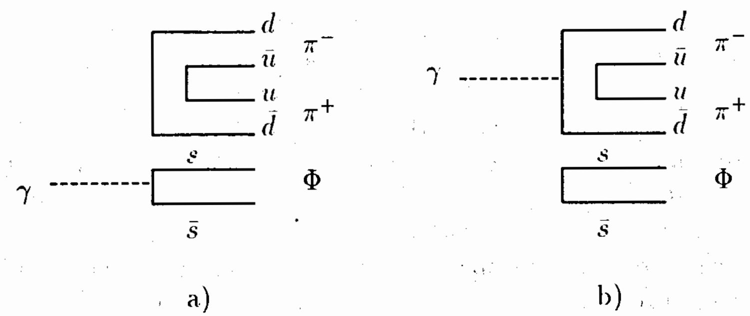

Figure 3: Different diagrams of $\phi\pi\pi$ photoproduction.

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 (13)-(14). It means that the large values of the ϕ/ω ratio are not necessarily connected with something non-trivial. They may simply reflect some non-compensation of the contributions from different intermediate states.

However, as we see from Table 1, the OZI rule works surprisingly well, within a 10% accuracy, and there are not so many examples of its violation.

Thus in the diffractive photoproduction of ϕ mesons [38] a large value of the ϕ/ω ratio it was found:

$$\frac{\gamma A \to \phi\pi^+\pi^- A}{\gamma A \to \omega\pi^+\pi^- A} = (97 \pm 19) \cdot 10^{-3} \qquad (19)$$

However this result is not rather unexpected because 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. The corresponding diagrams are shown in Fig.3a and 3b. They are both disconnected diagrams. The difference is that quark lines of the strange quarks are connected in Fig.3a and disconnected in the diagram of Fig.3b. So one possible interpretation of the large ϕ/ω ratio (19) is that the degree of the OZI rule violation depends on the flavor of the quarks in the disconnected part.

A similar trend was seen in the charmonium decays (see discussion in [35]). The decay $J/\psi \to \phi\pi^+\pi^-$, where quark lines of the strange and light quarks are disconnected, has a small absolute branching ratio $BR = 0.21 \pm 0.09\%$ and strongly suppressed relative to e^+e^-.

However, there is a decay $\psi'(3685) \to \psi\pi\pi$, which is also OZI-forbidden, but here only light quarks are disconnected. This process has a large absolute branching ratio $BR = 50 \pm 3\%$ and a large relative ratio to e^+e^-, three orders of magnitude higher than in the $J/\psi \to \phi\pi^+\pi^-$ decay.

These examples teach us that the substantial violation (more than 10 %) of the OZI rule is possible. In this sense, the recent data on ϕ production in $\bar{p}p$ annihilation at rest obtained at LEAR (CERN), which have demonstrated a significant, by a factor of 30-50, violation of the OZI–rule, do not seem to be something remarkable. However the pattern of the OZI–violation seen in different channels of ϕ production in antiproton annihilation is really non–trivial.

3 Experimental data on ϕ production in $\bar{p}p$ annihilation at rest

The existing experimental data on ϕ production in annihilation of stopped antiprotons are summarized in Table 2.

TABLE 2. The ratios $R = \phi X/\omega X$ for production of the ϕ and ω - mesons in antinucleon annihilation at rest. The parameter Z of the OZI-rule violation is calculated for $\delta = \Theta - \Theta_i = 3.7^0$, assuming identical phases of the ϕ and ω production amplitudes. The data are given for annihilation in liquid hydrogen target (percentage of annihilation from P-wave is $\sim 10 - 20\%$), gas target (~61% P-wave) and LX-trigger [41] (~86-91% P-wave).

Final state	Initial states	B.R.$\cdot 10^4$	$R \cdot 10^3$	$\|Z\|$ (%)	Comments
$\phi\gamma$	$^1S_0, ^3P_J$	0.17 ± 0.04	243 ± 86	42 ± 8	liquid,[39]
$\phi\pi^0$	$^3S_1, ^1P_1$	5.5 ± 0.7	96 ± 15	24 ± 2	liquid,[39]
$\phi\pi^0$		2.46 ± 0.23	114 ± 24		gas, [40]
$\phi\pi^0$		1.9 ± 0.5			gas, [41]
$\phi\pi^0$		0.3 ± 0.3			LX-trigger, [41]
$\phi\pi^-$	$^3S_1, ^1P_1$	9.0 ± 1.1	83 ± 25	22 ± 4	liquid,[42]-[44]
$\phi\pi^-$		14.8 ± 1.1	133 ± 26	29 ± 3	$\bar{p}d, p < 200\ MeV/c$, [45]
$\phi\pi^-$			113 ± 30	27 ± 4	$\bar{p}d, p > 400\ MeV/c$, [45]
$\phi\pi^+$			110 ± 15	26 ± 2	$\bar{n}p$, [46]
$\phi\eta$	$^3S_1, ^1P_1$	0.9 ± 0.3	6.0 ± 2.0	1.3 ± 1.2	liquid,[47]
$\phi\eta$		0.87 ± 0.21			gas, [40]
$\phi\eta$		0.37 ± 0.09			gas, [41]
$\phi\eta$		0.41 ± 0.16			LX-trigger, [41]
$\phi\rho$	$^1S_0, ^3P_J$	3.4 ± 0.8	6.3 ± 1.6	1.4 ± 1.0	gas, [41],[48]
$\phi\rho$		4.4 ± 1.2	7.5 ± 2.4	2.1 ± 1.2	LX-trigger, [41],[48]
$\phi\omega$	$^1S_0, ^3P_{0,2}$	6.3 ± 2.3	19 ± 7	7 ± 4	liquid, [49],[50]
$\phi\omega$		3.0 ± 1.1			gas, [41]
$\phi\omega$		4.2 ± 1.4			LX-trigger, [41]
$\phi\pi^0\pi^0$	$^{1,3}S_{0,1}, ^{1,3}P_J$	1.2 ± 0.6	6.0 ± 3.0	1.3 ± 2.0	liquid,[47]
$\phi\pi^-\pi^+$		4.6 ± 0.9	7.0 ± 1.4	1.9 ± 0.8	liquid,[51]
ϕX, $X = \pi^+\pi^-, \rho$		5.4 ± 1.0	7.9 ± 1.7	2.4 ± 1.0	gas, [41],[48]
ϕX, $X = \pi^+\pi^-, \rho$		7.7 ± 1.7	11.0 ± 3.0	4.0 ± 1.4	LX-trigger, [41],[48]

From the data in this Table one could see that the strong OZI rule violation was observed in the experiments of three collaborations at LEAR: ASTERIX, OBELIX and Crystal Barrel. It was seen in the following channels:

$$\bar{p} + p \to \phi + \gamma \tag{20}$$
$$\bar{p} + p \to \phi + \pi^0 \tag{21}$$
$$\bar{n} + p \to \phi + \pi^+ \tag{22}$$
$$\bar{p} + n \to \phi + \pi^- \tag{23}$$

for annihilation in liquid and gas hydrogen and deuterium targets. The values of the ϕ/ω ratio are significantly higher than the OZI rule predictions. The highest deviation is for the $\phi\gamma$ channel where $R(\phi/\omega)\cdot 10^3 = 243\pm 86$, i.e. about 50 times larger than the OZI prediction $R(\phi/\omega)\cdot 10^3 = 0.15-4$.

So the very existence of strong deviation from the OZI rule in annihilation of stopped antiprotons is a firmly established experimental fact seen by different groups in different reactions.

It is interesting that the OZI rule violation strongly depends on the quantum numbers of the initial state. The conservation of P and C–parities strictly fixes the possible quantum numbers of the $N\bar{N}$ initial state in binary reactions of ϕ production. The allowed initial states are listed in Table 2. Thus, the $\phi\pi$ final state is possible either from the spin triplet $^3S_1$ state, or from the spin singlet $^1P_1$ state. The ASTERIX collaboration observed [41] that the $\phi\pi$ channel from the $^3S_1$ initial state has the branching ratio $B.R.(\bar{p}p \to \phi\pi^0) = (4.0\pm 0.8)\cdot 10^{-4}$ and the ratio $R = \phi/\omega\cdot 10^3 = 76.9\pm 17.1$. However no ϕ's at all were seen in the same channel for annihilation from the $^1P_1$ initial state!

This experimental fact was confirmed now by the OBELIX collaboration [40],[56]. It was found that the $\phi\pi^0$ yield from the $^3S_1$ state is $B.R.(\bar{p}p \to \phi\pi^0) = (5.22\pm 0.48)\cdot 10^{-4}$, whereas from the $^1P_1$ initial state no ϕ's are created with the limit of $B.R.(\bar{p}p \to \phi\pi^0) < 1.1\cdot 10^{-5}$ 95% $C.L.$.

So it was found that not only a large ratio ϕ/ω, which may happen as it was discussed in the previous Section. But it was discovered that this ratio changes 50 times depending upon the initial state.

Howevere it was not clear if the observed absence of the $\phi\pi^0$ mode from the $^1P_1$ initial state is connected with the changing of the spin of the initial state or with transition from S- to P-wave. In fact, there were speculations [59] that the yield of kaons should be suppressed for annihilation from the P-wave.

A comprehensive study of this and another topics of OZI violation was performed recently by the OBELIX collaboration. We took advantage of the OBELIX spectrometer to work with different targets and effectively register charged kaons.

In Fig. 4 the effective mass distributions of the $K^\pm\pi^0$ and K^+K^-

systems in the reaction

$$\bar{p} + p \to K^+ + K^- + \pi^0 \qquad (24)$$

for annihilation of stopped aniprotons in liquid and gas targets at NTP and 5 mbar pressure are shown [56].

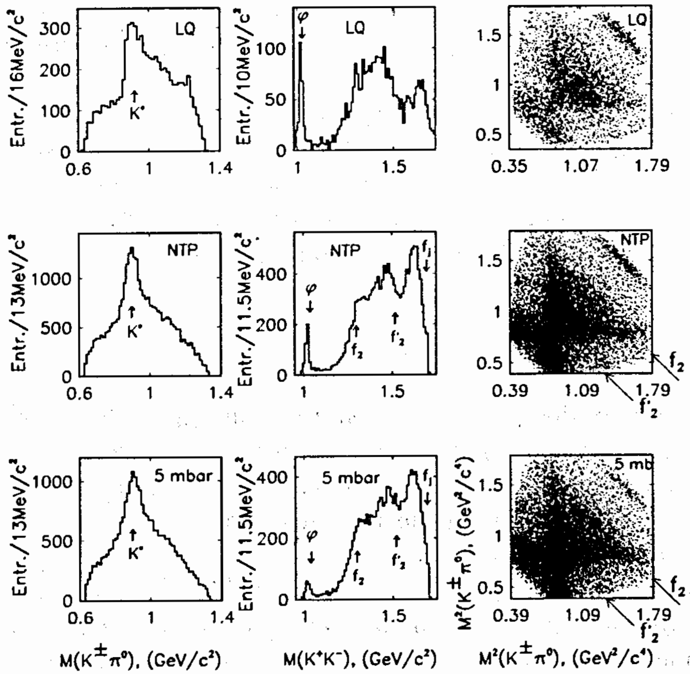

Figure 4: The Dalitz plots and effective mass distributions of the $K^\pm\pi^0$ and K^+K^- systems for annihilation $\bar{p}p \to K^+K^-\pi^0$ in a liquid and gas H_2 target at NTP and 5 mbar.

It is commonly believed that for annihilation in a liquid hydrogen target the percentage of annihilation from the P-wave is small $\sim 10-20\%$, whereas for a gas target at NTP it increases up to $\sim$61% [41] and at low pressure 5 mbar gas target the annihilation from the P-wave is dominant ($\sim$85% P-wave [57]). So the spectra in Fig. 4 reflect the behaviour of the kaon production in reaction (24) at different initial states where the percentage of the P-wave annihilation increases with decreasing density of the target.

In Fig. 4 one can see a very prominent feature: K^* and ϕ mesons production is different. The peak of K^* increases whereas the peak from ϕ mesons decreases with decreasing target density. So it looks like ϕ production being "decoupled", not connected with production of K^*. However, if the ϕ mesons are created via K^*K intermediate states, as advocated in some models [58], then their production pattern should follow that of K^*.

Preliminary results of the partial wave analysis [56] of reaction (24) shows that the overall yield of the $K^+K^-\pi^0$ final state increases from the liquid to the 5 mbar data sample. It means that there is no kaon suppression for annihilation from the P-wave in this reaction.

A rather nice testbench for verification of the spin effects in ϕ production is the reaction

$$\bar{p} + p \rightarrow \phi + \pi^- + \pi^+ \qquad (25)$$

Here ϕ could be produced either from the spin-triplet $^3S_1$ initial state or from the spin-singlet $^1S_0$ one. So for stopped antiproton annihilation in liquid, where the S-wave dominates, one could directly compare the spin-triplet amplitude with the spin-singlet one of the same angular momentum.

Partial wave analysis of reaction (25) shows [60] that for a good description of the data it is enough to consider only the one spin-triplet $^3S_1$ amplitude. It is important that the same dominance of spin-triplet states was found for annihilation from the P-wave in the analysis of the 5 mbar data sample . It occurs that the $^1P_1$ state percentage is only 16 ± 3 %. The rest of ϕ production comes from ^3P_J states.

So now the strong dependence of the ϕ yield on the quantum numbers of the initial state is also a firmly established experimental fact seen by different groups in different reactions.

It is important to note that not all chanells of ϕ production in $\bar{p}p$ annihilation at rest exhibit violation of the OZI rule. There are no problems with OZI for the $\phi\eta$, $\phi\rho$, $\phi\omega$ and $\phi\pi\pi$ channels.

If one plots the dependence of the ratio $R(\phi X/\omega X)$ on the mass of the system X created with ϕ (see Fig.5), then one could see an interesting tendency: especially high OZI rule violation in two-body reactions $\bar{N}N \rightarrow \phi(\omega)X$ was seen for the processes, where the mass of X was small ($X = \gamma$ and π). For annihilation at rest decreasing of the mass X means an increase in the momentum transfer to ϕ. Does the degree of the OZI rule violation depends on the momentum transfer?

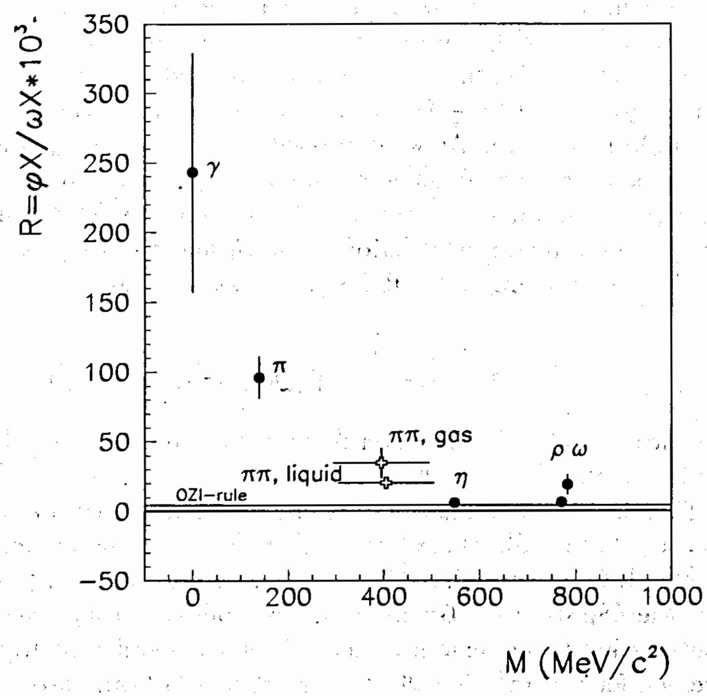

Figure 5: The ratio $R = \phi X/\omega X \cdot 10^3$ for different reactions of $\bar{p}p$ annihilation at rest as a function of the mass M of the system X.

To answer on this question the data obtained by the OBELIX collaboration on the reaction of ϕ production (25) was compared with the similar reaction of ω production with two pions [61]. The ratio $R = Y(\phi\pi^+\pi^-)/Y(\omega\pi^+\pi^-)$ for annihilation of stopped antiprotons in a gaseous and a liquid hydrogen target was measured at different invariant masses of the dipion system.

It occurs that for all events, without any selection on the dipion mass, the ratio R 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 $300\ MeV < M_{\pi\pi} < 500\ MeV$ the degree of the OZI rule violation increases (see Fig.5) and it seems to depend on the target type.

The observed increase of R at small dipion masses could be explained as a manifestation of different spin structure of the amplitude of ϕ and ω production. The conservation laws unambigously couple the spin-triplet $^3S_1$ initial state with the $\phi(\omega)\pi\pi$ final state when two pions are in the S-wave relative to each other. The spin-singlet initial $^1S_0$ state is coupled with the $\phi(\omega)\pi\pi$ system when two pions are in the P-wave, i.e. to the $\phi(\omega)\rho$ final state. As we discussed above, the partial wave analysis [60] of the $\phi\pi\pi$ channel demonstrates that in the S-wave the production of ϕ mesons completely dominated by the spin-triplet $^3S_1$ initial state. Whereas for ω meson production both $^3S_1$ and $^1S_0$ states are important [51]. So the measured ratio R for annihilation in liquid is

$$R = \frac{Y(\phi\pi^+\pi^-)}{Y(\omega\pi^+\pi^-)} = \frac{Y(\phi(\pi^+\pi^-)_S)}{Y(\omega(\pi^+\pi^-)_S) + Y(\omega\rho)} \tag{26}$$

It is clear that at small dipion masses, far from the ρ peak, this ratio should increase.

Therefore, for annihilation in liquid, at small dipion masses, the ratio $R = Y(\phi(\pi^+\pi^-)_S)/Y(\omega(\pi^+\pi^-)_S)$ was measured for annihilation from the $^3S_1$ state. It is observed that the OZI-rule violation for annihilation from the $^3S_1$ state exists but is rather modest: $R(^3S_1) \approx 16 \cdot 10^{-3}$. It is interesting to understand why this value is different from the ratio observed for the $\phi\pi^0$ channel, which also comes from $^3S_1$ but the degree of the OZI rule violation is substantial: $R(\phi\pi^0/\omega\pi^0) \approx 100 \cdot 10^{-3}$ [40]-[41].

There are two possible reasons for the different degree of the OZI rule violation. It may be connected with the mass difference between the systems produced with ϕ, reflecting in this way possible dependence of the OZI rule on the momentum transfer. Or it may be connected with the different quantum numbers of the system created with ϕ. The $\pi\pi$ system in the relative S-wave is a scalar $J^{PC} = 0^{++}$, so the results could be interpreted as follows. When ϕ is created from the $^3S_1$ initial state with a scalar 0^{++}, the OZI rule violation is less than in the case of ϕ production with a pseudoscalar 0^{-+}.

The best way to clarify this problem is to perform direct measurements of the t-dependence of the differential cross sections of the $\phi\pi$ and $\omega\pi$ channels for $\bar{p}p$ annihilation in flight. In a similar experiment on ϕ production in the $\pi^{\pm}N \to \phi N$ interaction [22] it was found that the $d\sigma/dt$ distribution of ϕ production at large t differs significantly from the one for the ω-meson, leading to the increase in the ϕ/ω ratio at large t. The largest momentum transfer in ϕ production by stopped antiproton annihilation is available in the so-called Pontecorvo reaction

$$\bar{p} + d \to \phi + n \tag{27}$$

It was predicted [12] that one may expect very high ϕ/ω ratios in reactions of this type.

Recently the OBELIX collaboration [62] has measured reaction (27) and the Crystal Barrel collaboration has measured the Pontecorvo reaction with ωn in the final state [63]. Preliminary estimations of the branching ratio of (27) show that the ratio ϕ/ω is rather large indeed:

$$R = Y(\phi n)/Y(\omega n) = (230 \pm 60) \cdot 10^{-3}$$

It is two times greater than in the annihilation on a free nucleon $\bar{p}p \to \phi\pi^0$ and twice as large as the prediction of the two-step model [64] which gives correct description in the case of other Pontecorvo reactions.

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

Another interesting topic concerns the violation of the OZI rule for tensor mesons, in particular, for production of $f_2'(1525)$ compared to the $f_2(1270)$. Already in the EGK paper [1] some data on serious violation of the OZI rule for f_2' production in $\bar{p}p$ annihilation in flight [32],[65] were discussed. However, the scarce statistics in these experiments prevented any definite conclusions.

It is expected from the quadratic mass formula, that the ratio R' for the yields of $f_2'(1525)$ and $f_2(1270)$, without phase space correction, will be

$$R' = \frac{Y(f_2'(1525)X)}{Y(f_2(1270)X)} = 16 \cdot 10^{-3} \tag{28}$$

The measurements of the $K^+K^-\pi^0$ final state (reaction (24)) for annihilation of stopped antiprotons in liquid, gas at NTP and 5 mbar pressure, which were performed by the OBELIX collaboration [56], gave new information for this problem too. The corresponding Dalitz plots and effective mass distributions of the $K^{\pm}\pi^0$ and K^+K^- systems are shown in Fig. 4 .

A band around 1500 MeV/c^2 at the K^+K^- effective mass is seen in the NTP and 5 mbar Dalitz plots. Remarkably, the corresponding band is absent in the Dalitz plot of the annihilation in liquid. This indicates that $f_2'(1525)$ is formed mainly from annihilation in the P-wave. Preliminary estimations [56] of the ratio R' are rather intriguing:

$$R' = \frac{Y(f_2'(1525)\pi^0)}{Y(f_2(1270)\pi^0)} = (65 \pm 27)\cdot 10^{-3}, \text{for NTP data} \quad (29)$$

$$= (73 \pm 25)\cdot 10^{-3}, \text{for 5 mbar data} \quad (30)$$

The production of f_2' in the $\bar{p}p \rightarrow f_2'\pi^0$ reaction was calculated in [66] via final state interactions of K^*K and $\rho\pi$. The obtained production rates of f_2' are rather small, about 10^{-6}. It means that if any violation of the OZI rule is firmly established for f_2', it will definetely rule out the rescattering models.

An interesting result was reported by the Crystal Barrel collaboration [52] which measured the $\phi\pi$ cross section for antiproton annihilation in flight. The $\phi\pi$ production rate at 600 MeV/c is $Y = 1.18\cdot 10^{-4}$, i.e. about 5 times smaller than at rest whereas the production rate of the K^*K seems to be constant or slightly decreases. It may indicate that the degree of the OZI rule violation decreases with energy. However direct measurements of the $\omega\pi$ reaction for annihilation in flight are needed.

4 Polarized intrinsic nucleon strangeness

The review of various theoretical approaches used today for the explanation of the strong OZI–rule violation in antiproton annihilation could be found in [53]. It is remarkable that the approaches based on the traditional concepts seem to be unable to reproduce all features of the ϕ production discussed above. At the same time, unconventional ideas like polarized intrinsic strangeness in the nucleon [12], [13] offer a rather natural explanation of the observed facts and suggest a number of new effects to be measured.

First of all it is assumed that the OZI rule itself is valid. Its violation is only apparent and could be regarded as a signal of complicated nucleon

structure. It is supposed [12],[13] that the abundant ϕ meson production could be the consequence of an admixture of $\bar{s}s$ pairs in the nucleon. In this case the ϕ production in NN or $\bar{N}N$ interactions is described by the diagrams with connected s–quark lines.

At first glance, the intrinsic strangeness of the nucleon should lead to the same enhancement of the ϕ production in all annihilation channels. This is contrary to the experimental data. To solve this principal difficulty it was assumed [12] that the $\bar{s}s$ component in the nucleon is polarized.

Indeed, the results from the deep inelastic lepton-nucleon experiments indicate that strange quarks and antiquarks in the nucleon have a net polarization opposite to the proton spin [7]:

$$\Delta s \equiv \int_0^1 dx[q_{\uparrow}(x) - q_{\downarrow}(x) + \bar{q}_{\uparrow}(x) - \bar{q}_{\downarrow}(x)] = -0.10 \pm 0.03. \quad (31)$$

Adopting this observation from the deep inelastic scattering one may ask what happens if the nucleon wave function, even at small momentum transfers, contains an admixture of $\bar{s}s$ pairs with spins of both strange quarks oriented opposite to the nucleon spin.

Let us consider NN interaction from a spin–triplet initial state in which the nucleon spins are parallel (see, Fig.6). In this case the $\bar{s}$ and s quarks in both nucleons will also have parallel spins. If the rearrangement diagram of Fig. 6 is dominant and the polarization of the strange quarks is not changed during the interaction, then the $\bar{s}$ and s quarks will have parallel spins in the final state as in the quark-model wave function of the ϕ meson. If the NN initial state is an S wave, the $\bar{s}s$ pair will probably also be in an S wave as in the ϕ meson. Therefore, the maximum enhancement of ϕ production is expected in the $^3S_1$ channel, as observed in the $\bar{p}p \rightarrow \phi\pi$ channel.

This model also qualitatively suggests why ϕ production may be more enhanced in $\bar{p}p$ annihilation at rest than in other hadronic interactions. The reason is that higher–energy collisions involve an increasing admixture of partial waves, implying that the "rearrangement" into the $\bar{s}s$ spin–triplet S–wave state of ϕ–meson becomes progressively more diluted. On the contrary, in the $\bar{p}p$ annihilation at rest only one pure spin state $^3S_1$ is possible for $\phi\pi$ production in S–wave annihilation.

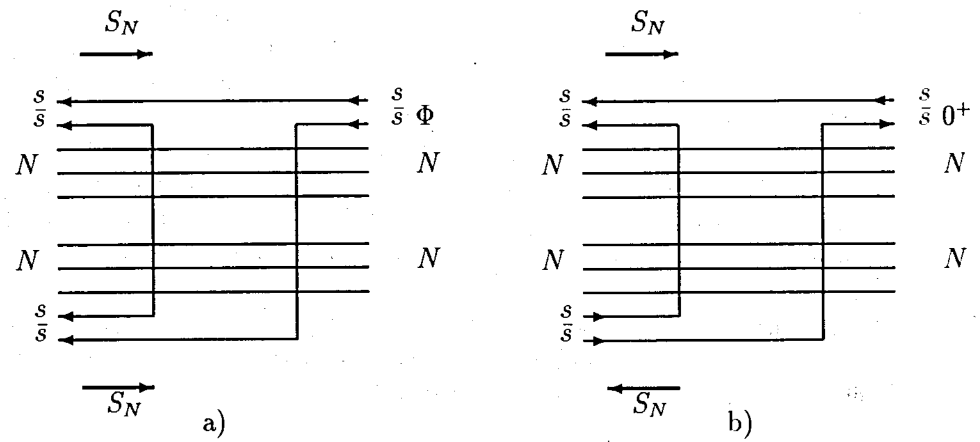

Figure 6: Production of the ϕ meson in NN interaction from the spin triplet (a) and spin singlet (b) states. The arrows show the direction of nucleons and strange quark spins.

An important step was done in the work of M.Alberg, J.Ellis and D.Kharzeev [13], where a possible mechanism for the creation of the negative polarization of the strange quarks was suggested. The idea is based on the result from the QCD sum rules [54] that the density of the strange quark-antiquark pairs in QCD vacuum is comparable with the value of light quark condensate:

$$< 0\,|\bar{s}s|\,0 >= (0.8 \pm 0.1) < 0\,|\bar{q}q|\,0 > \qquad (32)$$

The standard value of the light quark condensate [55] is $< 0\,|\bar{q}q|\,0 >= (225 \pm 25\ MeV)^3$. It corresponds to about one strange quark-antiquark pair in the fm^3 of the vacuum.

What has happened with the basic $|uud>$ proton state immersed in the QCD vacuum? Some interaction between valence quarks of the

proton and the vacuum quarks should appear and the main assumption of [13] is that this interaction corresponds to the strong attraction between quarks and antiquarks in the pseudoscalar channel with $J^{PC} = 0^{-+}$. Considering that the masses of pions and kaons are small in comparison with the typical hadron scale of $\approx 1\ GeV$, this assumption seems to be rather natural.

The consequence of the assumption about strong attraction between $\bar{q}q$ in the $J^{PC} = 0^{-+}$ system is straightforward: it should induce strong correlation between light valence quarks of the proton and vacuum strange antiquarks with opposite spins. So the spin on $\bar{s}$ quarks should be oriented opposite to the proton spin. These strange antiquarks are from the vacuum. It means that they should accompanied by the strange quarks and the quantum numbers of these $\bar{s}s$ pairs must be the vacuum ones $J^{PC} = 0^{++}$. To preserve the vacuum quantum numbers the $\bar{s}s$ pair must be in the spin-triplet $^3P_0$ state. Therefore the spin of the strange quarks must be aligned opposite to the proton spin.

So, this polarization of the vacuum induced by the proton valence quarks creates a pair of strange quarks which is polarized in the direction opposite to the proton spin.

Of course, the proposed model is idealized and a number of problems should be clarified. For instance, it is not clear why the diagram of Fig. 6 should be dominant, to what extent the polarization of the strange quarks changes during the interaction, what is the role of the rearrangement processes, when the ϕ is created from the $\bar{s}s$ quarks of one nucleon. Such "shake-out" of the nucleon intrinsic strangeness is rather interesting to analyze. It is clear that if the $\bar{s}s$ pair has $^3P_0$ quantum numbers in the initial state then it will be hard to rearrange it to the $^3S_1$ $\bar{s}s$ state of ϕ meson in the final state. Strangeness is stored in the nucleon not in the form of the ϕ or any other known mesons. This explains quantitatively why the overall yield of ϕ mesons in $\bar{p}p$ annihilation at rest is rather small, about 5–10% of the total yield of kaons. It is not clear how the production of "open" strangeness, like kaons or K^*, should be treated in this model. However some qualitative predictions are obvious [12]. For instance, in the reaction of K^* production

$$\bar{p} + p \rightarrow K^* + \bar{K}^* \qquad (33)$$

spins of two kaons should be correlated in such a way that if annihilation take place from the initial spin-triplet state then the state with the total spin of K^* $S_{tot} = 2$ should be dominant.

In some sense reaction (33) is similar to the Λ production process

$$\bar{p} + p \to \Lambda + \bar{\Lambda} \tag{34}$$

Here the spins of Λ and $\bar{\Lambda}$ could be coupled into either a spin–singlet or a spin–triplet state. Both are possible a priori but only one - spin-triplet - is realized. The experiments [67] showed that the the spin–singlet fraction F_s in the final state of (34) is $F_s = -(7.8 \pm 5.2)\%$ at 1.546 GeV/c and $F_s = -(3.2 \pm 3.0)\%$ at 1.695 GeV/c. It was demonstrated that F_s is equal to zero within statistical errors .

The intrinsic polarized strangeness model explained this fact naturally, like dissociation of the polarized $s\bar{s}$ pair into two strange quarks, which determine the polarization of the hyperons and "remember" that they were polarized in the initial state.

5 Conclusions

The absence of the spin singlet component F_s in the $\Lambda\bar{\Lambda}$ final state of reaction (34) was analyzed in the framework of different approaches (see discussion in [13]). The explanation of this effect in terms of nucleon intirinsic strangeness is not unique. Discussing this paradox I would like to demonstrate a simple but important fact that the intrinsic nucleon strangeness model does not contradict to the already known experimental information on the baryon structure and reactions.

Moreover, all tests of the predictions of this model [12] performed up to date gave positive results. As it was discussed previously, the strong OZI violation was found not only for the vector mesons but also for tensor ones just in annihilation from the P-wave, as predicted. The effect of dominant ϕ production from the spin triplet initial state was confirmed for $\phi\pi$ and $\phi\pi\pi$ final state in $\bar{p}p$ annihilation. Especially strong violation was found in the Pontecorvo reactions of $\bar{p}d$ annihilation.

Now it is interesting to perform a systematic investigation of the spin effects in the production of strange particles. Thus it is predicted [12] that in the interaction of a polarized proton beam with a polarized proton target

$$\vec{p} + \vec{p} \longrightarrow p + p + \phi \tag{35}$$

the ϕ production should be enhanced for parallel spins of both nucleons in the initial state and suppressed for the antiparallel configuration. Corresponding experiment is proposed now at the ANKE spectrometer at COSY(Juelich) [68].

The same effect of spin dependence of the ϕ yield should manifest itself in polarized proton interactions with polarized deuterons

$$\vec{p} + \vec{d} \longrightarrow {}^3He + \phi, \tag{36}$$

It is predicted [12] that ϕ production will be enhanced when spins of the proton and deuteron are parallel. When spins of the beam and target particles are in the opposite direction, the ϕ production is predicted to be suppressed.

The measurements of the ϕ (and ω) yields in reaction (36) were performed at Saturne II for the unpolarized beam and target configuration [69]. A large deviation from the OZI rule prediction was revealed:

$$R(\phi/\omega) = (63 \pm 5) \cdot 10^{-3} \tag{37}$$

These results are promising and give credence to study the polarization effects of the OZI rule violation in these processes. The main physical advantage of studying reactions (36) of ^3He production is that they provide a possibility to studying OZI rule violation in the high momentum transfer region.

It is remarkable that the "standard" two–step model of ^3He production in reaction (36) predicts completely different behaviour. It was calculated [70] that if the vector mesons are created via the $pp \to d\pi$ and the $\pi N \to XN$ chain, then they should be produced mainly from the antiparallel orientation of the proton and deuteron spins. The value for the asymmetry

$$A = \frac{Y(\uparrow\uparrow) - Y(\uparrow\downarrow)}{Y(\uparrow\uparrow) + Y(\uparrow\downarrow)} \tag{38}$$

(where Y is the yield of ^3He for the parallel and anti-parallel orientations of the spins of protons and deutrons) near the threshold is $A = -0.95$. The intrinsic polarized strangeness model predicts that $A \approx +1$.

So it will be extremely interesting to perform these measurements.

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